Light path design for optical disk systems

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Peter Jutte
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Ter nagedachtenis aan mijn vader
Aan mijn moeder
Aan Monique
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Introduction
1.1 Why has optical recording become such a success?

Around 1925, the gramophone gave people the possibility to listen to their favorite music at the moment they liked. However, the sound quality of these 78 rotations per minute records was rather poor. Around 1950 the long play disk was introduced with a much better sound quality and extended playing time. The gramophone was the predecessor of the audio Compact Disc player. Except for some special applications the gramophone has almost disappeared. The main reason was the superior robustness and sound quality and compact size of the CD.

The gramophone was in fact the most popular so-called “storage device” for the normal consumer for a very long period. Storage devices gave people free and independent access to their favorite music, movie or other data at any moment. The well-known storage devices of today are magnetic tape recorders, floppy disk drives, hard disk drives, solid-state memories and optical disk players, recorders and drives.

In 1963 Philips Hasselt invented the compact cassette. The bright idea was to put the two reels in one small cartridge, which seriously improved the robustness and user-friendliness, in particular for start up and reverse. The compact cassette has conquered all corners of the world. All kind of analog and digital cassette tapes for data, video and audio recording followed. The storage capacity and data rate of digital tape can be very high. A disadvantage of tape is the long access time, because the tape has to be wound to the right position. A second disadvantage is the limited life time due to wear and aging. The readout of optical disks is contactless, which means no wear. The extrapolated lifetime of the various types of optical disks is more than 100 years. Next to the read-only disk the mentioned lifetime expectation applies also for the writable CD and DVD disks (besides quality incidents). However, restrictions are that the user does not expose the dye or phase change layer to extreme circumstances like intense sunlight and high temperature.

15 years ago the capacity of fixed hard disks was in the order magnitude of 20 MB. This has increased up to about 250 GB nowadays for desktop computers. The recently introduced Blu-ray Disc has a maximum storage capacity of 50 GB. In terms of capacity hard disks have won the race with optical storage. The big advantage of optical storage compared with the fixed hard disk is its removability and compatibility. The optical disk can be removed easily from the drive to be played or recorded on another drive. This makes optical storage very suitable for data distribution. Removable hard disks like Jaz, and Zip drives have not been widely accepted. The floppy disks are disappearing, because its capacity of 1.4 MB is a little dated, despite its ease of use.

Removable solid-state memories are now becoming more and more popular for portable data storage in many formats, connectors and slots. These very compact storage devices are applied in for example personal computers, digital cameras and organizers. The capacity is varying from about 128 MB up to 2 GB. The USB sticks are now widely used for hand carrying data between personal computers. They have in fact replaced the floppy disk. One of the main reasons is probably standardization of the connector: the Universal Serial Bus. A disadvantage is that the cost of the medium is rather high. If we compare optical storage with solid-state memories we notice a big price difference in the media. The price of a DVD+R (4.7GB) is nowadays roughly 1 Euro, because the disks are replicated and manufactured in an efficient process. This results in a price per MB of 0.02 Euro cents. The price of a solid-state memory of 256 MB is about 30 Euro. This is 9 Euro cents per MB. The low price per MB makes optical storage much more suitable for permanent storage and distribution. However, the most important property of CD and DVD is that it has become a standard that almost everyone is now using including the music, movie and software industry.

The main features of optical storage in comparison with other storage devices are summarized in Table 1.

<table>
<thead>
<tr>
<th></th>
<th>Optical</th>
<th>Magnetic Tape</th>
<th>Hard disk</th>
<th>Solid state</th>
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<tr>
<td>Capacity</td>
<td>++</td>
<td>--</td>
<td>++</td>
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<tr>
<td>Data rate</td>
<td>++</td>
<td>++</td>
<td>++</td>
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<tr>
<td>Access time</td>
<td>++</td>
<td>++</td>
<td>++</td>
<td>++</td>
</tr>
<tr>
<td>Removability medium</td>
<td>++</td>
<td>++</td>
<td>--</td>
<td>+</td>
</tr>
<tr>
<td>Interchangeability</td>
<td>++</td>
<td>++</td>
<td>++</td>
<td>++</td>
</tr>
<tr>
<td>Cost medium</td>
<td>++</td>
<td>++</td>
<td>--</td>
<td>+</td>
</tr>
<tr>
<td>Life time medium</td>
<td>++</td>
<td>++</td>
<td>0</td>
<td>++</td>
</tr>
<tr>
<td>Small size</td>
<td>++</td>
<td>0</td>
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</tr>
</tbody>
</table>

Table 1: Indicative comparison with other storage principles. The main advantages of optical recording are a low cost medium, removability, interchangeability and a long lifetime. With removability is meant that the medium can be removed from the drive. With interchangeability is meant that the medium can be read out or recorded on an arbitrary drive.

Next to the storage devices, the Internet has become more and more popular for data distribution during the last years. One may think that storage devices will become obsolete for the consumer in the future, because it is possible to download almost all your desired information from the Internet. Of course some way of payment must be applied, when the information is not free. However, the first thing you do if you want to keep the information is storing it on a hard disk, CD/DVD or solid-state memory. Furthermore, some information is not available on the Internet, e.g., private recordings. Moreover, the data rate of the Internet is sometimes too low to get an acceptable downloading time for large files like movies and computer software. Downloading a movie of 4.7 GB would take approximately one hour for a broadband connection of 10 Mb/s. Distribution via DVD seems to be most practical for this example. Another issue is that one has to rely on the fact that the wanted information remains available in the Internet, which is not always the case.

One may conclude that despite the alternatives, it is still impossible to imagine today’s life without the applications of optical storage. In the next section we will explain some basic principles of optical recording.
1.2 Optical recording, some basics

An optical disk is read out or written by a diffraction-limited light spot on the information surface [1]. The most widespread optical disks are a pre-recorded, recordable and rewritable CD and DVD disks. In this section the basic principles and typical values of these disks will be treated briefly.

1.2.1 Pre-recorded disks

A sketch of a pre-recorded disk (or read-only disk) is shown in Fig. 1.2. The disk substrate (or cover layer) is usually polycarbonate. It protects the information layer. The information layer consists of pits in the aluminum reflective layer. When a disk is read out, the pits are illuminated with a laser. Pits and land result in different phases in the reflected beam. The pits are narrower than the light spot on the disk. The depth of the pits is in the order of $\lambda/4$, where $\lambda$ is the wavelength of the laser. When the spot is located on a pit, the reflected wave front on the pit area is in anti-phase with the reflected wave front just outside the pit area. However, when the light spot is on a land, the entire wave front has equal phase. As a result, the reflected intensity is low when the spot is on a pit and high when it is on a land. During readout the pits generate a high frequency or RF (Radio Frequency) signal that contains the data.

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![Fig. 1.2: A simplified outline of optical disk readout.](image_url)

A simplified configuration of a optical scanning system is given is Fig. 1.2. The radiation beam of a semiconductor laser is reflected by a beamsplitter towards the objective lens, which focuses the beam on the information layer of the disk. The objective lens catches the reflected light from the disk, which will be transmitted via the beamsplitter towards the detector. Various servo systems keep the spot in focus, on the track and the disk on the appropriate rotational speed.

In the approximation of Fraunhofer diffraction of a homogeneous beam and neglecting aberrations, the spot on the disk is an Airy pattern. The FWHM (Full Width Half Maximum) diameter of the spot is $0.51\lambda/\text{NA}$, where $\text{NA}$ is the numerical aperture of the objective lens on the disk side. Table 2 shows some typical values of parameters for CD and DVD disk.
The capacity of a disk is in first order approximation inversely proportional to the spot area, hence proportional to \((NA/\lambda)^2\). As a result, the higher the numerical aperture and the smaller the wavelength, the smaller the spot and therefore the larger the possible storage capacity of the disk will be. For DVD \(NA\) is increased and \(\lambda\) is decreased in order to increase the capacity.

The same argumentation holds, when we discuss the disk capacity in terms of spatial frequency radial tracks \(1/6q'\) and spatial frequency per radial direction \(\lambda/(12q' NA)\). In the CD system \(1/6q'\) is defined as the covered distance on a track corresponding with one bit. Both for CD and DVD the shortest pit is \(3c_b\) long. Therefore, the spatial frequency of the shortest pits in the direction parallel with the tracks (the tangential direction) is \(1/6c_b\). When these values are calculated for CD and DVD, the frequency of the shortest pit is 48% of the cutoff frequency for CD and 68% for DVD. For the other direction, the direction perpendicular to the tracks (the radial direction), the spatial frequency is \(1/6q'\), where \(q'\) is the track pitch. This spatial frequency is 54% and 73% of the optical cutoff frequency for CD and DVD, respectively. The higher \(NA\) and lower \(\lambda\) result in more critical optical and mechanical tolerances for the DVD system. The relative higher spatial frequency with respect to the cut off frequency results in an even higher capacity for DVD, but it makes the DVD system extra critical for tolerances. The capacity ratio CD/DVD is 4.7/0.68 = 6.9. The ratio \((NA/\lambda)^2\) results in a factor of 2.6 in capacity. Including the higher relative spatial frequencies this factor becomes 4.9. The rest of the capacity gain is obtained by a more efficient coding technique of the DVD format and a little smaller start radius of the information area (23 mm instead of 24 mm).

The coma in case of tilt between the objective lens and the disk is proportional to \(NA^2D/\lambda\) [2] [3], where \(D\) is the cover layer thickness (Fig. 1.1). In order keep the tolerance against disk tilt reasonable, the thickness of the cover layer of the DVD disk is 0.6 mm instead of the 1.2 mm of CD. Mechanically the DVD disk has a total thickness of 1.2 mm for a proper stiffness. The 0.6 mm disk is glued against a 0.6 mm dummy as shown in Fig. 1.3.

An outline of the principle of recordable disk is given in Fig. 1.4. Typical for CD and DVD recordable disks (CD-R, DVD+R and DVD-R) is the dye material between the cover and metal reflective layer (Au or Ag). This dye material has a high refractive index \(n_d\) for the recording wavelength \((n_d \approx 3)\). Examples of these organic dye materials are merocyanine, phthalocyanine and azomethine. The dye layer is locally heated up until about 300°C by the high intensity light spot focused by the objective lens on the recording layer.

A combination of three different recording mechanisms occurs in the disk during the recording process of a recordable disk [4]. One mechanism is based on creating bubbles in the dye. A bubble is formed in the dye material during the heating of the disk by the spot (Fig. 1.4b). At the position of the bubble the high refractive index dye material has disappeared. Consequently, the optical path to the reflective layer has also decreased. This is equivalent to a pit on the pre-recorded disk (Fig. 1.4a). The optical depth of such a bubble pit is \(2(n_d - 1)A ,\) where \(A\) is the mechanical height of the effect, which is for this case the bubble height. Another recording mechanism is that a pit is formed in the dye layer (Fig. 1.4c) with an optical depth of \(2n_d A\). The third mechanism is a bump in the interface of the dye and cover layer (Fig. 1.4d). The
optical depth is \(2(n_c - n_r)\lambda_c\), with \(n_c\) the refractive index of the cover layer. The cover layer is made from polycarbonate, therefore: \(n_c \approx 1.57\). The optical depth of the total recorded effect is in the order of magnitude of \(\lambda/4\), equivalent to the pit on the read-only disk. Because of the properties of the dye material, the disks are very wavelength sensitive for both recording and reading. A big advantage of the recordable disk is its high reflectivity. For instance, a written CD-R disk meets the specification of the Compact Disc standard, hence it can be played on every CD-player in the world.

Both for CD-R(W) and DVD+-R(W) the marks are written on a pre-groove. This pre-groove is necessary for tracking on an empty disk. It carries also time and address information and other disk properties like type of disk and required recording power. The value of \(N.A\) of a CD or DVD recorder is a little higher in comparison with the reader: 0.5 for CD and 0.65 for DVD in order to increase the power density and writing accuracy.

### 1.2.3 Rewritable disks

The principal of the current CD and DVD rewritable disks (CD-RW, DVD+RW and DVD-RW) is phase change recording [5] [6]. This technique makes use of the difference in optical constants between the amorphous and the crystalline state of a material. Examples of phase change materials are GeSbTe and AgInSbTe. The amorphous state has a lower reflectivity than the crystalline state. This means that amplitude pits are made instead of phase pits. A schematic layout of the disk is shown in Fig. 1.5.

![Fig. 1.5: The phase change rewritable disk.](image)

The phase change layer is surrounded by two interference layers \(I_1\) and \(I_2\). The interference layers enhance the optical effectiveness and influence the thermal properties like heat conductance. The key issue here is the time of cooling down. During writing, amorphous domains are made due to the quenching rate. For instance, a pit with a length of 3 times the channel bit \(c_1\) is written with short pulses of the write power \(P_w\), in the light spot as shown in Fig. 1.5. During writing the cooling down time is shorter than the time for crystallization. Erasing is performed by constant power of about half the write power: the erase power \(P_E\) (amorphous-crystalline annealing step). In that case the time for cooling down is longer than the time for crystallization. Direct overwrite of old data with new data is possible. A lower reflectivity of the disk often means a higher absorption in the information layer and thus a better sensitivity. The reflectivity of rewritable disk is therefore rather low (\(\approx 25\%\)). Therefore “Multi Read” CD-players are adapted in order to be able to read the low reflectance CD-RW disks. The DVD+RW disk can be read out by the majority of the DVD players, because they have to read also the low reflective pre-recorded dual layer disks (See Section 2.1.2.).

### 1.3 Scope

The light path or the optics of a DVD recorder consists of the lasers, the detectors, the lenses and the other optical components. It generates the diffraction-limited light spot on the disk and the electro-optical signals from the disk, like the RF signal from the pits and the signals for focusing, radial tracking, address or timing readout and laser power measurement. The light path is part of the optical pick-up. The optical pick-up contains, in addition to the light path, the magnetic objective lens actuator for focusing and tracking movement, and front-end electronics: detector preamplifiers and laser drivers.

The author has designed several generations of light paths for CD and DVD recording for Philips Optical Storage, in which a number of new principles have been applied. Some of these designs have proven themselves in practice extensively, because these optical pick-ups have been or are still manufactured in mass production. Several aspects of the mentioned designs are discussed in this thesis including theoretical modeling and results.

DVD recorders are relatively low cost consumer products, nevertheless, they have to record and read at sometimes difficult circumstances, e.g., at a high environmental temperature on low quality disks. The recording and readout speed of the disks is the most important specification aspect of a drive. The DVD system tolerances are more critical than the CD system tolerances, which will have impact on the optical design of the recorder. Compatibility with the CD standard is required for DVD recorders: the possibility of reading or recording disks according to the old lower density standard must be provided. How the various requirements can be translated in design choices of the light path will be described in this thesis. Various new principles will be treated.
1.4 Thesis outline

On order to place the results of this thesis in a framework several trends in optical recording are discussed in Chapter 2. The history of optical recording will be dealt with, starting with the Video Long Play disk in the early seventies until the recently announced blue laser drives. Typical trends of optical recording products are outlined. The various important disk types are compared briefly. The future of optical storage is discussed: What will be the successor of the recently introduced Blu-ray Disc?

An introduction in the most important optical principles applied for reading or writing a disk, including a brief description of the rest of the system of a recorder, is given in Chapter 3. We deal with the light path, the optical pick-up, the principle of optical disk readout, the recording spot and the generation of optical servo signals. Dynamics and servo systems and front-end electronics will be outlined briefly.

A geometrical model is used during the design of the light paths. This geometrical light path model of the three spots astigmatic optical pick-up is given in Chapter 4. It results in various analytical expressions of the relations between the light path design parameters.

Designing a light path for an optical pick-up unit is a complicated task with many disciplines involved. The general approach is presented in Chapter 5 with the description of a multidisciplinary design process with technical and non-technical aspects. The light paths described in this thesis are designed following this process.

The light path that will be discussed first, is the dual detector light path. This is the subject of Chapter 6. This light path applies the finite conjugate compatibility principle for CD readout. A major disadvantage of the finite conjugate compatibility principle is the coma due to the stroke of the objective lens, which is necessary for radial tracking. The solution that was invented for this problem is treated by analytical modeling and numerical simulation with a ray-tracing program. This dual detector light path, including the mentioned solution, has been applied in the first generation Philips DVD video recorders.

In Chapter 7 the design of the single detector light path is discussed. It is the logical successor of the dual detector light path. In the design process of the single detector light path, the focus has been on maximum power efficiency in order to allow for a high rotation speed of the disk during recording, while not compromising on a low cost price and a good reliability. It contains various new principles to combine these ambitious requirements. The new principles are founded by analytical modeling and simulation. This single detector light path is applied in several DVD+R(W) data drives and video recorders.

The next step is the application of the dual wavelength laser principle for DVD recording as considered in Chapter 8. A dual wavelength laser is a laser device that has two laser cavities in order to generate two beams with different wavelength. The issue is how to integrate a dual wavelength laser in a single detector light path in such a way that the drive is suitable for high-speed DVD and CD recording. Several design innovations that fulfill these requirements are proposed and explained by means of theoretical modeling.

When a designed light path is applied in a practical recorder, several system aspects should be investigated in more detail. An example is discussed in Chapter 9. In order to be able to record a writable CD or DVD disk, the recorder needs timing or address signals and information about the disk properties. For the DVD system, these signals appeared to be very sensitive for optical tolerances, which were not fully understood. Therefore, the effect of aberrations and other imperfections on the quality of these signals is explored by simulation and theoretical modeling.

The main conclusions of this thesis are given in Chapter 10.
Trends in optical Recording
2.1 Disk types in historical perspective

In this section the optical disk types and standards are discussed in historical context. An overview of the history is presented in Section 2.1.1. Section 2.1.2 discusses the trend of the increasing capacity of the disks. The parameters of the most relevant disk types are outlined in Section 2.1.3. Diagrams with the relations between the many CD and DVD disk standards [7] are given in Appendix A.

2.1.1 The history of optical recording and its disk standards

The history of optical recording started in the late nineteen-sixties, when, among others, the Philips Research laboratories studied the feasibility of storing signals on an optical disk [8].

Analog video disks

The analog Video Long Play (VLP) system was presented to the international press on September 5, 1972 [9]. The market introduction was in the United States in 1978 with the name “Laser Vision”. The outer diameter of the disk was 30 or 20 cm. The analog video disk consisted of two 1.3 mm PMMA (polymethyl methacrylate) substrates with two information layers configured in such a way that it could be played on two sides. Each side could contain about one hour of video [1]. The reading spot on the disk was generated by a HeNe gas laser and an objective lens with a numerical aperture of 0.40. Infrared semiconductor lasers were applied in later players. In order to get an equal spot size with this new wavelength the numerical aperture of the objective lens was increased to 0.50. The analog audio signal was replaced by a digital signal around 1985. The name was changed into “CD-Video”. Despite the revolutionary technology of the analog video disk the big breakthrough in Europe for the consumer did not occur. However, it became a success in Japan (especially for Karaoke) and in the United States. Professional applications were found in the interactive mode, for instance, for training aids and flight simulators. Nevertheless, the most important impact of this system was that it laid the technological foundation for the Compact Disc.

CD-Audio

Digital signal processing in combination with the optical disk technology resulted in the possibility to store about one hour of high quality digital audio on a small optical disk. The first models of the Compact Disc player were shown to the international press in 1979. In the same year Sony and Philips signed an agreement to cooperate in system development with the aim of establishing CD as a world standard for digital audio. The players could be small-sized from the beginning, because this system was based on the small AlGaAs semiconductor laser. The size of the disk should be limited to the dimension of a beer coaster in order to be carried anywhere easily. The definite CD system was fixed in 1980. This was also the case for the dimensions. The diameter of the CD is now 12 cm. In the beginning the diameter was slightly smaller. However, the 9th symphony of Ludwig von Beethoven consists of four movements that are preferably united on one single disk. When conducted by Herbert von Karajan, the duration was about 72 minutes. The diameter was chosen to 12 cm, consequently the capacity was 74 minutes, which was enough for Beethoven’s 9th. The diameter of the center hole should be between a gramophone single and long play disk in order to enable a new clamping method of the disk. The diameter of a Dutch “Dubbeltje” (10 cent coin) was estimated to be a good compromise: 15 mm [10]. The market introduction started in 1982 in Japan. The European and American introduction took place in 1983. About two years later, which was earlier than expected, Compact Discs started to outsell gramophone disks. The main reason for the success of the CD-Audio was its superior audio quality, robustness and compactness compared to the gramophone disk. Many other (mainly Japanese and Korean) companies started developing and manufacturing CD-players.

CD-ROM

When it is possible to put sound in a digital form on an optical disk, it is also possible to do so with computer data. Therefore, Philips and Sony agreed on a standard for Compact Disc Read Only Memory (CD-ROM) in 1983. It took approximately ten years before almost every personal computer had a CD-ROM drive and most software packages were distributed via CD-ROM, because most of them had become too big to be put on a reasonable number of floppy disks. Another reason for the success of CD-ROM was that it was based on the same standard as the already widely accepted CD-Audio.

Professional Write Once systems

A category of recordable disks was based on an ablative technique. The process was irreversible, like the current recordable disks. Hence, these systems were called “Write Once” systems [1]. The most commonly applied technique was hole burning in a Te-alloy. The reflectance of these disks was rather low: about 40%, measured on a non-recorded part of the disk. This is much different from the reflection of CD-Audio and CD-ROM disks, which is approximately 80%. Many mainly professional Write Once systems were launched in the nineteen-eighties under various names (sometimes emphasizing a feature of the system) like WORM (Write Once Read Many), DRAW (Direct Read After Write) and DOR (Digital Optical Recording).

Magneto-optical recording

Erasing and rewriting of the data is possible by magneto-optical recording. The Magneto-Optical disk (MO-disk) is based upon the Kerr effect in reflection (see [11] for details). Several systems based on this technology were introduced at the end of the nineteen-eighties. Many companies introduced different formats using 5.25 inch disks and 3.5 inch disks. A disadvantage of all these different MO data drives is that exchangeability between the systems is not possible. Mini Disc (MD) is a small MO-system with a disk diameter of 2.5 inch. The data density was equal to CD. It could contain one hour of compressed audio. Sony launched the MD in 1992. A disadvantage of magneto-optical recording is that a more complex recorder and read-only player is necessary, because of the polarization sensitive readout and the magnetic field required for recording.
CD-Recordable

Dye materials have also been used for professional Write-Once systems (mostly ablative). In 1988 the company Taiyo Yuden invented a write once disk featuring a dye metal layer stack, resulting in high sensitivity at the 780 nm recording wavelength as well as a high reflectivity and a high signal modulation at the same wavelength. This technology made a writable disk possible that could fulfill for 100% the CD-standard, which is demanding high reflective disks with a recording power that is in reach of a cheap semiconductor laser. Hence, such a disk could be played on any existing CD-Audio or CD-ROM player. The threshold for acceptance of such a system was expected to be very low. This disk was called “CD Write Once”, because the data can be written only once. The name was later changed into “CD Recordable” or CD-R in order to emphasize the positive side instead of the negative property. The first applications were professional audio recording, professional data recording and Photo-CD.

CD-ReWritable

The disadvantage of CD-Recordable was that it is still a write-once system despite the new name. The erasable disk was found in the phase change technology [5] [6]. The first attempts were to find a high reflective material in such a way that it is possible to make a 100% CD compatible disk like the CD-R disk. This requirement appeared to be too difficult. Therefore low reflectivity disks were chosen. Consequently CD-Audio and CD-ROM players and recorders were adapted with an extra amplification in case of play back of such a disk (since 1995). The name “CD-ReWritable” or CD-RW was chosen. A few years later almost every personal computer had a “CD Burner” drive for recording on CD-R and CD-RW disks.

Cd-i and Video-CD

Cd-i (Compact Disc interactive) was launched in order to get an interactive CD medium in 1987. The main purpose was learning and entertainment. It was a rather limited success. Some years later, these kinds of applications were played on the personal computer by means of CD-ROM. However, based on the CD-i technology, a digital video disk was defined with 74 minutes of compressed video. The name was “Video-CD” or VCD. This medium became very popular in China around 1996. One of the reasons was that the video tape recorder was almost absent in China. Video-CD should not be confused with the earlier analog CD-Video, which was explained earlier.

DVD

The CD system was based on the infrared (λ = 780 nm) AlGaAs semiconductor laser. In the beginning of the nineties the red AlGaInP semiconductor lasers became commercially available. Furthermore, a more capacity was required on a single disk, in particular for digital video to get a better picture quality. In 1994 Philips and Sony decided to use a λ = 635 nm laser, which wavelength was very close to the HeNe laser. The disk capacity was 3.7 GB with N.A = 0.52. The cover layer thickness D was 1.2 mm in order to keep the disk manufacturing process equal to the CD process and to make compatible players with CD in an easy way. The disk was called Multi Media CD (MMCD). A dual layer disk of 7.4 GB with one full reflective and one semi-transparent information layer in order to double the capacity was also an option. Other companies, with Matsushita and Toshiba in the lead, introduced in the same period their own standard: 5 GB, D = 0.6 mm and λ = 650 nm. The disk was named Super Disc (SD). In December of 1995 the systems were merged into DVD (Digital Versatile Disc). Parts from both previous standards were incorporated in the new one. For instance, λ = 650 nm and D = 0.6 mm was taken from SD and the channel code EFM+ from MMCD resulting in a capacity of 4.7 GB on a single layer disk and 8.5 GB on a dual layer disk. The dual layer disk was also taken over from MMCD. DVD became in particular popular for video players. Most of the DVD players are also able to read CD and CD-R(W). In 1999, the first DVD/CD-R(W) Combo’s or Combo’s were introduced: a combination of DVD-read and CD-R(W) recording. This was just an intermediate step. DVD recording is far more interesting.

DVD recordable and DVD rewritable

Several DVD recordable and rewritable systems were launched around 1996. The companies came with rather low-density systems in comparison with DVD read-only. Matsushita and Toshiba and some others introduced DVD-RAM (Random Access Memory) with a capacity of 2.6 GB. Pioneer came with DVD-R 3.9 GB based on a high power 635 nm laser. Philips and Sony came with their +RW system of 3.0 GB. None of these systems really survived, because DVD is 4.7 GB and therefore the DVD rewritable systems were expected to have also 4.7 GB. DVD-RAM, DVD-R, DVD-RW, DVD+RW and DVD+R were all upgraded to 4.7 GB (1998-1999). The different recordable and rewritable DVD disks and some technical properties and mutual differences will be explained in Section 2.1.3.

Blu-ray Disc

Blue lasers are investigated for many years already. They will make a new step in disk capacity possible. Various types are possible, for instance, frequency doubling of λ = 820 nm infrared lasers, and real blue lasers: ZnSe and GaN. The GaN-laser of the company Nichia turned out to be the most attractive one. In 1997 Philips and Sony started discussions on the “DVR” (Digital Video Recorder) system. The first 9.2 GB system was based on a red laser λ = 660 nm, D = 0.1 mm and N.A = 0.85. A blue laser version was appropriate for about 25 GB on one layer. The standard was announced in April 2002 and supported by 9 companies (Philips, Sony, Matsushita, Pioneer, Hitachi, Samsung, LG, Thomson and Sharp). The name was changed into Blu-ray Disc. Toshiba and NEC came with a competing format AOD (Advanced Optical Disc); this name was later changed into HD-DVD (High Density DVD). This disk contains 15 to 20 GB on one side with N.A = 0.65 and D = 0.6 mm.
2.1.2 Capacity increase by the introduction of new disk standards

The trend of increasing capacity on a 12 cm disk is given in Fig. 2.1 for the CD, DVD and Blu-ray Disc (BD) formats. Each new standard contains approximately a factor of 5 to 7 more capacity on one layer than its predecessor does: CD typically 680 MB \(^{(*)}\), DVD 4.7 GB \(^{(*)}\) and BD typically 25 GB \(^{(*)}\).

![Graph of capacity increase](image)

Fig. 2.1: Trend of increasing capacity \(^{(*)}\) of optical disk standards in case of data disks \(^{(**)}\).

As mentioned in Chapter 1 the capacity increase is gained due to a lower \(\lambda\), a higher NA and smaller pits relative in respect to the spot diameter, which became possible due to smarter signal processing. The utilization of more than one layer is an extra possibility to increase the disk capacity with approximately a factor of two. This technique is applied in DVD and Blu-ray discs. The diffraction-limited spot can be focused on two layers with a mutual distance \(D\), as shown in Fig. 2.2.

![Diagram of dual layer disk](image)

Fig. 2.2: The dual layer disk contains two information layers: one with a fully reflective layer and one with a semi-reflective layer with a reflection coefficient of approximately 30%. The distance \(D\), between the layers is called the spacer layer distance.

The signals from such a disk are lower than from a single layer disk, because the layer on the bottom is semi-transparent while the upper layer on the top is fully reflective, in order to be able to readout both layers.

2.1.3 Comparison of some parameters of the disks

The specific numbers of CD, DVD and BD are given in table 2.1. The pit structure is becoming finer and finer from CD towards DVD and BD. The linear rotation speed \(v_{\text{rot}}\) increases also. This results, together with the smaller pits, in a higher frequency of the shortest pits. The final user data rate and the capacity are determined by the efficiency of the channel code. The capacity of a dual layer DVD disk is not exactly a factor of two, because some margin is reserved for the extra spherical aberration, which arises due to the extra spacer layer of 55 \(\mu\text{m}\).

The ratio of the spatial frequency of the shortest pits with respect to the optical cutoff frequency as discussed in Section 1.2.2 is 80% for BD, which is even higher than for DVD (68%). The coma, which arises in the case of disk tilt, is approximately proportional to \(\lambda\text{ND}/\lambda\) \(^{[2]}\) \(^{[3]}\). Therefore the cover layer thickness \(D\) of the BD disk is decreased to 0.1 mm in order to get a reasonable disk tilt sensitivity with \(\lambda\text{NA}/\lambda = 0.85\) and \(\lambda = 405\text{ nm}\). However, the thinner the cover layer the smaller the beam on the cover layer top. This makes BD very critical for dust particles and scratches on the cover layer top. Measures to overcome this problem are a disk cartridge or a hard coat on the cover layer topside, which allows cleaning without making scratches.

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\(^{(*)}\) The origin of the name “byte” is the expression “by eight”. A byte is generally 8 bits. There is confusion about the capacity of kilobyte. It can be 1000 bytes (kB) or 1024 bytes (KB). This is also the case for megabyte (MB) that can be 1024\(^{2}\) bytes or 1000\(^{3}\) bytes or even 1000-1024 bytes (floppy disk). A gigabyte (GB) can be 1000\(^{3}\) or 1024\(^{3}\) bytes. The IEC has decided in 1998 to use the factors of 1000. Therefore, for the capacity of an optical disk in this thesis, 1 MB is considered as \(10^{6}\) bytes and 1 GB as \(10^{9}\) bytes.

\(^{(**)}\) A 74-minutes CD-Audio disk has a capacity of 0.815 MB. However, a CD data disk (for instance, CD-ROM) contains a storage capacity of 0.680 MB typically due to the used capacity, which is needed for the extra error correction.
Table 2.1: Specific typical numbers of the CD, DVD and BD disk (* = dual layer disk).

Table 2.2 displays some differences in optical system parameters between CD-R(W), DVD+R(W), DVD-R(W) and DVD-RAM. The objective lens numerical aperture NA for CD and DVD recording has a slightly higher value than for read-only for CD and DVD+R(W). The higher value of NA results in a slightly smaller spot for better recording properties and also in a higher power density. In practice, most DVD-RAM and DVD-R(W) players also have NA = 0.65.

Table 2.2: Comparison of CD-R(W), DVD+R(W), DVD-R(W) and DVD-RAM.
A CD-R(W) disk also contains a wobble. It is a frequency-modulated signal with a carrier frequency of 22.05 kHz at a scanning speed of 1x. So the period is approximately 60 μm, which is much longer than the pits. The signal retrieved from the wobble is called "Absolute Time in Pre-groove" (ATIP).

DVD-RAM is a completely different format. A DVD-RAM disk belongs to the so-called "land groove" systems. This means that one track is written on a groove, the second (neighboring) track is written on a land and the third track is written on the next groove. DVD-RAM applies "headers" for the address signal. In this case the pre-groove is interrupted by an area with pits, which contains the address information. It is only available as rewritable disk. It this thesis DVD-RAM is not treated in detail, because this format is not as widely used as DVD+R(W) and DVD-R(W).

The radial tracking and wobble and pre-pit signal are read out as "push-pull signals", which means that the two halves of the beam from the disk are measured independently in radial direction and subtracted in order to get the signal. This will be explained in more detail in Chapter 3.

2.2 Optical storage applications (PC and audio/video market)

Most applications of optical storage were professional at the beginning: dedicated specifications, low production quantities and high selling prices. Examples are the interactive Laser Vision and old Write-Once systems. CD-Audio was dedicated to consumer usage from the start. Most of today’s applications of optical storage are consumer applications: standard specification, high production volume and low cost price. The main applications are for the personal computer and for audio/video players and recorders.

2.2.1 The market for personal computer applications

Very typical for the personal computer market and, therefore, also for the optical storage products is the rapid succession of new products. A speed upgrade of a drive is introduced every few months.

This is called the "speed race". The so-called "x-factor" is the multiplication factor of the reference velocity $v_{ref}$ which is typically 1.41 m/s for CD and 3.5 m/s for DVD as given in table 2.1. Fig. 2.4 and 2.5 indicate the speed races for CD and DVD for ROM, recordable and rewritable for desktop computers. The speed race for recordable products shows the same picture a few years later. In the end the maximum speed recording is equal to the maximum speed of reading. The speed upgrades are covered.
by new disk standards as shown in appendix A for the CD case. This is in particular necessary for rewritable disks, because high-speed rewritable disks cannot be written at very low speed, since the cool down time is a typical parameter of phase change recording as explained in Section 1.2.

The speed race for CD reading and recording ends at about 48x to 52x. This figure is 16x to 20x for DVD. The mentioned figure is the speed at the outer radius of the disk (58 mm). Hence, the maximum angular velocity is about 160 Hz. The angular velocity is limited by mechanics. The centrifugal force and the air friction are both proportional to the angular velocity squared. The forces on the disk and drive and the power dissipation are becoming too high. On the other hand the improvement in absolute waiting time becomes smaller and smaller. Because of the angular velocity limitation for the higher speeds, the disk is running at on a constant angular velocity (CAV) instead of a constant linear velocity (CLV). Therefore, the mentioned speed is for CAV only obtained when the diffraction-limited spot has reached the outer radius of the disk (see Section 3.8.3).

The fast succession of speed upgrades of computer drives means that, for instance, an optical pick-up unit should be designed in such a way that it can follow the speed race only by a few adaptations like a new laser (more power) or a modified objective lens actuator. If a company can follow this speed race, a proper price can be asked for his products.

Fig. 2.5: The speed race for DVD (ROM, recordable, rewritable and recordable dual layer: DL). The x-factor is the multiplication factor of the reference velocity $V_{ref}$.

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Fig. 2.6: World market optical storage drives for the personal computer (Estimation, source: [12] Philips Optical Storage).

2.2.2 The market for audio, video and game applications

For audio and video fast succeeding upgrades are not required, however the product price combined with a high quality are discriminating factors for the customers. Due to a heavy competition, a price erosion occurs. The price of a DVD player is nowadays about 80 Euro. At the start of a new disk system the prices are about ten times higher. High quality means good lifetime, robustness and playing and recording of all disks (also disks of bad quality). This means a challenge in designing robust and cheap components. High production volumes are necessary in order to have some margin. Therefore, synergy with the personal computer products by using the same or alike components will help.
Figures of the world market for audio, video and game products are given in Fig. 2.7. The CD player function is still important. CD players have replaced cassette players with hard disk recorders for temporary storage give people the possibility to record a disk if they want to keep their recordings. The audio CD-recorder has almost disappeared. One of the reasons is the special CD-R and CD-RW audio disk with extra fee.

Super Audio CD generates very high quality audio in 5 or 6 channels. This disk can be played also on a normal CD player in stereo, because it has two information layers: one CD layer at 1.2 mm and one high-density layer at 0.6 mm distance from the substrate surface. The high-density information layer is put on a dichroic coating, which is transparent for $\lambda = 780$ nm and reflective for $\lambda = 650$ nm.

Next to audio and video, optical storage is used in many other consumer applications. Computer game consoles like “Xbox” and “PlayStation 2” get very realistic due to the usage of DVD disks. Car drivers are guided by the car navigation systems to find their destination. CD-s and DVD-s are also applied in these systems.

2.3 What will be the next step after Blu-ray Disc?

2.3.1 Higher capacity

The difference in storage capacity between the several generations of optical disk systems, CD, DVD and BD, is a factor of 5 to 7 as shown in Fig. 2.1. A new, even higher density system may come after BD. The next step should also be a factor of 5 to 7 more capacity on a disk in order to make it worthwhile to develop a new system. Several techniques are possible that all have their pros and cons. The most obvious way is to increase the numerical aperture and/or decrease the wavelength. The options are outlined in this section.

**Solid Immersion Lens**

For the numerical aperture of the objective lens $N_A$ holds: $N_A = n_c \sin \alpha$, where $n_c$ is the refractive index of the cover layer material and $\alpha$ is the half cone angle of the focused beam towards the disk. The principle of frustrated total internal reflection is applied. When the distance between disk and objective lens is lowered to a small gap of a few nanometers, the light can go from objective lens towards disk. Such a lens is called a Solid Immersion Lens or SIL [13] [14] [15]. This principle is also called “near-field readout”. Two technologies are possible to keep the distance between disk and lens at such a low distance. One is to use the “Slider” technique with a small air film in the gap between disk and lens acting as an air bearing like on a magnetic hard disk. This technique is not preferable for a removable disk system, because of dust. Another possibility is using a normal magnetic lens actuator, which keeps the distance at about 50 nm in combination with an error signal measuring of the amount of light coupled into the disk. The higher the refractive index of the material of the disk, the higher the numerical aperture and the disk capacity can be. By using, for instance Bi$_2$Ge$_3$O$_9$ ($n_c \approx 2.3$) and $N_A = 2.05$ it is possible to store about 150 GB on a 12 cm disk with $\lambda = 405$ nm [16]. A dual layer disk in combination with a SIL is possible when using a slightly lower numerical aperture [17].

**Deep-UV**

By applying a deep-UV (Ultra Violet) laser the wavelength is decreased towards, e.g., $\lambda = 260$ nm. When using $\lambda = 260$ nm instead of $\lambda = 405$ nm, the capacity is increased by factor of 2.4. A semiconductor laser type is required in order to make a compact and cheap drive. However, deep-UV semiconductor lasers are nowadays far from feasible. Another important disadvantage of deep-UV recording is that plastics and many glasses are not applicable anymore, which result in extra cost for a drive.

**Super resolution**

Super resolution is a technique in the recording layer, which substantially enlarges very small effects, when they are heated by a laser spot. These temporarily enlarged effects are detectable for an optical readout system. A well-known example is the MAMMOS technology: Magnetically Amplifying Magneto Optical Systems [18]. When the disk is heated up in combination with a magnetic field the magnetic domains are enlarged (domain expansion). It is possible to reach about a factor of 7
with respect to Blu-ray disk with $NA = 0.9$ and $\lambda = 405$ nm. Prototype players based on this technique have been shown already. Another possibility is Super RENS (Super Resolution Near field Structure) [19] [20]. With this technique based on phase change a factor of 5 in capacity gain is possible. However, Super RENS is still in a very early stage.

**Multi-layer structures**

The DVD and BD system already have the option of a dual layer disk. When the number of layers is increased towards more layers the disk capacity will be increased proportionally to the number of layers. However the most important penalty is the loss of signal to noise. Fluorescence layers in the disk can improve this issue. These layers enhance the signal from the disk [21]. Another consequence of the multi-layer disk is the extra spherical aberration that arises due to the varying number of layers, which have to be passed by the beam towards the read or written information layer. The spherical aberration is, in good approximation, proportional to $NA^4$ and inversely proportional to $\lambda$ [2]. Several techniques are available to correct for this spherical aberration, for instance, movable lenses or a liquid crystal cell. A 4-layer BD disk will contain 100 GB storage capacity on a 12 cm disk.

**Holographic data storage**

A principle to increase the disk capacity towards very high values is holographic data storage. It has been explored and discussed in the literature for more than 25 years. The principle of holographic data storage is based on the retrieval of a wave front [22] [23] [24]. A picture of the configuration is given in Fig. 2.8.

![Fig. 2.8: A schematic picture of the configuration of holographic data storage.](image)

A laser beam is split into a reference beam and a signal beam. The signal beam is modulated by a “Spatial Light Modulator”. When the two beams interfere a volume interferogram arises in the disk. The hologram is read back with an array of photo detectors when the disk is illuminated by the reference beam. By varying the impinging angle of the reference beam with respect to the disk, several holograms can be read-out. Another method for separating the holograms is changing the wavelength. A set of holograms in a volume in the disk is called a “book”. The different volumes can be readout by rotating the disk. The target value of storage capacity is about one TB (1000 GB) on a 12 cm disk. Recently, several breakthroughs have been achieved on recording materials. Next to the non-linear crystals, organic polymers are coming up [25] [26]. A disadvantage of holographic data storage is the rather complex optics in comparison with the normal disk with pits. For the Spatial Light Modulator a liquid crystal array can be applied. CMOS or CCD cells are suitable detector arrays. Next to the huge capacity an advantage of this system is the high data rate due to the parallel readout of many bits.

**2.3.2 Miniature drives**

Another possible type of successors to the Blu-ray Disc format might be the miniature optical drive. Since the start of CD the typical diameter of the most popular optical drives disk is 12 cm. When a high storage density is available, it can be interesting to put a reasonable storage capacity on a small disk. Such a system may be suitable for all kind of portable applications where the advantages are required of optical storage mentioned in Chapter 1 like a removable cheap medium. Examples are camcorders, organizers, mobile phones or small notebook PC’s. When using the BD technology, 1 GB can be stored on a 2 Euro coin sized disk. Figure 2.9 shows a prototype of such a very small drive [27] [28]. The main problem for such kind of small optical drives is how to compete with the very compact solid-state memories.

![Fig. 2.9: Prototype of a very small optical drive using a blue laser.](image)
2.4 Summary

This chapter gives an overview of the trends in optical storage. Optical disk types and standards are discussed in the historical context. The parameters of the most relevant disk types are discussed. After several professional optical disk systems the 12 cm diameter CD was the first generally accepted optical disk. The capacity of optical disks is increased by introducing a new disk generation with the same diameter. The time between these introductions is roughly 10 to 15 years. The increase of the storage capacity of the optical disk starting with CD, via DVD towards the recently introduced Blu-ray Disc is approximately a factor of 5 to 7 in capacity for each step. The possibility of reading out the smaller pits is largely achieved by an increase of the numerical aperture of the objective lens and a decrease of the laser wavelength. The utilization of more than one layer is an extra possibility to increase the disk capacity for DVD and Blu-ray Disc with approximately a factor of two. Within a disk generation the data rate of the computer drives is enlarged by increasing the rotation speed of the disk during reading or writing the disk, the so-called “speed race”. The speed is limited by the angular rotation speed of the disk, which is approximately 160 Hz, due to mechanical constraints.

A possible next generation optical disk after the Blu-ray Disc can be reached by different methods. Decrease of the laser wavelength towards deep-UV is not very likely, because this wavelength excludes the application of plastic and most glass types, which makes a cheap player, recorder or drive difficult. A further increase of the numerical aperture beyond a value of 1 is possible with the Solid Immersion Lens technology, which can result in a capacity increase of roughly a factor of 6 with respect to the Blu-ray Disc format. A possibility to increase the disk capacity towards very high values is holographic data storage, by using the volume of the disk. However, disadvantages of holographic data storage for non-professional applications are the rather complex optics and the totally different disk technology in comparison with the current disks. Therefore, it is more expected that the increase in capacity will also come from the utilization of more than two layers in combination with the Blu-ray Disc numerical aperture.

In this chapter a description is given of the history and the trends in optical recording for the reader to be able to understand the framework of the various light path designs described in this thesis. In the next chapter the most important optical principles as they are applied for reading or writing a disk, including a brief description of the rest of the system of the recorder, will be discussed.
3.1 Introduction

In this chapter an overview of the optical principles and technologies of an optical disk recorder will be given, including an outline of the other disciplines applied in the recorder.

In Section 3.2 the principle of reading out an optical disk will be explained briefly, using scalar diffraction theory, as described in the literature. The intensity distribution and wave front aberrations of the beam and its effect on the diffraction-limited spot on disk will be treated in Section 3.3.

The light spot follows the pits or pre-groove in the information layer in two directions: perpendicular to the disk surface (focusing) and perpendicular to the direction of the tracks (radial tracking). The optics generates signals for de servo loops for focusing and radial tracking. The most important optical focusing and radial tracking methods are explained in Section 3.5 and 3.6, respectively.

The composition of laser(s), optical components and detector(s) that generates the diffraction-limited spot and the electro-optical signals from the disk, is called the light path. The relevant light path principles for this thesis and its components are presented in Section 3.7.

An optical disk recorder is a complicated system. It would take a few hundred pages to describe it all in detail and this would be out of the scope of this thesis. Nevertheless, in order to understand the relation with the optical system, the basic engine of the recorder will be explained briefly in general in Section 3.7, while the mechatronical aspects are outlined in Section 3.8. The most relevant parts of the electronic system principles for reading and recording the data are discussed in briefly in Section 3.9 and 3.10, respectively.

3.2 The Principle of optical disk readout

3.2.1 Introduction

In Fig. 3.1 (a) shows a schematic picture of the pits on a disk and the RF signal. When the spot on disk is on a pit the power on the detector is low. When the spot is on a land the power on the detector it is high. Fig. 3.1 (b) shows the "eye-pattern".

![Fig. 3.1: The RF signal on the detector and the pits (a) and the "eye-pattern" (b).](image)

The “eye-pattern” is a multitude of curves of the RF signal of several pit sequences put upon each other, starting at a random position $Kc_b$ with $K$ an integer and $c_b$ the channel bit length. When the RF signal is shown on an oscilloscope with a proper trigger setting, the “eye”-pattern arises. A practical example will be shown in Chapter 7 (Fig. 7.18). The diamond shaped empty spaces are called “eyes”. The pictures indicate that short pits have a lower modulation than the long pits. How these and other signals from the disk can be calculated is subject of this section.

Most of the phenomena relevant for this thesis can be described by the scalar diffraction theory, therefore the treatment is limited to the scalar effects. In order to get insight in the readout principle, the scalar diffraction theory will be explained in a short overview. A general treatment of diffraction optics can be found in [29]. Various articles on scalar diffraction theory related to reading out an optical disk exist in the literature: One of the first rigorous treatments was made by H.H. Hopkins [30]. A clear description of the readout principle of an optical disk is given by Braat in Chapter 2 of [1] and by Braat and Bouwhuis in [31]. Other treatments are given in [32] and [33]. Polarisation dependent diffraction effects are only explained by means of the more thorough vector diffraction theory as provided in [34], [35] and [36]. In the next sections an outline is given of the of the scalar diffraction theory equivalent to the treatment in Chapter 2 of [1].
3.2.2 Huygens-Fresnel

The capacity of an optical disk is limited by the diffraction of light. Therefore, in this section the diffraction at the stop or pupil of the objective lens is considered. Fig. 3.2 shows a sketch of an aperture with monochromatic light and a plane of observation. The aperture represents the stop in front of the objective lens. The wave front is focused towards the observation plane or disk plane. The radius of the wave front equals the image distance $v$ of the objective lens to the focus point on the disk. The distance between the lens plane and observation plane is $z$.

According to the Huygens principle the wave in the aperture can be considered as a new source, which consists of secondary point sources. The new wave front can be found by constructing the envelope of the secondary wavelets generated by the point sources. Fresnel stated that at the amplitudes of all waves originating at various points must be added in order to get the final wave in the observation plane.

![Fig. 3.2: Aperture and observation plane of the diffracted light of a spherical wave front of a focused beam form a lens with image distance $v$.](image)

The mathematical expression of this Huygens-Fresnel principle is written as

$$F(x_a, y_a) = \int \int h(x_a, y_a; x_b, y_b) f(x_b, y_b) dx_b dy_b, \quad (3.1)$$

where the interference factor $h(x_a, y_a; x_b, y_b)$ is given by:

$$h(x_a, y_a; x_b, y_b) = \frac{1}{i\lambda} \frac{\exp(ikr_{ab})}{r_{ab}} \cos(\vec{n} \cdot \vec{r}_{ab}), \quad (3.2)$$

where $k = 2\pi / \lambda$. $\lambda$ is the wavelength of light in air. $f(x_b, y_b)$ and $F(x_a, y_a)$ are the electro-magnetic fields in the pupil and the observation plane, respectively.

3.2.3 The objective lens as Fourier transformer

When the distances in the observation plane in $x$ and $y$ direction are small with respect to $z$, $\cos(\vec{n} \cdot \vec{r}_{ab}) \approx 1$. Under these conditions, the denominator of (3.2) will not differ significantly from $z$:

$$h(x_a, y_a; x_b, y_b) = \frac{1}{i\lambda} \frac{\exp(ikr_{ab})}{z} \cos(\vec{n} \cdot \vec{r}_{ab}). \quad (3.3)$$

The exact expression for the distance $r_{ab}$ is:

$$r_{ab} = \sqrt{(x_b - x_a)^2 + (y_b - y_a)^2},$$

which can be rewritten (using $z^2 = v^2 - x_a^2 - y_a^2$) as:

$$r_{ab} = \sqrt{1 + \frac{x_a^2 + y_a^2}{v^2} - 2 \frac{x_a x_b + y_a y_b}{v^2}}. \quad (3.4)$$

Equation (3.4) can be approximated by the Taylor expansion of the square root, which is equivalent to the approximation of the spherical wave by a paraboloid:

$$r_{ab} \approx v + \frac{x_a^2 + y_a^2}{2v} - \frac{x_a x_b + y_a y_b}{v}, \quad (3.5)$$

if $v \gg \sqrt{x_a^2 + y_a^2}$ and $v \gg \sqrt{x_a x_b + y_a y_b}$. \quad (3.6)

Therefore Equation (3.1) becomes:

$$F(x_a, y_a) = \frac{\exp(ikv)}{z i\lambda} \exp\left[\frac{ik(x_a^2 + y_a^2)}{2v}\right] \int \int_{\text{aperture}} \exp\left[-\frac{ik}{v} (x_a x_b + y_a y_b)\right] f(x_b, y_b) dx_b dy_b. \quad (3.7)$$

Equation (3.7) shows that the electro-magnetic field in the observation plane is the Fourier transform of the electro-magnetic field in the aperture. The first multiplicative term in front of the integral is an irrelevant phase term. The second term expresses the fact that the Fourier transform is projected onto a sphere.

The observation plane or disk coordinates $x_a$ and $x_b$ are scaled with a factor $\eta_p$:

$$\eta_p = \frac{\lambda}{Nz} = \frac{\lambda}{NA} \quad \frac{\lambda}{R_p}, \quad (3.8)$$

where $Nz$ is the numerical aperture of the objective lens. With the introduction of the dimensionless coordinates $u$ and $v$ in the disk plane:
and (3.9) and with the introduction of the reduced coordinates $x$ and $y$ in the pupil plane:

$$x = \frac{x}{R_p}, \quad y = \frac{y}{R_p},$$

(3.10)

where $R_p$ is the aperture radius. Equation (3.7) is transformed into:

$$F(u, v) = R_p \exp \left[ \frac{i\pi\lambda}{2\nu N A^2} (u^2 + v^2) \right] \int_{apert} \int \exp \left[-2\pi i (ux + vy)\right] f(x, y) \, dx \, dy,$$

(3.11)

where the homogeneous phase factor $\exp(ik\nu)/zi\lambda$ is eliminated. When we also neglect the spherical phase factor and disregard the constant term $R_p$, the following expression is obtained:

$$F(u, v) = \int_{apert} \int \exp \left[-2\pi i (ux + vy)\right] f(x, y) \, dx \, dy.$$

(3.12)

The aperture is in practice defined by the stop that is located in front of the objective (Fig. 3.24). We will call this the "pupil". The electromagnetic field distribution on an optical disk is the Fourier transform of the electromagnetic field distribution in the pupil in the objective lens. In other words the far field in the pupil is Fourier transformed in order to get the near field on disk. The function $f(x, y)$ is called the pupil function.

3.2.4 Calculation of the spot on the disk

Because the lens is a circularly symmetrical system, polar coordinates will be used in order to calculate the spot on the disk:

$$x = r \cos(\phi); \quad u = \rho \cos(\phi);$$

$$y = r \sin(\phi); \quad v = \rho \sin(\phi).$$

(3.13)

In the simple case of an aberration free situation and a homogeneous circular pupil, the pupil function is given by:

$$f(r, \phi) = \begin{cases} 1 & \text{for } r \leq 1; \\ 0 & \text{for } r > 1. \end{cases}$$

(3.14)

Consequently, Equation (3.12) can be written as:

$$F(\rho, \phi) = \int_0^{2\pi} \int_0^\rho \exp(-2\pi i \rho \phi \cos(\phi - \theta)) r dr d\phi,$$

(3.15)

By means of the properties of Bessel functions and some mathematics, the following expression is found for the electromagnetic field amplitude distribution on the disk [37]:

$$F(\rho) = \frac{2\pi}{\rho} \int_0^1 J_0(2\pi \rho r) r dr = \frac{2\pi J_1(2\pi \rho)}{2\pi \rho}.$$

(3.16)

When the peak height is normalized to 1, Equation (3.16) becomes:

$$F(\rho) = \frac{J_1(2\pi \rho)}{\pi \rho}.$$

(3.17)

The intensity distribution or irradiance of the spot on the disk is:

$$I(\rho) = \left[ \frac{J_1(2\pi \rho)}{\pi \rho} \right]^2.$$

(3.18)

Fig. 3.2: The spot on the disk in electromagnetic field amplitude distribution and in intensity distribution. The FWHM of the spots in intensity distribution is 0.512 N A. The diameter of the first dark ring is 1.22 λ/NA.
Graphs of the electromagnetic field (3.17) and the intensity distribution (3.18) are given in Fig. 3.2. The relative heights of the rings are much smaller for the intensity in comparison with the electromagnetic field amplitude distribution. The diameter of the first dark ring seen from the center is 1.22/NA.

The light inside the first dark ring of the intensity distribution is called the Airy disk. The intensity distribution is called the Airy pattern. Its FWHM (Full With Half Maximum) has a diameter of 0.51/NA. A larger NA and a shorter wavelength result in a smaller spot. The FWHM spot diameters are for CD-R(W) 0.8 μm and for DVD+R(W) 0.5 μm, respectively.

### 3.2.5 Fourier optics including disk described as a periodical function: diffracted orders

In this section we will calculate the signals of the pits and/or the pre-grooves on the disk. The disk surface is considered as a periodical function, which can be expanded in a Fourier series in two dimensions as proposed by Hopkins [30]. The complex reflection function on the disk is represented by $R(u,v)$. The electro-magnetic field at the disk is written as:

$$E_r(u,v) = F(u,v)R(u,v).$$  \hspace{1cm} (3.19)

The light that is reflected back into the pupil is now the inverse Fourier transform of the field distribution on disk including the disk properties:

$$e_p(x,y) = \int \int \exp[2\pi i (ux + vy)]E_r(u,v) \, du \, dv.$$

In other words: The far field back in the pupil is the inverse Fourier transform of the near field on disk. When using the convolution theorem of Fourier transforms we find:

$$e_p(x,y) = \int \int [R(u,v) \exp[2\pi i (ux + vy)]] \, du \, dv.$$

Equation 3.26 shows that the signal from the disk is the sum of all diffracted orders from the disk. The factor $r_{mn}$ is the amplitude and phase of the diffracted orders. The exponential function describes the phase shift between the orders due to the position of the spot on the disk. The functions $f(x-m/p, y-n/q)$ are pupils, which are shifted in position depending on the diffracted order.

Fig. 3.3 shows the (0,0)-order and one of the shifted orders $(m,n)$. We see that the signal is only detected as far as the orders contribute the field within the unit circle, because only this part is captured by the pupil in the path towards the detector.

$$r_{mn} = \frac{1}{pq} \sum_{m=-\infty}^{\infty} \sum_{n=-\infty}^{\infty} \int \int R(u,v) e^{2\pi i \left(\frac{m}{p} u + \frac{n}{q} v\right)} \, du \, dv,$$

or

$$r_{mn} = \sum_{m=-\infty}^{\infty} \sum_{n=-\infty}^{\infty} r_{mn}.$$

with

$$r_{mn} = \frac{1}{pq} \int \int R(u,v) e^{2\pi i \left(\frac{m}{p} u + \frac{n}{q} v\right)} \, du \, dv.$$

$m$ and $n$ are the numbers that represent the diffraction orders in the $x$ and $y$ or $u$ and $v$ direction, respectively.

Combination with convolution (3.21) results in:

$$e_p(x,y) = \sum \sum r_{mn} f\left(x - \frac{m}{p}, y - \frac{n}{q}\right).$$

(3.24)

A displacement over the disk with a value of $u_0$ and $v_0$ can be calculated by means of the Fourier shift theorem:

$$r_{mn} \rightarrow r_{mn} \exp\left(2\pi i \left(-\frac{m}{p} u_0 + \frac{n}{q} v_0\right)\right).$$

(3.25)

Consequently,

$$e_p(x,y) = \sum \sum r_{mn} \exp\left(2\pi i \left(-\frac{m}{p} u_0 + \frac{n}{q} v_0\right)\right) f\left(x - \frac{m}{p}, y - \frac{n}{q}\right).$$

(3.26)

Equation 3.26 shows that the signal from the disk is the sum of all diffracted orders from the disk. The factor $r_{mn}$ is the amplitude and phase of the diffracted orders. The exponential function describes the phase shift between the orders due to the position of the spot on the disk. The functions $f(x-m/p, y-n/q)$ are pupils, which are shifted in position depending on the diffracted order.
The $(0,0)$ order and first orders are most important, because they have the largest amplitude. In order to find some general considerations, this treatment is limited to the $(0,0)$ and first orders in two directions. See Fig. 3.5.

For instance, in the overlap area I between $(0,0)$ and $(1,0)$, $r_{0,0}$ and $r_{1,0}$ play a role.

The $(0,0)$ order and first orders are most important, because they have the largest amplitude. In order to find some general considerations, this treatment is limited to the $(0,0)$ and first orders in two directions. See Fig. 3.5.

For instance, in the overlap area I between $(0,0)$ and $(1,0)$, $r_{0,0}$ and $r_{1,0}$ play a role.
Fig. 3.6: A detector behind the exit pupil for push-pull and central aperture readout.

The power in the top segment of the detector behind the pupil according to Fig. 3.6 is proportional to:

\[ P_t = |r_{0,0}|^2 + A_t \left[ |r_{1,0}|^2 + 2 |r_{1,0}| |r_{0,0}| \cos \left( \psi + \frac{2 \pi \theta_0}{p} \right) \right]. \quad (3.31) \]

A similar reasoning yields for the bottom segment, with overlap area II:

\[ P_b = |r_{0,0}|^2 + A_b \left[ |r_{-1,0}|^2 + 2 |r_{0,0}| |r_{-1,0}| \cos \left( \psi - \frac{2 \pi \theta_0}{p} \right) \right], \quad (3.32) \]

where \( A_t \) and \( A_b \) are defined as the overlap areas between the zero and first diffracted orders of the disk normalized by the total pupil area. The sign of the factor \( 2 \pi \theta_0/p \) has changed because of the \(-1\) order instead of the \(+1\) order. When the power of both detector segments is added, the "central aperture signal" \( P_{cA} \) is obtained:

\[ P_{cA} = P_t + P_b = |r_{0,0}|^2 + 4 MTF_{cA}(p) |r_{0,0}|^2 |r_{0,0}| \cos(\psi) \cos \left( \frac{2 \pi \theta_0}{p} \right). \quad (3.33) \]

The square of the first orders is neglected. This signal is in most cases applied for the RF signal of the pits. This RF signal was drawn in Fig. 3.1. The function \( MTF_{cA}(p) \) is the modulation transfer function for central aperture detection. It is equal to ratio of the overlap areas between the first orders and zero order and the total pupil area: \( A_1 \) and \( A_u \) in Equation (3.31) and (3.32).

In order to calculate what this means for the pit depth, the relation between \( \psi \), \( p/p \), \( q/q \) and \( \theta_0 \) is needed. When the reflection coefficient in the pits is 100% (\( \alpha_p = 1 \)) the following relation is found after some mathematics [1]:

\[ \psi = \pi - \arctan \left( \frac{\cos \left( \frac{\theta_0}{2} \right)}{1 - 2 \frac{p \theta_0}{p q}} \right). \quad (3.35) \]

The duty cycle for CD and DVD pits is such that \( p/p \approx 0.5 \) and \( q/q \approx 0.33 \). When the pits are \( \lambda/4 \) deep: \( \theta_0 = \pi \) and \( \psi = \pi \). Therefore the central aperture readout is optimal, however, no push-pull readout is possible. When the pits are \( \lambda/16 \) deep \( \theta_0 = 3\pi/4 \) and \( \psi = 0.66 \pi \), which results in balanced push-pull and central aperture readout. The push-pull signal is further discussed in Section 3.5 as radial tracking signal.

3.3 The pupil function in practice: pupil filling and aberrations

For the previous treatment we assumed the above pupil function to be homogeneous in magnitude and phase. A more practical pupil function describes the amplitude distribution and the wave front distortion in the pupil:

\[ f(r, \varphi) = \sqrt{I_d(r, \varphi)} \exp(2 \pi i W(r, \varphi)) \]

for \( r \leq 1 \);

\[ f(r, \varphi) = 0 \]

for \( r > 1 \),

where \( W(r, \varphi) \) is the wave front function described with Zernike or Seidel coefficients [37] [38]. \( I_d(r, \theta) \) is the intensity distribution in the pupil. First, the wave front function is discussed.
3.3.1 Aberrations

The wave front function \( W(r, \phi) \) can be written as:

\[
W(r, \phi) = \sum_{m,n} W_{mn}(r, \phi), \tag{3.37}
\]

where \( W_{mn} \) are the coefficients and \( S_{mn} \) the expressions of the aberrations. The coefficients \( W_{mn} \) are the Seidel coefficients.

\( W(r, \phi) \) expressed in Zernike polynomials is:

\[
W(r, \phi) = \sum_{m,n} A_{mn} Z_{mn}(r, \phi), \tag{3.38}
\]

where \( A_{mn} \) are the Zemike coefficients and \( Z_{mn} \) are the Zemike polynomials. The primary aberrations, which are relevant for optical recording, are astigmatism, coma and spherical aberration. Defocusing is also of interest. The aberrations are summarized in Table 3.1.

<table>
<thead>
<tr>
<th>m</th>
<th>n</th>
<th>Name aberration</th>
<th>Seidel</th>
<th>Zernike</th>
<th>Orientation</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>0</td>
<td>Defocusing</td>
<td>( r^2 )</td>
<td>(-1 + 2r^2 )</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>Astigmatism</td>
<td>( r^2 \cos^2(\phi - \Phi_2) )</td>
<td>( r^2 \cos(2\phi) )</td>
<td>0°</td>
</tr>
<tr>
<td>2</td>
<td>-2</td>
<td>Astigmatism</td>
<td>( r^2 \sin(2\phi) )</td>
<td></td>
<td>45°</td>
</tr>
<tr>
<td>3</td>
<td>1</td>
<td>Coma</td>
<td>( r^3 \cos(\phi - \Phi_3) )</td>
<td>(-2r + 3r^2 \cos(\phi) )</td>
<td>0°</td>
</tr>
<tr>
<td>3</td>
<td>-1</td>
<td>Coma</td>
<td>( r^3 \cos(\phi - \Phi_3) )</td>
<td>(-2r + 3r^2 \sin(\phi) )</td>
<td>90°</td>
</tr>
<tr>
<td>4</td>
<td>0</td>
<td>Spherical aberration</td>
<td>( r^4 )</td>
<td>( 1 - 6r^2 + 6r^4 )</td>
<td></td>
</tr>
</tbody>
</table>

Table 3.1: Seidel and Zernike. The orientation with respect to the azimuth for description in Seidel coefficients is defined as \( \Phi_1 \) and \( \Phi_2 \). For Zernike polynomials astigmatism at 0° with the reference is \( A_{22} \) and at 45° \( A_{22} \) and \( A_{22} \). For coma it is \( A_{31} \) and \( A_{31} \) for 0° and 90°, respectively.

The appearance of the primary aberrations and defocusing when considering the rays is shown in Fig. 3.7 [39]. For the case of spherical aberration the marginal rays cross the optical axis closer to or further from the lens than the paraxial rays. A spherical lens in a parallel beam with will show this aberration. This is the reason for the name. Astigmatism results in two focal lines instead of one single focal point. In case of coma the marginal rays cross each other on a different distance from the optical axis than the paraxial rays. When looking at Table 3.1 in particular to the Seidel expressions and its dependence on the radius \( r \), it is understandable that defocusing and astigmatism are proportional to \( NA^2 \), coma to \( NA^3 \) and spherical aberration to \( NA^4 \). In case of \( NA \) values beyond 0.8 these simple relations are no longer valid [40]. Aberrations are generated in the practical situation by non-ideal components, the disk and misalignments.

Fig. 3.7: Defocusing and the primary aberrations astigmatism, coma and spherical aberration.

The value of the Seidel coefficients \( W_{mn} \) is the deviation of the wavefront (expressed in units of \( \lambda \)) at the at the rim of the pupil with a radius equal to 1. For the effect on the system the RMS value of the aberrations \( W_{RMS} \) is most relevant. The RMS value is for the description of the wavefront in Seidel coefficients:

\[
W_{RMS} = \sqrt{\sum \left( W(r, \phi) \right)^2}, \tag{3.39}
\]

with

\[
\bar{W} = \frac{1}{\pi} \int_0^{2\pi} W(r, \phi) r dr d\phi, \tag{3.40}
\]

\[
\bar{W}^2 = \frac{1}{\pi} \int_0^{2\pi} W(r, \phi)^2 r dr d\phi. \tag{3.41}
\]

When using Equation (3.39) the RMS values can be found in case of single type of aberration by dividing the Seidel coefficient by \( \sqrt{12} \), \( \sqrt{24} \), \( \sqrt{72} \) and \( \sqrt{180} \) for \( W_{20} \), \( W_{22} \), \( W_{31} \) and \( W_{40} \) respectively.
For the Zemike coefficients:

\[ W_{\text{RMS}} = \frac{1}{\pi} \int_0^{2\pi} W(r, \phi)^2 \, r \, dr \, d\phi. \]  

(3.42)

The RMS value of each aberration type is:

\[ A_{\text{RMS}} = \frac{1 + \delta_{\text{mp}}}{2(n+1)} A_{\text{mp}}. \]  

(3.43)

where \( \delta_{\text{mp}} \) is the Kronecker delta symbol. Because the Zernike polynomials are orthogonal the RMS value of the total wave front \( W_{\text{RMS}} \) is easily found:

\[ W_{\text{RMS}}(\text{TOT}) = \left( \sum_{m,n} \left( A_{\text{RMS}} \right)^2 \right)^{1/2}. \]  

(3.44)

According to [37] the Strehl ratio \( S \) can be calculated for small values of \( W_{\text{RMS}} \) by means of

\[ S = 1 - (2\pi W_{\text{RMS}})^2. \]

The Strehl ratio is the ratio of the peak height of an aberrated spot and an aberration free spot (Fig.3.2). According to the Maréchal criterion a spot is diffraction-limited if \( S > 0.8 \). This is the case if \( W_{\text{RMS}} \leq 70 \text{ m} \lambda \) in the practical recorder.

Because of the lower peak power in the spot, the power density is lower and therefore aberrations result in a higher total required recording power.

![Fig. 3.8: The overlap areas in case of an aberrated wave front.](image)

Aberrations will also affect the homogeneous wave front in the overlap areas (Fig.3.8). They will cause lower modulation amplitude and position or timing error in the RF signal as indicated in Fig. 3.9. The timing error is called “jitter”. A clock is retrieved from the data by the electronics (see also section 3.9). The length of a clock pulse is equivalent to a channel bit length \( c_0 \). The average value of the RF signal is determined by the electronics: the slicing level. The so-called data-to-clock jitter is defined as the RMS-value of the timing error between the crossings of the RF signal with the slicing level and the clock pulses. This parameter can be expressed in a percentage of \( c_0 \) or in ns.

![Fig. 3.9: An aberrated wave front causes lower modulation amplitude and “jitter”, which is a position or timing error of the high-frequency signal. In this picture the disk is assumed to be ideal, nevertheless, in practice, jitter can also be generated by a position error of the pits.](image)

As an example, a simulation of jitter data is given in Fig. 3.10. In case of a misalignment of the angle between the disk and the objective lens coma arises. The coma causes increase of jitter. The graphs of coma versus jitter are so called “jitter bathtubs”. The radial and tangential direction is defined as the direction perpendicular and parallel to the tracks on the disk, respectively.

The parameters applied are according to a DVD recording and CD read-only spot: \( NA = 0.65 \) for DVD and \( NA = 0.45 \) for CD. Next to the coma the DVD and CD spots contain in total approximately 40 m\( \lambda \) RMS of other aberrations in a combination of defocusing, astigmatism and spherical aberration [41]. This is more or less comparable with the practical situation. The jitter is simulated including an equalizer filter that boosts the amplitude of the smaller pits (see Section 3.9). The jitter simulations are carried out with a simulation program developed within Philips based on the scalar diffraction theory [42].

The coma sensitivity with disk tilt is for DVD a factor of two more than for CD despite the thinner cover layer of DVD. The jitter that arises due to the coma shows an even bigger difference between DVD and CD. The Maréchal criterion for coma is reached for DVD at a tilt angle of about 0.5° and for CD at about 1°, with a jitter of 15% and.
between 7 and 11%, respectively. The maximum allowed tilt angle between objective lens and disk is for DVD significantly lower. Measurement data of jitter data are given in Chapter 6. 15% jitter is the limit for the system.

3.3.2 Pupil filling

The Gaussian intensity profile of a semiconductor laser yields the following intensity distribution \( I_s(r, \theta) \) in the pupil [43] [44] [45]:

\[
I_s(r, \theta) = I_{s0} \exp\left(-r^2 \left(\sigma_r^2 \cos^2(\varphi - \beta) + \sigma_z^2 \sin^2(\varphi - \beta)\right)\right),
\]

(3.45)

where \( \beta \) is the direction of the laser far field distribution with respect to the tracks and \( \sigma_r \) and \( \sigma_z \) are parameters, which determine the width of the intensity profile of the beam in the pupil. A semiconductor laser has a far field FWHM \( \theta_i \) and \( \theta_i \) parallel and perpendicular to the active layer, respectively. The values of \( \sigma_r \) and \( \sigma_z \) are then:

\[
\sigma_r = \ln(2) \left(\frac{N_A}{\sin(\theta_i)}\right)^2 \quad \text{and} \quad \sigma_z = \ln(2) \left(\frac{N_A}{\sin(\theta_i)}\right)^2,
\]

(3.46)

where \( N_A \) is the numerical aperture at the laser side, which is determined by the part of the laser beam that is going through the pupil. The relative intensity at the rim \( r = 1 \) of the pupil in relation with the top in the directions parallel and perpendicular to the laser stripe are called the rim intensities \( I_{s0} \) and \( I_{s1} \):

\[
I_{s0} = \exp(-\sigma_r^2) \quad \text{and} \quad I_{s1} = \exp(-\sigma_z^2).
\]

(3.47)

The total power of the spots is very important for recording. During recording the disk is heated up locally by the diffraction-limited spot. The disk has a linear velocity \( v_d \) and a laser pulse profile as a function of the time \( H_s(t) \) during recording. The energy \( E_s(u', v') \) that is exposed is according to Chapter 5 of [1]:

\[
E_s(u', v') = P_0 \int_0^{v'} \int_0^{u'} H_s(t) dt dV,
\]

(3.48)

where \( P_0 \) is the total power in the spot on disk and \( u' \) and \( v' \) the coordinates in real space on disk. One can conclude from (3.48) that the higher the recording speed the more power is required in order to record a disk. The higher \( N_A \), the higher the power density in the spot. The available power in the spot determined by the available power out of the laser and the transmission of the optical components between the laser and the disk determined by the coupling efficiency of the laser power in the pupil. The coupling efficiency is depending on \( N_A \) and the far field distribution of the laser. The coupling efficiency \( C_e \) of the laser beam into the aperture or pupil of the light path is:

\[
C_e = \frac{\int_0^{\pi/2} \int_0^{2\pi} I_s(r, \varphi) \sin(\varphi) d\varphi d\theta}{\int_0^{\pi/2} \int_0^{2\pi} I_s(r, \varphi) \sin(\varphi) d\varphi d\theta}.
\]

(3.49)

\( C_e \) should be as large as possible for a recorder, because high power lasers are expensive or not available and high-speed disks require high powers. On the other hand the maximum value of \( N_A \) is limited by the required rim intensity. When the rim intensity becomes too low, the modulation of the short pits becomes small and extra sensitive for aberrations, which results in a higher jitter.

The Gaussian intensity distribution of the laser beam of a semiconductor laser has an elliptical shape due to the diffraction of the beam by the wave-guide structure of the semiconductor laser. The value of \( \theta_i \) differs about a factor of 2 from \( \theta_i \). This means that the minimum value of \( N_A \) is limited by the smallest value.

![Figure 3.10](image_url)
The electro-magnetic field distribution on the disk is the Fourier transform of the pupil function, which, in case of the aberration free situation, can be written as:

\[ F(u', v') = \frac{2\pi \lambda}{\sin(\varphi - \beta)} \exp \left( - \frac{2\pi rN\alpha}{\lambda} (u'\cos(\varphi - \beta) + v'\sin(\varphi - \beta)) \right) J_0 (r, \varphi) r dr d\theta, \quad (3.50) \]

The intensity distribution is:

\[ I(u, v) = |F^2(u, v)|, \quad (3.51) \]

Fig. 3.11 shows the relative intensity profile for an elliptical far field. Due the Fourier transform the direction with the low intensity in the pupil will result in a wider spot on disk than direction with the high rim intensity. In case of low rim intensity the rings of the Airy spot will fade out.

Fig. 3.11: Cross-sections of the Gaussian intensity profile in the pupil \( I_g(r, \varphi) \) and the spot intensity profile \( I(u, v) \) for a typical CD-R(W) situation \( N_A = 0.14 \), \( \theta_1 = 23^\circ \) and \( \theta_0 = 8^\circ \), \( \lambda = 790 \) nm and \( N_A = 0.5 \). \( C_z = 50\% \) for this example.

The orientation angle \( \beta \) of the Gaussian beam with respect to the track on disk is relevant. See Fig. 3.12 for a schematic representation. A Radial Oval Spot (ROS) has the best resolution along the tracks so the best properties for read and recording jitter. A tangential Oval Spot (TOS) has the best radial resolution. A Diagonal Oval Spot (DOS) is a compromise.

Fig. 3.12: Various spot orientations depending on the orientation of the Gaussian laser beam with respect to the tracks on the disk.

Because the spatial frequencies of shortest pit and the radial tracks with respect to optical cut off are \( \lambda/(12N_A c) \) and \( \lambda/(12N_A q') \), the rim intensity is more critical for DVD than for CD (See Table 1.1.). Therefore, the elliptical Gaussian laser beam for DVD recording spot is preferably circularized by means of a beam shaper, which means that the ratio \( \theta_r/\theta_0 \) is made equal to a value which is close to 1. A beamshaper can be a prism or a lens with different magnification in \( x \) and \( y \) [46].
3.4 Focusing methods

The optics generates a focus error signal for the focus servo loop in order to keep the spot on focus on the information layer of the disk. It is a signal from the photo detectors as a function of the distance from focused spot to information layer on the disk. The most applied focusing methods are based upon the consideration that the information layer of the disk is a good approximation of a flat mirror. It should have a zero crossing when the spot is perfectly focused on the information layer. This signal is used in the focus control loop (Section 3.8.3). It is called “focus S-curve” and looks like the sketch in Fig. 3.13.

Fig. 3.13: The focus S-curve.

The focusing methods that are most applied in optical pick-ups are discussed in this section.

3.4.1 Foucault focusing* or knife edge pupil obscuration

This method applies a “knife”, which blocks half of the beam (see Fig. 3.14). The laser spot is imaged on the reflective surface of the disk, which is subsequently imaged on the detector. If the spot is not focused on the information layer then the returned image is also axially displaced with respect to the original object. The position of the chief ray remains the same on the detector. Because of the shadow of the knife the asymmetry on the detector is a function of the axial spot position on the detector. When the disk is becoming too far out of focus, the spot on the detector becomes too large to fit on the detector segments and the focus error signal starts to drop.

*) The name “Foucault focusing” is originally used for the knife-edge method in the focused spot [47]. This method is not used any more in optical recording.

The focus error signal $FE$ is the differential signal of the two detector segments 1 and 2: The focus signals are sometimes normalized by the sum of the two segments, which means for this example: $FE = \frac{1-2}{1+2}$. Normalizing makes the focus error signal independent of the reflectance of the disk and laser power variations.

3.4.2 Astigmatic focusing

For this method an astigmatic spot on the detector is created by means of a cylinder lens or a tilted plane parallel plate (Fig. 3.15). The photo detector is a quadrant cell. Similar as above the returned image is axially displaced with respect to the original object if the spot on disk is not focused on the information layer. When the spot on disk is in focus, the spot appearance on the detector is circular (in the geometrical approximation). When disk is too close or too far from the objective lens, the appearance becomes elliptical. The peaks of the focus S-curve in Fig. 3.12 coincide with the focal lines on the detector. Normalized signals may look like $FE = \frac{(1+3)-(2+4)}{1+2+3+4}$ or $FE = \frac{1-4}{1+4} + \frac{3-2}{2+3}$, where the number indicates the segments of the quadrant detector.
3.4.3 Spots size detection

In this method the spot size is measured in front and behind a focus point on the detector, which can be achieved in practice by means of a mirror and a half mirror (Fig. 3.16). When the spot on disk is in focus, the spots on the detector in front and behind the focus point have the same size. When the spot on the disk is not in focus, the size of one detector spot increases while the other spot decreases, which yields the focus error signal.

Disk in focus:

Disk too close:

Disk too far:

Fig. 3.16: Spot size detection. The focus error signal is the signal of detector segment 1, 3 and 5 minus segment 2, 4 and 6.

3.5 Radial tracking

The radial deviation of the spot from the track center is detected by optical means. For the generation of the error signal the most used methods are explained in this section.

3.5.1 Push-Pull radial tracking

The push-pull signal $P_{pp}$ in Equation 3.34 is well suited for this purpose as stated in Section 3.2.6. The pupil is imaged on a split detector. The difference between the signals of the two detector sections yields the error signal (Fig. 3.17).

Disk in focus:

Disk too close:

Disk too far:

Fig. 3.17: Push-pull radial tracking. The picture of the zero and first diffractive orders on the detector that the left overlap area decrease in intensity, while the area on the right increases.

The push-pull signal can also be detected in the circle of least confusion in case of a combination with astigmatic focusing. Tolerance calculations of disk tilt and push-pull signals are given in [48].

3.5.2 Three spots central aperture radial tracking

In the three spots central aperture method a diffraction grating in the beam towards the objective creates two satellite spots on each side of the main one (see Fig. 3.18). This grating is positioned in front of the laser (see Section 3.6.1). The envelope of the central aperture high frequency signal $CA_c$ of the main spot $C$, which passes a low pass filter, is described as a function of the detracking $x$ as:

$$ CA_c = (1+3+5) - (2+4+6) $$
where $y$ is the grating ratio (the ratio of the power of the mean beam and the satellite beams). $m_{CA}$ is the central aperture modulation of the envelope, which is 0.15 for CD and 0.1 for DVD typically. $q^*$ is the real track pitch in $\mu$m. The signal of the two satellite spots $CA_a$ and $CA_b$ are described as:

$$CA_a(x) = 1 - m_{CA} \cos \left( \frac{2\pi(x - x_0)}{q^*} \right),$$  

$$CA_b(x) = 1 - m_{CA} \cos \left( \frac{2\pi(x + x_0)}{q^*} \right),$$  

where $x_0$ is the distance of the satellites with respect to the track followed by the main spot.

The radial error signal $RE$ is:

$$RE(x) = CA_a(x) - CA_b(x) = 2m_{CA} \sin \left( \frac{2\pi x}{q^*} \right) \sin \left( \frac{2\pi x_0}{q^*} \right).$$  

The distance $x_0$ is adjusted in the optical pick-up by rotating a grating around the optical axis. The spots are set at a distance to the track followed by the main spot of quarter track pitch ($x_0 = q^*/4$) for maximal radial error signal:

$$RE = 2m_{CA} \sin \left( \frac{2\pi x}{q^*} \right).$$  

The distance $x_0$ is critical for the signal amplitude. When $x_0$ is not set properly (Fig. 3.18),

$$x_0 = q^*/4 + \Delta x_0.$$

The radial signal amplitude and slope are decreasing with $\Delta x_0$, which can be expressed as follows by using Equation (3.54) and (3.56):

$$RE = 2m_{CA} \sin \left( \frac{2\pi x}{q^*} \right) \cos \left( \frac{2\pi \Delta x_0}{q^*} \right).$$  

For the mechanical angle error of the hypothetical centre line through the spots $\phi_0$, the following holds if the angle is small:

$$\Delta x_0 = s \phi_0,$$  

where $s$ is the distance between the main spot and the satellite spot on the disk, which is typically 20 $\mu$m (see Fig. 3.18). Such an error can also occur if the course of the objective lens does not meet the center of the tracks on the disk, for instance, due to eccentricity of the track with respect to the center hole of the disk (Fig. 3.19).

Fig. 3.18: Three spots radial tracking method. The central aperture signal of $A$ and $B$ are subtracted in order to generate the three spots central aperture signal. The three spot push-pull signal or differential push-pull signal is generated by a combination of the push-pull signals of the three spots $A$, $B$ and $C$. The detector geometry is given when this method is combined with astigmatic focusing.

Fig. 3.19: Errors in the three spots radial tracking system.
The angle error is then:

$$\phi_s = \frac{\Delta \psi}{R_d}$$  \hspace{1cm} (3.58)

where $\Delta \psi$ is the error of the course of the objective lens and $R_d$ is the radius of the tracks on the disk.

The error $\Delta \psi$ becomes more critical when the track radius is small, which is at the inner side of the disk.

The three spots central aperture radial tracking signal is applied in most CD read-only players and drives.

### 3.5.3 Differential push-pull or three spots push-pull radial tracking

For an unrecorded writable disk with only a pre-groove, $m_{c,t}$ is very low. A minimum value of $m_{c,t}$ is also not guaranteed in the standards of the writable disks. Therefore the so-called differential push-pull method is applied for CD and DVD recorders.

Differential push-pull or three spots push-pull radial tracking use the push-pull signal of three spots. Fig. 3.18 also shows a picture of three spots push-pull radial tracking in combination with astigmatic focusing. The push-pull signal of the main spot C and the two satellites A and B are described as a function of the detracking $x$ as:

$$PP_c = m_{pp} \sin \left( \frac{2\pi}{q'} (x - x_0) \right)$$

$$PP_a = m_{pp} \sin \left( \frac{2\pi}{q'} (x + x_0) \right)$$

$$PP_b = m_{pp} \sin \left( \frac{2\pi}{q'} (x + x_0) \right)$$  \hspace{1cm} (3.59)

where $m_{pp}$ is the push-pull modulation, which is 0.15 for CD and 0.1 for DVD typically.

The radial error signal is described as:

$$RE = PP_c - \frac{1}{2} (PP_a + PP_b) = m_{pp} \sin \left( \frac{2\pi}{q'} \right) \left( 1 - \cos \left( \frac{2\pi x_0}{q'} \right) \right)$$  \hspace{1cm} (3.60)

When adjusting the angular orientation of the grating lines, the satellite spots are set at a distance to the track followed by the main spot of ($x_0 = q'/2$) where the radial error signal is maximal:

$$RE = 2m_{pp} \sin \left( \frac{2\pi}{q'} \right)$$  \hspace{1cm} (3.61)

The advantage of this tracking method in relation with the single spot push-pull method is the offset correction of the push-pull signal of the main spot with the push-pull signal of the two satellites, in case of decentering of the three spots on the detector. This asymmetric error arises when the lens actuator makes a radial stroke. The inaccuracy of the distance between the satellites and the main spot on the detector is also corrected.
After some mathematics, one can find that for this case the slope is proportional to:

\[
\frac{dRE}{dx} \propto \frac{1 - \cos \left( \frac{2 \pi \Delta \theta}{q'} \right)}{2 - m_p \left( 1 - \cos \left( \frac{2 \pi \Delta \theta}{q'} \right) \right)}.
\]  

(3.64)

We are now considering four different situations for calculating the sensitivity of the amplitude on the mechanical angle error \( \psi_s \): CD and DVD with three spots central aperture radial tracking and CD and DVD with differential push-pull radial tracking [50]. The value of \( q' \) are for CD and DVD 1.6 \( \mu \)m and 0.74 \( \mu \)m respectively. \( s \) is considered to be 20 \( \mu \)m for all situations. The differential push-pull is non-normalized. The graphs are shown in Fig. 3.22.

The DVD system is more sensitive to angle errors than the CD system. Three spots central aperture is much more sensitive than differential push-pull. For a DVD read-only disk push-pull is not guaranteed and three spots central aperture is so sensitive for errors in \( x_0 \) that for the DVD disk another method is applied. This is the subject of the next section.

### 3.5.4 DPD or DTD

According to the Equations (3.33) and (3.34), the pit depths for optimal central aperture signal and optimal push pull signal are different. When the RF signal is optimized, the push-pull modulation is not guaranteed in the standard of DVD read-only disks. Therefore another single spot tracking method is applied: Differential Phase Detection or Time Differential Phase Detection (DPD or DTD) [51]. In this technique the contribution of the radial offset to the phase of the \((\pm 1, \pm 1)\)-orders is exploited (Fig. 3.23). The tracking offset results in a different time or phase difference between the high frequency signal in the \((\pm 1, \pm 1)\)-orders. Due to the Fourier shift theorem, the phase for the first orders with respect to the zero order is as presented in Table 3.2.

<table>
<thead>
<tr>
<th>Tangential</th>
<th>Radial</th>
<th>Phase</th>
</tr>
</thead>
<tbody>
<tr>
<td>+1</td>
<td>+1</td>
<td>( \psi + 2\pi (u/p + v/q) )</td>
</tr>
<tr>
<td>+1</td>
<td>-1</td>
<td>( \psi - 2\pi (u/p - v/q) )</td>
</tr>
<tr>
<td>-1</td>
<td>+1</td>
<td>( \psi - 2\pi (u/p + v/q) )</td>
</tr>
<tr>
<td>-1</td>
<td>-1</td>
<td>( \psi + 2\pi (u/p - v/q) )</td>
</tr>
</tbody>
</table>

**Table 3.2: The phase of the \((1, \pm 1)\)-orders.**

![Fig. 3.23: The \((1, \pm 1)\)-orders contain radial and tangential information. Their phase difference depends on the radial and tangential position of the spot with respect to the pits.](image-url)
The phase or time difference between the RF signal of (1+3) and (2+4) is a measure for the position on disk \( v_0 \) (See Fig. 3.24). The detector can be a quadrant cell similar to the one used with the astigmatic focusing method.

\[ \psi \pm 2(\alpha_1 \psi_1 + \alpha_2 \psi_2) \]

Track

\[ \psi \pm 2(\alpha_3 \psi_3 + \alpha_4 \psi_4) \]

Detector

Fig. 3.24: DPD or DTD radial tracking. The phase or time difference of the RF signal between the detector segments (1+3) and (2+4) is a measure for the tracking offset \( v_0 \).

Therefore, it is very easy to implement this method in the optical pick-up in combination with astigmatic focusing. However, it requires signal processing for the measurement of the phase difference of the detector segments. For the combination with spot size detection as given in Fig. 3.21 the radial error signal is the phase difference between \((a1+a2+a7+a8)\) and \((a3+a4+a5+a6)\).

3.6 The light path and its components

The composition of laser(s), optical components and detector(s) that generates the diffraction-limited spots and the electro-optical signals, is called the light path. In this section the relevant light path configurations for a player and recorder meant for a single disk generation will be treated here. Light paths for multi disk generations will be treated in the next chapters.

3.6.1 The CD read-only light path with plate beamsplitter

A schematic lay out of a standard optical layout for CD read-only is given in Fig. 3.25. It resembles the schematic light path in Section 1.1.2.

A transparent phase grating behind the semiconductor laser generates three beams, which are used for the three spots radial tracking method. Analogous to the calculation in Section 3.2.5 and 3.26, the diffracted beams can be calculated by means of a Fourier transform. The pitch of the grating determines the angle \( \alpha_g \) between the diffracted orders [52].

\[ p_g \sin(\alpha_g) = K\lambda, \tag{3.65} \]

where \( p_g \) is the grating pitch and \( K \) is an integer. The pitch of such a grating is in the order of magnitude of 10-100\( \mu \)m.
The transmitted power of the zero diffractive order and of the first diffractive order of the grating is \( I_0 \) and \( I_1 \), respectively. In case of a 50\% duty cycle binary grating \( I_0 \) equals:

\[
I_0 = \frac{1}{2} I_{in} \left[ 1 - \cos \left( 2\pi (n-1) \frac{h_g}{\lambda} \right) \right],
\]

where \( I_{in} \) is the power of the incoming beam. The energy in the first orders is in that case:

\[
I_1 = \frac{1}{2} I_{in} \left[ 1 - \cos \left( 2\pi (n-1) \frac{h_g}{\lambda} \right) \right] \sin \left( \frac{n}{2} \frac{2}{\lambda} \right),
\]

where \( h_g \) is the height of the grating structure and \( n_g \) the refractive index of the grating. The ratio \( I_0/I_1 \) is the of Equation (3.52) and (3.59-3.63) and is has practical values between 4 and 6 in case of read-only optics.

A plane parallel beamsplitter plate reflects the beams towards the disk. This beamsplitter is a thick plate, which contains a half mirror coating. The beam is focused on the information layer of the disk by means of an objective lens. The lens is an aspherical plastic lens. The beam is limited by a stop close to the objective lens, which defines the pupil. After reflection on disk the beam is transmitted via the lens through the plane parallel plate. Because of the thickness of the plane parallel plate (about 1-3 mm) and the convergent beam, astigmatism for the astigmatic focusing is generated. From [2] and [3] we find that the plane parallel plate introduces a shift of the focal point of \( \Delta f_p \) in the plane perpendicular to the rotation angle of the plane parallel plate \( \alpha_p \) with the optical axis:

\[
\Delta f_p = \left( n_g^2 - 1 \right) \sin^2 \left( \alpha_p \right) \frac{d_p}{2},
\]

where \( n_g \) is the refractive index of the material (glass) of the plane parallel plate and \( d_p \) its thickness. \( \Delta f_p \) is in the order of magnitude of 1 mm. The detector is an array of photo diodes with a configuration that is similar to the detector for three spots central aperture drawn in Fig. 3.17. The size of the spot on the detector is typically between 40 and 100 \( \mu \)m.

**3.6.2 The CD read-only light path with hologram beamsplitter**

A grating can also be applied as a beamsplitter. With a grating beam splitter, a compact component with laser, detector and grating beamsplitter can be made [53] [54]. Such a component is called a Laser Detector Grating Unit or LDGU. One example is shown in Fig. 3.26.

![Fig. 3.26: The CD read-only light path with a grating beam splitter in the LDGU.](image)

The LDGU contains two diffraction gratings on one a single substrate of glass or plastic. On the bottom a three spots grating is located in order to generate three beams for three spots radial tracking. On the top a holographic Foucault grating is located for the beam splitter function. For the RF and radial signal the total pupil area is used. One pupil half is diffracted towards a split detector for Foucault focusing. Using only one pupil half is equivalent to the Foucault knife of Fig. 3.14. The pitch of the Foucault grating is very small. The order of magnitude is 1-2 \( \mu \)m. Therefore the +1 and -1 order in the path towards the disk are not captured in the stop in front of the objective lens. On the way back the beam is diffracted towards the detector in two pupil halves due to a slightly different pitch. A practical value of the power ratio \( I_0/I_1 \) for the Foucault grating is 2.

One of the main advantages of the LDGU is that the light path is very stable against drift of the spots from the center of the detector during lifetime. When the spot is decentered on the detector, the focus and radial tracking signals are affected by offsets and crosstalk, for instance, crosstalk of the radial error signal into the focus error signal. Decentering of the spot on the detector is called a “beamlanding error”. The stability of an LDGU is due to fixation of the detector and laser in the same housing and due to the application of the hologram beamsplitter. A rotation of a plate beamsplitter of 1 mrad will result in a significant beam landing error, because of the relative large distance between the laser/detector and beamsplitter. This sensitivity is not valid for the hologram beamsplitter. A disadvantage of the LDGU is its low power efficiency from the laser towards the disk and from the disk towards the detector.
3.6.3 The CD recorder light path

A typical light path for CD-R and CD-RW is given in figure 3.27 [55]. It is drawn schematically: The right part of the light path (folding mirror, \(\lambda/4\) plate, objective, disk) is actually rotated 90° into the plane perpendicular to this paper. The radial tracking method is differential push-pull, because three spot central aperture signal is not available on an empty disk as explained in Section 3.5.3. The high power laser beam goes through the three spots grating in order to generate three spots for differential push-pull radial tracking, and is transmitted by the PBS (polarizing beam splitter). The beam is made parallel by the collimator lens. It is reflected by the folding mirror and afterwards the linear polarization state is transferred into circular polarization by the quarter wave plate. The beam is focused on the disk by the objective lens. After reflection on disk, the polarization is rotated 90° with respect to the original state by the \(\lambda/4\) plate. Finally, the laser beam is transmitted by the PBS and the servo lens towards the detector. The servo lens has a cylindrical surface for generating astigmatism for the astigmatic focusing and a negative spherical lens for focus adjustment on the detector. Polarizing optics is applied in order to get maximum power on the disk and a robust signal on the detector for high frequency signal processing of the power control of CD-R(W). The laser power is measured with a forward sense photo diode. A separate collimator lens and objective lens are applied, because applying one lens (see Fig. 3.25) would result in a varying coupling efficiency depending on the height of the objective lens, when following the disk in focus. The detector is an array of photo diodes with a configuration similar to the detector for differential push-pull as given in Fig. 3.18.

![Fig. 3.27: The CD recorder light path with polarizing optics.](image)

3.7 The basic engine of the recorder

In order to understand the function of the signals generated by the light path, the basic engine of the recorder will be explained briefly in the next sections.

A block diagram with the main functions in a data drive or DVD video recorder is presented in Fig. 3.28. It contains the optics, electronics, mechanics and firmware.

![Fig. 3.28: The basic engine of the recorder contains the optics, the read channel, the write channel and the servo channel including motors/actuators. The host is, for instance, a personal computer, or the back-end of a recorder. The data path controls the data communication between host system and basic engine. 1 is the sledge motor, 2 is the motor that rotates the disk and 3 is the lens actuator.](image)

The light path generates the diffraction-limited spot on the disk and generates the RF and servo signals on the photo detector.

The electronics of the system can be divided into several main functions that will be explained below. During operation the electronics is assisted and controlled by firmware.

The signals from the photo detector are processed and decoded in the so-called “read channel” in order to read the data from the disk. The data is further processed in the “data path” in order to make the data suitable for the host system. The host system is, for instance, a personal computer, an audio recorder or a video recorder.

The path towards the laser is called the “write channel”. The data to be stored is encoded and processed into pulses for the laser. In combination with the spot shape and the disk properties the laser pulses yield the written pits on the disk.
An optical drive contains a mechatronic system. A spindle motor rotates the disk. The lens actuator moves the objective lens in the focus and the radial direction in order to keep the focus point of the lens on the information layer and to follow the track. The sledge carrying the optics and the lens actuator is moved in radial direction with a separate sledge motor in order to get a large radial stroke all the way from the inner to the outer radius of the disk. These control loops and drivers are located in the "servo channel".

The sledge described in the previous paragraph is the optical pick-up unit (OPU). This separate mechanical unit is an important key component in the basic engine of the recorder. A schematic view of the optical pick-up is given in Fig. 3.29. It contains the light path, the lens actuator and electronics for driving the semiconductor laser and amplifying the detector signals.

In the next section an overview of the basic engine functions apart from the optics will be given in order to understand its relations with the optics.

3.8 Dynamics and servo systems

3.8.1 The lens actuator

The lens actuator is a linear Lorentz motor, which can move the objective lens in the focus and the radial directions [56]. The focus and radial forces are generated by means of a coil and magnet system (Fig.3.30). The current $I_{act}$ generated by the coils produces in combination with the magnetic field $B$ results in the Lorentz force $F_{act}$ according to:

$$F_{act} = I_{act} l_{coil} \times B,$$

where $l_{coil}$ is the length of the coil wires in the magnetic field. The dynamics of the actuator fulfills the following equation between force and the displacement $x$ as a function of the time $t$:

$$F_{act}(t) = M_{act} \frac{d^2x(t)}{dt^2} + D_{act} \frac{dx}{dt} + C_{act}x,$$

where $M_{act}$ is the moving mass, $D_{act}$ is the damping constant and $C_{act}$ the spring constant.

The maximum stroke of the actuator is typical ± 1 mm for focus and ± 0.3 mm for the radial direction. The displacement force in relation with current is given by:

$$F_{act} = K_{act} I_{act}.$$
where $K_{act}$ is the "K factor" of the actuator, which is typically 0.3 N/A. When using $x = A_{act} \sin(\omega t)$, the transfer function $H_{act}(\omega t)$ of the actuator can be written as:

$$H_{act}(\omega t) = \frac{x}{I_{act}} = \frac{K_{act}}{\sqrt{(C_{act} + M_{act} \omega^2)^2 + \omega^2 D_{act}^2}} \sin \left[ \omega t - \arctan \left( \frac{\omega D_{act}}{C_{act} - M_{act} \omega^2} \right) \right].$$

(3.72)

The resonance frequency $f_{res}$ is:

$$f_{res} = \frac{1}{2\pi} \frac{\omega_{res}}{\omega_{act}} = \frac{1}{2\pi} \sqrt{\frac{C_{act}}{M_{act}}},$$

(3.73)

For frequencies far beyond the resonance frequency of Equation (3.70) can be simplified with $x = A_{act} \sin(\omega t)$ as:

$$F_{act}(t) = M_{act} \frac{d^2x(t)}{dt^2} = A_{act} M_{act} \omega^3 \sin(\omega t).$$

(3.74)

$f_{act}$ is typically 50 Hz for a CD or DVD actuator. For the dissipated power in the actuator $P_{act}$ holds:

$$P_{act} = I_{act}^2 R_{act},$$

(3.75)

where $R_{act}$ is the coil resistance, which is about 10 Ω. Combination of Equation (3.71), (3.74) and (3.75) leads to:

$$P_{act} = \frac{A_{act}^2 \omega^6 \sin^2(\omega t) M_{act}^2 R_{act}}{K_{act}^2}.$$

(3.76)

The power dissipation in the actuator is proportional to $\omega^4$. For higher speeds, a low mass of the moving parts and therefore for the lens is very important. The moving mass is typically 400 mg. The mass of a glass lens is about 100 mg. The mass of a plastic lens is about 30 mg. Therefore a plastic lens is preferred for a high-speed data drive.

A tilt angle between the lens and the disk introduces coma as shown in Section 3.3.1. One of the critical parameters of the lens actuator is therefore its tilt as a function of its radial and focus stroke.

### 3.8.2 Drive mechanics

The optical pick-up unit is build as a sledge in a drive mechanism. Fig. 3.31 shows a schematic overview of this drive mechanism. It contains the disk motor and a sledge driving mechanism. The disk is put on the turntable$^1$. The disk motor rotates the turntable. The lens actuator covers the small stroke radial tracking caused by, for instance, the disk eccentricity, while the sledge moves in the radial direction by means of the sledge motor and gear wheels for the large radial stroke. Two shafts guide the sledge parallel to the disk surface and in such a way that the movement of the objective lens is directed to the motor center. This is important for three spots radial tracking methods as explained in Section 3.5. The stiffness of the actuator hinges in combination with the sledge tracking servo loop keeps the lens in its nominal radial position.

*In case of most portable drives this disk is put directly on the turntable. Most computer drives and audio/video recorders and players have a loading mechanism and loading tray. The disk is pushed down on the turntable by means of a clumper using a magnet or a spring.*
3.8.3 The servo channel (control loops)

The servo channel contains several control loops such as the focus control loop in order to keep the spots in focus, the radial control loop in order to keep the spot on track and the disc motor speed control loop. As an example the focus control loop is discussed briefly. The basic focus control loop is shown in Fig. 3.32. The desired focus position is $X_d$, the actual focus position is $X_a$ and the error is $e_f$.

$$e_f(o) = X_d(o) - X_a(o) = \frac{X_d(o)}{1 + H_f(o)}$$

where $H_f(o)$ is the open loop transfer function, which is the path from detector signals towards actuator as shown in Fig. 3.32. The point in the focus loop where the actual spot position $X_a$ and the desired spot position $X_d$ are compared is in fact the optics in combination with the disk. The detector signals are preprocessed into a focus error signal. The RF signal is filtered by means of a low-pass filter.

A PID controller is preferably used. The maximum allowed focus deviation of the information layer of the disk is specified for the lower frequencies (< 50 Hz for the 1x reference speed for CD and DVD). The integrator action results in a large gain of the $H_f(o)$ at low frequencies. The differentiator action creates a stable system at high frequencies. At a certain frequency that is called the bandwidth $|H_f(o)| = 1$. When the phase of $H_f(o)$ approaches 180° one can avoid that the system becomes instable. The power driver amplifies the signals of the PID controller in order to drive the actuator.

This defocusing in Seidel coefficients [1] [2] is given by:

$$W_20 = \frac{\Delta_s NA^2}{2L}$$

where $\Delta_s$ is the maximum allowed defocusing. According to the Maréchel criterion, the maximum allowed defocusing is 70 mλ RMS or $W_{20} = \lambda/4$. For CD-R(W) $\Delta_s = 1.6 \, \mu m$ and for DVD+R(W) $\Delta_s = 0.8 \, \mu m$. However, the Maréchel criterion is the total budget, which also includes contributions like offsets and other allowed aberrations. The disk itself can have a maximum axial runout of 0.5 mm for CD and 0.3 for DVD. This means that the magnification of the open loop transfer function $H_f(o)$ at low frequencies should be in the order of 1000.

The radial loop is essentially equivalent to the focus loop. The maximum allowed deviation from the center of the tracks is about 0.1 \, \mu m for CD and 0.05 \, \mu m for DVD. The disk and disk motor eccentricity is considered at the lower frequencies, while the unroundness or “potato shape” of the tracks is considered at higher frequencies. They are all compensated by the radial loop. The eccentricity of the disk and disk motor is approximately 0.1 mm, which means that $H_r(o)$ for the radial loop also is in the order of 1000.

The radial servo has an extra loop, which keeps the sledge at its nominal position as described in the previous section.

The motor control makes use of the RF signal on a pre-recorded disk or the wobble on an empty or R(W) disk to set the desired speed. Two ways of rotating the disk are possible: Constant Linear Velocity (CLV) or Constant Angular Velocity (CAV). CLV has the advantage that the data rate is constant. However, the rotation speed changes from the inner to the outer side of the disk. CAV has the advantage that the disk rotates at a constant speed, but now the data rate changes. The read channel should be able to follow these changes. CAV has big advantages for track jumps in order access to a certain area on the disk, because fast acceleration and braking of the disk will be avoided. Also in between solutions are possible, such as “quasi CLV” as described in [58].

Many other servo loops are present in a basic engine of the recorder, for instance: startup procedures, calibration procedures, track jump procedures, offset compensation, scratch detection, recovery procedures. They can be feedback or feedforward.

Feedforward loops are sometimes also utilized for focusing and radial tracking. The disk and motor eccentricity are equal for each disk revolution. This is also the case for the main part of the focus run out of the disk. For high-speed data drives self-learning repetitive control systems are sometimes applied, which compensates the same error for every revolution.
3.9 The read channel

The read channel is the part of the basic engine of the recorder that generates the data signal. A simplified block diagram is given in Fig. 3.33.

![Fig. 3.33: The read channel.](image)

A preamplifier amplifies the RF signal from the detector. The optical MTF is compensated electronically by means of an equalizer filter. This is a high pass filter that boosts the higher frequencies. After equalization the shorter pits get almost the same amplitude as the longer pits. The equalizer improves the jitter caused by aberrations, but also due to other effects like noise and imperfect pits on the disk.

The bit detector converts the RF signal into bits. The code of the channel bits is called EFM (Eight to Fourteen Modulation) for CD and EFM+ for DVD. This code has certain properties: the shortest pits and lands are 3 times longer than a channel bit \( c_b \) in order to avoid too small signals due to the optical modulation transfer function (MTF) and the maximum pit equals 11 times \( c_b \) for CD and 14 times \( c_b \) for DVD for proper data clock regeneration. The sequence of the pits is in such a way that the RF signal is DC free, which means that mean total pit length along the track equals the mean total land length. Because the majority of the errors during play black occur from scratches, dust and dirt, data that belongs to the same code words are spread over the disk. This is called “interleaving”. Extra bits are added for the error correction. The ratio of channel bits to user bits is 28% for CD and 42% for DVD as shown in Table 2.1.

The standard bit detection technique uses a threshold detector as explained in Fig. 3.34.

![Fig. 3.34: The equalized RF signal is converted to a digital signal by a threshold detector. The channel bits are a logical 1 in case of a transition.](image)

The average value of the RF signal is determined by the electronics: the slicing level. The digital signal is obtained comparing the RF signal with the slicing level. Each transition from pit into land or from land to pit is a logical 1. This is called NRZI coding (non return to zero inverted).

More advanced bit detectors are Pulse Response Maximum Likelihood detectors, which use the “Viterbi” algorithm [59]. They are applied in the Blu-ray Disc system. These bit detectors make use of the history and the properties of the channel. They are more robust for noise and aberrations and can also be applied in order to make a higher storage density possible with the same A/N.A., even when the spatial frequency of shortest pits is beyond the optical cutoff frequency. A special so-called “Limit” equalizer that can also improve the sensitivity for noise and aberrations is given in [60].

After regeneration, the data is stored in a FIFO (First In First Out) buffer memory. The decoder converts the channel data into user data and corrects the errors by using the error correction bits.

When the disk is read out in CLV, for instance, in a CD Audio player, the reference clock is used to generate a constant data stream in time. The disk motor speed is determined by the amount of data in the FIFO that should be half full on average. In the case of CAV, the data clock is generated by means of the bit detector. Much more details are found in [57].
3.10 The write channel

The block diagram of the write channel is given in Fig. 3.35.

The write channel converts the raw user data into laser pulses. The format detector locks to the wobble and reads the addresses and the timing signals and that is coded in the wobble or the embossed pre-pits. It generates also the clock for the write pulses. The raw user data is encoded into a stream of channel bits.

The profile of the exposed energy $E_d(u',v')$ on a rotating disk with linear velocity $v_d$ in case of a power $P_0$ in the spot is described by Equation (3.48) in Section 3.3.2:

$$E_d(u',v') = P_0 \int f(u'-v_d t,v') H_p(t) dt.$$ (3.79)

The energy depends on the intensity distribution $f(u',v')$ of the spot on disk and on the laser pulse profile $H_p(t)$. The laser pulses can get different amplitudes or they can vary in length. Therefore, the spot shape can be compensated partially by the pulse shape.

The write strategy is a disk-type-depending process that optimizes the laser pulses for proper pit formation on the disk. It takes thermal effects and properties of the spot shape into account. For instance, when only a short land is written between two pits, most recordable disks generate too short lands, because of pre-heating by the pit before the land and post-heating of the pit after the land. Recently, self-learning write strategy algorithms are being introduced. Such a system checks the quality of the written pits against variation in write strategy.

The forward sense detector controls the laser power, because the required power level for writing is very critical within a few percent in particular for recordable disks. When a blank disk is inserted in a recorder, the power required by a specific disk is calibrated by an optical power calibration procedure. The default power is given by the information present in the wobble of the disk or in the disk specific information in the drive created during the drive design. The exact power is determined by increasing the write power in steps while measuring the quality of the written pits. When the power on a recordable disk is too high, the pits become too long and too wide. This will cause asymmetry of the RF pattern, which is in particular visible for the short pits. The symmetry is a good measure for laser power calibration for recordable disks. The power calibration and write strategy tests are performed in a special reserved part at the inner and outer side of the disk.

Some disks may have dirty areas like fingerprints. The disk properties may change from the inner to the outer radius due to the recording material or cover layer. These effects will change the required recording power. This is compensated by means of a power control loop during recording of the disk. It can be a fast control that measures the change of reflection during recording or a slower one, which measures the quality of the written pits. The latter technique can only be used when the disk is written in parts; the write process must briefly be interrupted in order to be able to read and evaluate the previous part.
3.11 Summary

An overview of the optical principles of reading or writing an optical disk is given in this section. The other techniques applied in an optical disk recorder are touched briefly. The spots on disk can be calculated by means of a 2-dimensional Fourier transform of the pupil function. In the diffraction theory of reading out an optical disk profile with the pits can be considered as a function, which can be expanded in a Fourier series in 2-dimensions. The signals from the disk can be considered as the sum of diffracted orders of the disk. The zero and first orders are the dominant orders. The term central aperture signal means that the signal of the entire pupil from the disk is detected. This signal is used for the RF signal. The term push-pull signal means that the signal of one half pupil is subtracted from the other half. This signal is used for radial tracking and wobble or pre-pit detection. The pupil function towards the disk consists of a real part, which is determined by the Gaussian laser far field and an imaginary part, which is determined by the wave front.

Wave front aberrations affect the signals obtained from the disk. Disk tilt causes coma and coma generates increase of jitter. The DVD system is more critical on jitter versus disk tilt than the CD system. The higher the writing speed of a disk the more power is necessary to record a CD or DVD recordable/rewritable disk. Various methods for focus error signal generation are explained Foucault focusing, astigmatic focusing and spot size detection. The principles of four types of radial tracking methods are discussed: push-pull radial tracking, three spots central aperture radial tracking, three spots push-pull (or differential push-pull) radial tracking, and differential phase (or time) detection. The three spots signals are affected by misalignments in the drive, which are for DVD more critical than for CD. The light path or the optics of the recorder consists of the lasers, the detectors, the lenses and the other optical components. It generates the diffraction-limited spot on the disk and the electro-optical signals regenerated from the disk.

The basics of the read-only and recorder light paths principles are explained. The optical pick-up unit is a separate mechanical unit that contains the light path, the lens actuator and electronics for driving the semiconductor laser and amplifying the detector signals. The optical pick-up unit (OPU) is build as a sledge in a drive mechanism. The lens actuator covers the small stroke radial tracking (for instance, the disk eccentricity) while the sledge moves in the radial direction for the large radial stroke. The basic engine of the recorder contains the optics, read channel, write channel and the servo channel including motors/actuators. The servo channel contains several control loops. The read channel is the part of the basic engine of the recorder that generates the data signal. The write channel converts the data into laser pulses, which yields in combination with the light path and the disk properties the pits on a writable disk.

A general overview of the optical principles of reading or writing an optical disk was given in this section. We also gave a brief description of the rest of the system of the recorder. In the next section we will discuss a detailed light path model, which was used for the design of the light paths for DVD recording.
4.1 Introduction

The optics of an optical pick-up can be designed by means of a ray-tracing simulation program. However, more insight in the dependencies of the parameters of the optical design is obtained when the relations are expressed by means of analytical formulas. A quick evaluation of the impact of changes in the optical design can also take advantage of this approach. This section describes a geometrical model [61] of a light path with astigmatic focusing and three spots radial tracking. It is based on simple geometrical and paraxial optics [62] [63] [64]. The lenses are considered as thin lenses. This model has been used during the design of the DVD+/-R(W) light paths described in this thesis and several other optical pick-ups of Philips Optical Storage.

The derivation of the formulas and relations between the parameters of a light path are given in Section 4.2 for the main beam and in Section 4.3 for the satellite beams, respectively. A few examples of light paths are shown in Section 4.4. The comparison for some parameters with a ray-tracing program ("Zemax") is treated in Section 4.5. A summary of this chapter is given in Section 4.6.

4.2 Main beam

4.2.1 General

Fig. 4.1 shows a picture of a light path with three beam radial tracking and astigmatic focusing. It is similar to Fig.3.27, however the beamsplitter is a plane parallel plate instead of a cube.

The starting point of the analysis of the light path is the objective lens with focal length \( f_0 \) and its numerical aperture \( NA \). The pupil diameter is \( \Phi_0 \). Knowing that also for a perfect aspherical lens the numerical aperture is defined as the beam diameter divided by 2 times the focal length in case of a parallel beam towards the objective lens, we can write for \( \Phi_0 \):

\[
\Phi_0 = 2NAf_0, \tag{4.1}
\]

The focal length of the collimator lens is:

\[
f_c = \frac{\Phi_0}{2NA_c}. \tag{4.2}
\]

For a parallel beam, the positive magnification \( m_c \) from the disk towards the laser is:

\[
m_c = \frac{f_c}{f_0} = \frac{NA}{NA_c}, \tag{4.3}
\]

where \( NA_c \) is the numerical aperture of the collimator lens.

4.2.2 Servo lens

In this section the path from collimator towards detector will be modeled for the main beam. A servo lens can be applied in front of the detector (Fig. 4.2). This lens may have a cylindrical and a spherical surface. The spherical surface is also called "sensor lens", because it is applied to adjust the spot on the detector (= sensor). Therefore this lens is also referred to as "cylinder-sensor lens". The spherical lens and the cylinder lens are negative, because for this case the spots will be enlarged. As a result the signals will be less sensitive for decentering on the detector due to drift in lifetime.

Fig. 4.1: Three spot astigmatic light path. (The \( \lambda/4 \) plate is applied for to reduced feedback of light into the laser and has no effect on imaging).

Fig. 4.2: The servo lens or cylinder-sensor lens.
The cylinder lens generates the astigmatism, which is required for the astigmatic focusing. The spherical lens is implemented for the focus adjustment during assembly of the pick-up. The lens is translated along the optical axis in order to adjust the focus S-curve (Fig. 3.12) in such a way that its zero crossing coincides with a focused spot on the disk. The S-curve zero crossing is obtained when the spot on the detector is circular (Fig. 3.15). The detector itself can be adjusted perpendicular to the optical axis in order to center the spot on the detector.

The magnification of the spherical lens \( m \) is:

\[
m = \frac{NA_o}{NA_s} \cdot \frac{b_s}{v_s},
\]

where \( b_s \) is the image distance, \( v_s \) is object distance and \( NA_s \) is the numerical aperture of the beam towards the detector.

Using the lens maker's formula we find:

\[
v_s = f_s \left( 1 - \frac{1}{m} \right), \quad \text{with} \quad b_s = m_s \cdot v_s.
\]

4.2.3 Combination of cylinder and plane parallel plate

When a plane parallel plate is combined with a cylinder lens as shown in Fig. 4.3, two components introduce astigmatism. The plane parallel plate introduces a shift of the focal point of \( \Delta f \) in the plane perpendicular to the rotation angle of the plane parallel plate \( \alpha_p \), which is defined as y-z-plane as shown in Section 3.6.1:

\[
\Delta f_p = \frac{(n_p^2 - 1) \sin^3(\alpha_p)}{(n_p^2 - \sin^3(\alpha_p))^{3/2}} d_p,
\]

where \( n_p \) is the refractive index of the material (glass) of the plane parallel plate \( d_p \) is its thickness and \( \alpha_p \) is the angle of the plane with the optical axis, which is defined as z-axis.

The cylindrical axis of the cylinder lens is perpendicular to the y-z-plane. The distance between the cylinder lens and the undisturbed focus is defined as \( O \), for the y-z-plane. The distance between the cylinder lens and the focal line generated by the plane parallel plate is:

\[
O_p = O + \Delta f_p.
\]

\( O \) and \( O_p \) are considered as positive distances.

*) For object distance the Dutch "v" (voorwerp) and for image distance the Dutch "b" (beeld) will be used, because this saves indices in comparison with the English \( s', s_b \) or \( s_i \).
The distances between the two focal lines and the circle of least confusion, $z_{d1v}$ and $z_{d2v}$, are given by:

$$
\Phi_{d1v} = \frac{2AF_{v1} NA_{v1}}{NA_{d1} + NA_{d2}}, \\
\Phi_{d2v} = \frac{2AF_{v2} NA_{v2}}{NA_{d1} + NA_{d2}}.
$$

(4.12)

(4.13)

### 4.2.4 Imaging in the spherical lens

The next step is imaging these focal lines in the spherical lens. The spherical lens will form an image of all relevant points on the first focal line $v_5$, the circle of least confusion $V_{st}$ and the second focal line $v_{sc}$. The images are $b_5$, $b_{st}$ and $b_{sc}$ respectively as shown in Fig. 4.4.

The image distances $b_{st}$ and $b_{sc}$ for the circle of least confusion and the focal line perpendicular to the y-z-plane are, respectively,

$$
b_{st} = \frac{f_{v} v_{st}}{v_{st} - f_{s}} \quad \text{and} \quad b_{sc} = \frac{f_{v} v_{sc}}{v_{sc} - f_{s}}.
$$

(4.14)

The corresponding positive magnifications are

$$
m_{st} = \frac{b_{st}}{v_{st}} \quad \text{and} \quad m_{sc} = \frac{b_{sc}}{v_{sc}}.
$$

(4.15)

Therefore:

$$
z_{d1} = b_{d1} - b_{d1} \quad \text{and} \quad z_{d2} = b_{d2} - b_{d1}.
$$

(4.16)

The distance between the images of the two focal lines is:

$$
\Delta d = z_{d1} + z_{d2}.
$$

(4.17)

The spot diameter on the detector is (Fig. 4.5):

$$
\Phi_{d} = 2NA_{v} z_{d0}.
$$

(4.18)

or, with Equation (4.12):

$$
\Phi_{d} = \frac{2AF_{v} NA_{v1} NA_{v2} m_{d}}{NA_{d1} + NA_{d2}}.
$$

(4.19)

4.2.5 Sensitivity of the servo lens adjustment

The negative sensor lens will result in an increase of the length of the light paths on the side of the detector. We define the extension of the servo branch at the first focal line by the sensor lens as $p_{st}$ (Fig. 4.6):

$$
p_{st} = b_{s} - v_{s}.
$$

(4.20)

From the lens maker's formula we can derive:

$$
p_{st} = \frac{v_{st}^2}{v_{st} - f_{s}}.
$$

(4.21)
The sensitivity of the axial displacement of the spot on the detector due to the axial displacement of the servo lens can be expressed by means of Equation (4.21) as:

$$\frac{dp_{ld}}{dv} = \frac{f_f^2}{(v - f_f)^2}.$$  (4.22)

This expression is valid for the undisturbed focus or first focal line.

![Decentering of the servo lens versus decentering of the spot on the detector.](image)

Fig. 4.7: Decentering of the servo lens versus decentering of the spot on the detector.

The sensitivity for decentering of the spot on the detector versus drift of the servo lens perpendicular to the optical axis is (Fig. 4.7):

$$\frac{dv}{d\eta} = m_s - 1.$$  (4.23)

On one hand the larger the magnification $m_s$ of the spherical lens, the more the spot is enlarged, hence the less sensitive the signal is for decentering of the detector. On the other hand, a decentering of the servo lens will result in a larger spot displacement when $m_s$ is high.

### 4.2.6 Sensitivity of the radial stroke of the lens actuator

For push-pull and DPD detection in combination with astigmatic focusing with a quadrant cell, the orientation of the focal lines is $45^\circ$ with the tracks on the disk (Fig. 4.8). The radial stroke $s_r$ of the actuator can be resolved in components parallel and perpendicular to the first focal line $s_{r0}$ and $s_{r90}$. The actuator stroke results in spot displacements on the detector $\delta x_{r0}$ and $\delta x_{r90}$ for the two directions:

$$\delta x_{r0} = x_{r0} \frac{z_{d1r}}{f_c}$$
$$\delta x_{r90} = x_{r90} \frac{z_{d2r}}{f_c + z_{d1r} + z_{d2r}}.$$  (4.24)

which yields, in good approximation,

$$\delta x_{r0} = s_r \frac{M_{tot}}{2f_c + M_{tot}}.$$  (4.25)

The first focal line is located in front of the detector and the second behind the detector. The direction of the movement that is approximately rotated by $90^\circ$ with respect to the actuator stroke is shown in Fig. 4.8.

![Orientation of the focal lines with the tracks on the disk.](image)

Fig. 4.8: The orientation of the focal lines is $45^\circ$ with the tracks on the disk. This makes push-pull and DPD detection possible with a quadrant cell in combination with astigmatic focusing. This results in a $90^\circ$ rotation of the spot displacement on the detector due to the actuator stroke.

The displacement of the spot on the detector is as given in (4.24) is including the magnification of the spherical lens:

$$\delta x_{r0} = m_s x_r \frac{M_{tot}}{2f_c + M_{tot}}.$$  (4.26)
4.2.7 The focus S-curve length

The focal lines on the detector should result in a focus error signal, which determines the focus position of the spot on the disk (see Fig. 4.9). In order to calculate this focus S-curve, the two focal lines on the detector should be imaged on the disk. The distance between the images of the focal lines on the detector on the disk is the focus S-curve length \( \Delta z \). This calculation is worked out in detail in Appendix B. An approximation for the two S-curve halves \( \Delta z_1 \) and \( \Delta z_2 \) has been obtained with:

\[
\Delta z_1 = \frac{z_{d1}}{2m_i^2m_z} \quad \text{and} \quad \Delta z_2 = \frac{z_{d2}}{2m_i^2m_z} .
\]  

(4.27)

The factor of 2 is due to the mirror function of the disk.

The total S-curve length \( \Delta z \) is:

\[
\Delta z = \Delta z_1 + \Delta z_2 .
\]  

(4.28)

An approximation for the two S-curve halves \( \Delta z_1 \) and \( \Delta z_2 \) has been obtained with:

\[
\Delta z_1 = \frac{z_{d1}}{2m_i^2m_z} \quad \text{and} \quad \Delta z_2 = \frac{z_{d2}}{2m_i^2m_z} .
\]  

(4.27)

The factor of 2 is due to the mirror function of the disk.

The total S-curve length \( \Delta z \) is:

\[
\Delta z = \Delta z_1 + \Delta z_2 .
\]  

(4.28)

\[88\]

4.3 Satellite beams

4.3.1 The satellite beams towards the disk

As explained in Section 3.6.1 (Equation (3.65)) the pitch of the grating determines the angle \( \alpha_g \) between the diffracted orders:

\[
p_g \sin(\alpha_g) = K \lambda ,
\]  

(4.29)

where \( p_g \) is the grating pitch and \( K \) is an integer. The first diffractive orders \( (K = \pm 1) \) are used to generate the satellite spots. \( \alpha_g \) is in the order of magnitude of 25 mrad. In the paraxial approximation \( \sin(\alpha_g) = \alpha_g \), resulting in:

\[
\alpha_g = \frac{\lambda}{p_g} .
\]  

(4.30)

At the source side, the distance \( s' \) of the main spot with respect to the virtual satellite spots is (Fig. 4.10):

\[
s' = g \alpha_g ,
\]  

(4.31)

where \( g \) is the optical distance between the laser and the grating. Using Equation (4.30), \( g \) can be written as:

\[
g = \frac{s' \lambda}{p_g} .
\]  

(4.32)

\[89\]
The distance $s$ of the satellite spots on the disk is:

$$s = s' = \frac{s g}{m_v} \frac{p_j n_j}{}, \quad (4.33)$$

A semiconductor laser has a Gaussian intensity profile according to Equation (3.45). The maximum intensity in the nominal situation is in the center. The shift of the point of maximum intensity $A_r$ of the satellite beams in the pupil is (see also Fig. 4.10):

$$A_r = (f_j - g)\alpha_s + l_j \gamma,$$

where $l_j$ is the optical distance from collimator to pupil. The angle $\alpha_s$ between the ray of the satellite beams with maximum intensity and the optical axis can be written as:

$$\alpha_s = s' = \frac{s' g}{m_v} = \frac{g \alpha_s}{m_v f_o}, \quad (4.35)$$

So:

$$A_r = s' \left[ \frac{f_j}{g} - 1 + \frac{l_j}{m_v f_o} \right]. \quad (4.36)$$

Equation 4.36 shows that $A_r$ decreases with decreasing $l_j$ and increasing $g$, because $f_j/g > 1$.

### 4.3.2 Precise calculation of the satellite spots on the detector

In order to determine where the satellite spots land on the detector, we start with imaging the pupil in the collimator lens. One important parameter is the distance $l_j$ of the collimator towards the pupil. When $l_j < f_j$, a virtual image is obtained of the pupil as drawn in Fig. 4.11. This is the case for most optical pick-ups, nevertheless the calculations are also valid for $l_j > f_j$. Let us define:

- $h_{opt}$: the optical distance between the cylinder lens and the detector plane
- $b_{pu}$: the image distance of the pupil in the collimator lens
- $d_{pu}$: the distance between the cylinder lens and the image of the pupil

The image distance of the pupil by the collimator $b_{pu}$ equals:

$$b_{pu} = \frac{l_j f_j}{l_j - f_j}. \quad (4.37)$$

Fig. 4.11: The virtual image of the pupil.

For $d_{pu}$ holds:

$$d_{pu} = -h_{opt} + f_j + O. \quad (4.38)$$

The satellite spots are influenced in a different way by the cylinder lens and the plane parallel plate in the $x$-$z$-plane and in $y$-$z$-plane. The situation in the $x$-$z$-plane is examined first. The first treatments are without spherical sensor lens.

Fig. 4.12: The radial beams and the cylinder lens || to the cylindrical axis ($x$-$z$-plane).
Define \( s'_a \) and \( s'_b \) as the distance between the main spot to satellite spots in undisturbed focus and \( s'_{yd} \) and \( s'_{xd} \) as the distance main spots to satellite spot in detector plane. Thus:

\[
\frac{s'_{yd}}{d_{pu} + h} = \frac{s'_{yd}}{d_{pu} + O} \quad (4.39)
\]

\[
\frac{s'_{xd}}{d_{pu} + h} = \frac{s'_{xd}}{d_{pu} + O}
\]

The ratio of the lateral position of the satellite spot in the circle of least confusion in relation with the undisturbed focus in the \( x\)-\( z\) plane is defined as \( m_y \):

\[
m_y = \frac{d_{pu}}{d_{pu} + O} \left( 1 + \frac{h_{cy}}{d_{pu}} \right).
\]

(4.41)

The same in the \( y\)-\( z\) plane (Fig. 4.13):

\[
m_x = \frac{d_{pu}}{d_{pu} + O} \left( 1 + \frac{h_{cy}}{d_{pu}} \right).
\]

The position of the satellite spot on the detector, including magnification of the spherical lens with respect to the undisturbed focus can be found by a multiplication with \( m_{xt} \) for the \( y\)-\( z\) plane, respectively:

\[
m_{xt} = m_x m_{s_d} \quad \text{and} \quad m_{xt} = m_y m_{s_d}.
\]

(4.48)

Now define \( s_{xy} \) as the distance between the satellite spots on the detector and \( \phi_s \) as the angle of the satellite spots in the detector plane, including the magnification of the spherical lens (see Fig. 4.15).

In the paraxial approximation, the angle of refraction \( \xi_{cy} \) in the cylinder lens is

\[
\xi_{cy} = \frac{\rho_{cy}}{d_{pl}} \quad \text{with} \quad \rho_{cy} = \frac{s_{cy}}{d_{pl} + O_p},
\]

where

\[
s_{cy} = s'_{cy} + h_{cy} \xi_{cy}.
\]

(4.44)

\[
s_{cy} = \frac{d_{pu}}{d_{pu} + O_p} \left( 1 + \frac{h_{cy}}{d_{pu}} \right) s'_{cy}.
\]

(4.45)

Hence,

\[
s_{xy} = \frac{d_{pu}}{d_{pu} + O_p} \left( 1 + \frac{h_{cy}}{d_{pu}} \right) s'_{xy}.
\]

(4.46)

The ratio of the lateral position of the satellite spot in the circle of least confusion and the undisturbed focus in the \( y\)-\( z\) plane is defined as \( m_x \):

\[
m_x = \frac{d_{pu}}{d_{pu} + O_p} \left( 1 + \frac{h_{cy}}{d_{pu}} \right).
\]

(4.47)

The paraxial approximation, the angle of refraction \( \xi_{cy} \) in the cylinder lens is

\[
\xi_{cy} = \frac{\rho_{cy}}{d_{pl}} \quad \text{with} \quad \rho_{cy} = \frac{s_{cy}}{d_{pl} + O_p},
\]

where

\[
s_{cy} = s'_{cy} + h_{cy} \xi_{cy}.
\]

(4.44)

\[
s_{cy} = \frac{d_{pu}}{d_{pu} + O_p} \left( 1 + \frac{h_{cy}}{d_{pu}} \right) s'_{cy}.
\]

(4.45)

Hence,

\[
s_{xy} = \frac{d_{pu}}{d_{pu} + O_p} \left( 1 + \frac{h_{cy}}{d_{pu}} \right) s'_{xy}.
\]

(4.46)

The ratio of the lateral position of the satellite spot in the circle of least confusion and the undisturbed focus in the \( y\)-\( z\) plane is defined as \( m_x \):

\[
m_x = \frac{d_{pu}}{d_{pu} + O_p} \left( 1 + \frac{h_{cy}}{d_{pu}} \right).
\]

(4.47)

The position of the satellite spot on the detector, including magnification of the spherical lens with respect to the undisturbed focus can be found by a multiplication with \( m_{xt} \) for the \( y\)-\( z\) and \( x\)-\( y\) plane, respectively,

\[
m_{xt} = m_x m_{s_d} \quad \text{and} \quad m_{xt} = m_y m_{s_d}.
\]

(4.48)
The relation between \( s' \) and \( s_d \) is

\[
\begin{align*}
\frac{s' - s_d}{s_d} &= \frac{1}{\sqrt{m_{\text{m}}^2 + m_{\text{m}}^2}}. \\
\end{align*}
\]  
(4.49)

With (4.32) Equation (4.49) yields

\[
\begin{align*}
s_d &= \frac{g_0}{\sqrt{2}} \frac{m_{\text{m}}^2 + m_{\text{m}}^2}{g_{\text{m}}^2}. \\
\end{align*}
\]  
(4.50)

The angle of the satellite spots in the detector plane \( \varphi_s \) is given by:

\[
\varphi_s = \frac{\pi}{4} - \arctan \left( \frac{m_{\text{m}}^2}{m_{\text{m}}^2} \right) = \frac{\pi}{4} - \arctan \left( \frac{m_{\text{m}}^2}{m_{\text{m}}^2} \right). \\
\]  
(4.51)

The angle of the satellite spots with respect to the tracks is \( x_0/s \) (Fig. 3.17). Therefore the total \( \varphi_{\text{tot}} \) angle on the detector is:

\[
\varphi_{\text{tot}} = \varphi_s + \frac{x_0}{s}. \\
\]  
(4.52)

The effect of the angle \( x_0/s \) is very small for the previous calculations. Hence, it is not taken into account in the treatments above.

### 4.3.3 Relation between s-curve length and distance spots on disk

The relation between the focus S-curve length \( \Delta x \) and the distance between the main spot and satellite on the disk \( s \) is estimated below. From (4.18), and because \( N_A c = N_A c_2 \), a good estimation for the spot diameter without the spherical lens is, with Equation (4.12):

\[
\varphi_{\text{m}} = \Delta x / N_A c. \\
\]  
(4.53)

Because \( N_A c = N_A c_2 \) and using (4.3) and (4.11) we obtain:

\[
\Delta x = \frac{\varphi_{\text{m}}}{2 m_{\text{m}}}. \\
\]  
(4.54)

\( s' = s m_{\text{m}} \) should be larger than \( \varphi_{\text{m}} \sqrt{2} \). For this reason the following relation is found:

\[
s > 2 \sqrt{2} \Delta x / N_A \\
\]  
(4.55)

In order to make the radial signals less critical for misalignments according to Equation (3.56), (3.57), (3.62) and (3.64), the distance between the main and satellite spot on disk \( s \) should be as small as possible. Equation (4.55) shows that the minimum distance of the main spot to satellite on disk is proportional to \( N_A \) and the focus S-curve length \( \Delta x \).

### 4.4 Light path examples and conclusions from the calculations

In this section the results of the model are discussed on several light path examples in order to get insight in the relations between the light path parameters. One example is light path 1, which is the CD recorder light path with a beamsplitter cube as given in Fig. 3.27. Other examples are light paths 2 and 3 with a plane parallel plate as illustrated in Fig. 4.1. The difference between light path 2 and 3 is a different focal length of the collimator lens \( f_c \) and the numerical aperture \( N_A s \) of the servo lens. The two other examples are a DVD recorder light path with a cylinder lens and with a combination of a cylinder lens and a plate: light path 4 and 5, respectively. The actual light paths will be described in detail in Chapter 6 and 7. Calculated light path parameters are given in Table 4.1. Schematic drawings of the light paths are shown in Fig. 4.16. Several conclusions from the data in Table 4.1 are discussed in the next paragraphs.

**Light path 1 and 4:**

- **Objective lens**
- **Plane parallel plate**
- **Collimator lens**
- **Stop**
- **Detector**

**Light path 2 and 3:**

- **Objective lens**
- **Planet parallel plate**
- **Collimator lens**
- **Stop**
- **Detector**

**Light path 5:**

- **Objective lens**
- **Planet parallel plate**
- **Collimator lens**
- **Stop**
- **Detector**

**Fig. 4.16:**

Light path 1 and 4, with a cylinder lens, light path 2 and 3 with a plane parallel plate and light path 5 with a plane parallel plate and a cylinder lens.
When comparing light path 2 and 3 in Table 4.1, the magnification collimator/objective lens \( m_e \) is increased for light path 3. The magnification of the sensor lens \( m_s \) is kept constant. It is obvious from these calculations that the smaller the magnification from objective to collimator is, the smaller the S-curve length \( L_e \) from the same plate thickness will be. The spot diameter of light path 3 is smaller according to Equation (4.12).

Another conclusion is that a larger value of \( m_e \) also results in a smaller distance \( s \) of the main spot to satellite on the disk for the same grating pitch \( p_g \) and optical distance \( g \) between laser and grating. The smaller value of \( s \) for light path 3 agrees also with Beam diameter \( \phi_d = 3.58 \) mm.

The sensitivity of the spot position due to the actuator stroke is smaller for light path 3 in comparison with light path 2, because \( \Delta z_{opt} \) is equal and \( f \) is smaller as shown is Thickness plate \( d_p \). For a cylinder it results in a too long focus S-curve.

Table 4.2 shows some parameters varying with optical distance collimator pupil \( l_c \) for the parameter of light path 1. The rotation of the satellites is depending on \( l_c \). The shift of the radial beams in the pupil obviously increases with \( l_c \), in agreement with Equation (4.36). The optimum optical distance between the laser and the grating hardly changes.

<table>
<thead>
<tr>
<th>Light Path</th>
<th>Cylinder</th>
<th>Plate</th>
<th>Plate</th>
<th>Cylinder</th>
<th>Plate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Focal length objective ( f_c )</td>
<td>mm</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>2.754</td>
</tr>
<tr>
<td>NA objective</td>
<td>( N_A )</td>
<td>1.55</td>
<td>1.55</td>
<td>1.55</td>
<td>1.45</td>
</tr>
<tr>
<td>Beam diameter</td>
<td>( \phi_d )</td>
<td>( \mu m )</td>
<td>59.5</td>
<td>59.5</td>
<td>59.7</td>
</tr>
<tr>
<td>Focal length collimator</td>
<td>( f_c )</td>
<td>mm</td>
<td>10</td>
<td>10.15</td>
<td>12.79</td>
</tr>
<tr>
<td>NA collimator</td>
<td>( N_{Ac} )</td>
<td>0.15</td>
<td>0.15</td>
<td>0.10</td>
<td>0.14</td>
</tr>
<tr>
<td>Focal length servo lens</td>
<td>( f_s )</td>
<td>mm</td>
<td>-6</td>
<td>-6</td>
<td>-6</td>
</tr>
<tr>
<td>NA servo lens</td>
<td>( N_{As} )</td>
<td>0.10</td>
<td>0.10</td>
<td>0.067</td>
<td>0.10</td>
</tr>
<tr>
<td>Thickness servo lens</td>
<td>( d_s )</td>
<td>mm</td>
<td>0.9</td>
<td>0.9</td>
<td>0.9</td>
</tr>
<tr>
<td>Focal length cylinder lens</td>
<td>( f_{lc} )</td>
<td>mm</td>
<td>-27</td>
<td>-27</td>
<td>-27.6</td>
</tr>
<tr>
<td>Distance collimator pupil</td>
<td>( l_c )</td>
<td>mm</td>
<td>11</td>
<td>11</td>
<td>11</td>
</tr>
<tr>
<td>Angle plane plate opt. Ax.</td>
<td>( \alpha_p )</td>
<td>( \circ )</td>
<td>45</td>
<td>45</td>
<td>-</td>
</tr>
<tr>
<td>Thickness plate</td>
<td>( d_p )</td>
<td>mm</td>
<td>0.95</td>
<td>0.95</td>
<td>0</td>
</tr>
<tr>
<td>Refractive index plate</td>
<td>( n_p )</td>
<td>1.517</td>
<td>1.574</td>
<td>1.574</td>
<td>1.580</td>
</tr>
<tr>
<td>Magnification collimator objective</td>
<td>( m_r )</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>4.64</td>
</tr>
<tr>
<td>Magnification sensor lens</td>
<td>( m_s )</td>
<td>1.5</td>
<td>1.5</td>
<td>1.5</td>
<td>1.4</td>
</tr>
<tr>
<td>Magnification sensor lens for detector</td>
<td>( m_{sd} )</td>
<td>1.55</td>
<td>1.55</td>
<td>1.55</td>
<td>1.45</td>
</tr>
<tr>
<td>Spot diameter on detector</td>
<td>( \phi_d )</td>
<td>( \mu m )</td>
<td>11.05</td>
<td>11.52</td>
<td>5.12</td>
</tr>
<tr>
<td>Distance focal lines detector</td>
<td>( \Delta f_{ld} )</td>
<td>mm</td>
<td>0.65</td>
<td>0.62</td>
<td>0.62</td>
</tr>
<tr>
<td>Distance focal lines before sensor lens</td>
<td>( \Delta f_{ls} )</td>
<td>mm</td>
<td>0.27</td>
<td>0.26</td>
<td>0.26</td>
</tr>
<tr>
<td>Distance focal lines from cylinder Lens</td>
<td>( \Delta f_c )</td>
<td>mm</td>
<td>0.27</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Distance focal lines from plane plate</td>
<td>( \Delta f_{p} )</td>
<td>mm</td>
<td>0.26</td>
<td>0.26</td>
<td>0</td>
</tr>
<tr>
<td>S-curve length exact</td>
<td>( \Delta z_{ex} )</td>
<td>( \mu m )</td>
<td>11.05</td>
<td>11.52</td>
<td>5.12</td>
</tr>
<tr>
<td>S-curve peak 1 exact</td>
<td>( \Delta z_{pe} )</td>
<td>( \mu m )</td>
<td>5.77</td>
<td>5.77</td>
<td>2.57</td>
</tr>
<tr>
<td>S-curve peak 2 exact</td>
<td>( \Delta z_{pe} )</td>
<td>( \mu m )</td>
<td>5.27</td>
<td>5.74</td>
<td>2.55</td>
</tr>
<tr>
<td>S-curve length approximation</td>
<td>( \Delta z_{approx} )</td>
<td>( \mu m )</td>
<td>12.14</td>
<td>11.52</td>
<td>5.12</td>
</tr>
<tr>
<td>Sensitivity sensor lens</td>
<td>( \Delta v_{s} )</td>
<td>( \mu m )</td>
<td>1.25</td>
<td>1.25</td>
<td>1.25</td>
</tr>
<tr>
<td>Decentering sensitivity sensor lens</td>
<td>( \Delta v_{d} )</td>
<td>( \mu m )</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>Stroke actuator-detector</td>
<td>( \Delta \phi_d )</td>
<td>( \mu m )</td>
<td>1/59</td>
<td>1/62</td>
<td>1/92</td>
</tr>
<tr>
<td>Design wavelength</td>
<td>( \lambda )</td>
<td>nm</td>
<td>785</td>
<td>785</td>
<td>785</td>
</tr>
<tr>
<td>Grating pitch</td>
<td>( \phi_g )</td>
<td>( \mu m )</td>
<td>28</td>
<td>28</td>
<td>28</td>
</tr>
<tr>
<td>Distance spots diode</td>
<td>( s_d )</td>
<td>( \mu m )</td>
<td>130</td>
<td>130</td>
<td>130</td>
</tr>
<tr>
<td>Distance spots disk</td>
<td>( s )</td>
<td>( \mu m )</td>
<td>23.9</td>
<td>25.2</td>
<td>16.8</td>
</tr>
<tr>
<td>Distance grating laser</td>
<td>( g )</td>
<td>mm</td>
<td>2.85</td>
<td>3.00</td>
<td>3.00</td>
</tr>
<tr>
<td>Rotation on detector</td>
<td>( \psi_d )</td>
<td>( \circ )</td>
<td>2.8</td>
<td>2.8</td>
<td>2.8</td>
</tr>
<tr>
<td>Shift beams in pupil</td>
<td>( \Delta )</td>
<td>mm</td>
<td>0.29</td>
<td>0.29</td>
<td>0.40</td>
</tr>
</tbody>
</table>

Table 4.1: Parameters of five light path designs.
Distance collimator pupil \( l_c \) (mm) | 5 | 10 | 11 | 20
---|---|---|---|---
Distance grating laser optical \( g \) (mm) | 2.847 | 2.846 | 2.846 | 2.844
Distance spots diode for \( g = 2.846 \) mm (\( \mu \)m) | 130.1 | 130.0 | 130.0 | 129.9
Rotation satellites \( \phi_r \) (\(^\circ\)) | 2.37 | 2.73 | 2.80 | 3.43
Shift satellite beams in pupil \( \Delta r \) (mm) | 0.24 | 0.28 | 0.29 | 0.36

Table 4.2: Several parameters dependent on \( l_c \) for the parameters of light path 1.

For a cylinder lens the same S-curve and spot diameters on detector can be generated with two cylinder lens powers, when the distance of the cylinder to the detector is adapted (see Table 4.3). The S-curve is less symmetrical for the situation with the powerful cylinder lens. The rotation of the satellites and the increase of their distance to the main spot by the cylinder lens are larger for the powerful cylinder lens. The diameter of the spot on the detector is also more enlarged for this case. The diameter of the spot and the distance of the satellites to the main spot are decreased for a positive cylinder lens. However, a positive cylinder lens is not used in the designs described in this thesis.

### 4.5 Comparison with ray-tracing program (Zemax)

Results of our model are compared with the results of the ray-tracing program “Zemax” for light paths 1, 2 and 5: a light path with cylinder lens, with a plane parallel plate and a combination. As stated in the introduction of this chapter, the lenses are considered as thin lenses. The real distances and dimensions of the light path can be calculated by adding the extensions of the thick lenses and glass components to the calculated distances as described in [62] and [64]. The extension \( \Delta d \), of a flat glass or plastic component with refractive index \( n_o \) and thickness \( d_o \) is:

\[
\Delta d = \frac{n_o - 1}{n_i} d_o.
\]

Including these compensations, the nominal distances in the optical pick-up calculated with the model fitted well with the ray-tracing program. Small differences occurred in, for instance, the focus S-curve zero crossing. Light path 1, 4 and 5 are also verified in production in multimillion numbers.

A comparison of several main spot parameters: the S-curve length, the distance of the focal lines on the detector and the spot diameter is shown in Table 4.4. The S-curve for light path 1 and 2 is close to the Zemax case. For light path 5 the S-curve is shorter than in Zemax. The distance between the focal lines and the spot diameter on the detector agree reasonably.

<table>
<thead>
<tr>
<th></th>
<th>Light path 1</th>
<th>Light path 2</th>
<th>Light path 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>S curve length on disk ( \Delta z ) (( \mu )m)</td>
<td>Model 11.0</td>
<td>11.5</td>
<td>6.4</td>
</tr>
<tr>
<td></td>
<td>Zemax 11.0</td>
<td>11.0</td>
<td>5.6</td>
</tr>
<tr>
<td>Distance focal lines on detector ( \Delta f ) (( \mu )m)</td>
<td>Model 0.653</td>
<td>0.615</td>
<td>1.16</td>
</tr>
<tr>
<td></td>
<td>Zemax 0.672</td>
<td>0.612</td>
<td>1.13</td>
</tr>
<tr>
<td>Spot diameter on detector ( \phi_r ) (( \mu )m)</td>
<td>Model 60</td>
<td>60</td>
<td>78</td>
</tr>
<tr>
<td></td>
<td>Zemax 62</td>
<td>62</td>
<td>80</td>
</tr>
</tbody>
</table>

Table 4.4: Comparison of the main spot with Zemax.

Some satellite spot parameters are shown in Table 4.5. The distance of the main spot to the satellite spot on the disk \( s \) agrees well. Also the optimum optical distance between the laser and the grating \( g \) is fairly consistent. The rotation of the satellites \( \phi_s \) is in the same order of magnitude.
### Table 4.5: Comparison of the satellite spots with Zemax.

In Table 4.6, the change of $g$ and $\phi_s$ with $l_c$ of the model and Zemax in light path 1 are compared. The model and Zemax show the same sensitivity for both parameters.

### Table 4.6: Comparison in dependence of $g$ and $\phi_s$ with $l_c$ (light path 1).

4.6 Summary

A geometrical model of the three spots astigmatic light path is explained in detail. This model can be used as design tool for a quick evaluation of the light path parameters. The model is compared with the ray-tracing program "Zemax". The parameters calculated with this model agree with the parameters simulated with Zemax. The displacement of the objective lens and the spot on the detector are rotated $90^\circ$ with respect to each other. The smaller the beam diameter in an optical pick-up, the larger the displacement of the spot on the detector due to the actuator stroke will be. The minimum distance of the satellites is on the disk is depending on the focus S-curve length: the shorter the S-curve, the shorter this distance can be. The smaller the magnification from objective to collimator is, the smaller the S-curve from the same plate thickness will be. A large magnification for objective to collimator lens results in a smaller distance of the main spot to satellite on disk for the same grating pitch and optical distance from laser to grating. The model and simulations with Zemax both show that the angle of the satellites is depending on the distance between collimator and objective lens. Identical S-curve lengths and amounts of astigmatism on the detector can be achieved with a cylinder lens with a long focal length and a long distance to the detector or with a more powerful cylinder lens with a short distance to the detector. The rotation of the satellites and the increase of their mutual distance on the detector are larger for the latter case. The S-curve is less symmetrical for the situation with the powerful cylinder lens. The S-curve of a plate is symmetrical. The shift of the radial beams in the pupil increases with a decreasing grating pitch and an increasing distance between collimator and pupil.

In this chapter a model is discussed that is used to calculate the parameters of the designed light paths. In the next chapter the approach of the light path design is explained by means of a multidisciplinary design process.
The multidisciplinary design process of a light path for optical recording
5.1 Introduction

This thesis deals with designs and designing optics for DVD video recorders and data drives. The experiences and leanings of the design process is subject of this section. The way of working, the constraints and how to deal with the technical and other relevant information for a design and criteria and constraints are discussed. The design work is carried out in a product development environment and not in a research environment. The aim of this chapter is to show the typical approach of the light path design process in an industrial environment. The light paths described in this thesis are designed according to this process [65].

"Designing" stands for creating a solution, which fulfills the requirements of a device. A solution is not unique in contrast to the outcome of mathematical problem. Actually an infinite number solutions and designs are possible. As an example: no two cars equal, when they are designed independently. Designers make their sometimes-personal design choices, when considering the constraints of the design assignment and the available information.

A new generation optical pick-up is often developed in parallel with a new disk type and a new basic engine, which means that the design has a multidisciplinary character. The disciplines have a technical nature like optics, electronics, mechanics, manufacturing but also a more general nature like purchasing, marketing and project management. Designing optics of an optical pick-up is teamwork. It is a process with input from different points of view, which leads in the end to one single design. The design proposals are discussed with the people of the different disciplines in several steps, who give their comment. The choices in, e.g., the optics have their impact on the other disciplines.

Because the continuous improvement of the understanding all kind of issues, an optical pick-up, which is designed today, is different from one designed 5 years ago. When a new technology is applied, the choices we make are also depending on the amount of risk we can take for delay or failure in a particular development project.

The lifetime of an optical pick-up concept and its matching basic engine is normally much longer than the individual consumer products like a particular video recorder or data drive. For instance, the next generation, higher specified, product can be prepared by replacing some components (e.g., a higher power laser in the same optical pick-up) in order to be able to increase the available power on the disk the increase the recording speed.

How we can cope with the above-mentioned items is discussed in this chapter. Section 5.2 describes the design process. Some general design philosophy statements are given in Section 5.3. This chapter is summarized in Section 5.4.

5.2 The design process

A schematic representation of the design process[*] is shown in Fig. 5.1. The design starts with the available technical information and the constraints. The technical information is available knowledge. The constraints are factors, which focus and limit the design process. They are sometimes defined by the project assignment. Sometimes they are proposed by the designer in order to converge the design process.

5.2.1 Inputs

The explanation and examples on the technical inputs for a new development are listed below. The information can be divided in the sources, which deliver the information:

- New technology developed: Knowledge from research and new technology developments, for instance, a new component or a new assembly method.
- Supplier's information: Roadmap of new components and technology of the suppliers, for example new components or manufacturing technology.
- Competition information: Technical and market information from the competition.

The technical information can also be divided into information from the technical disciplines:

- Disk system information: Properties of the disk to be recorded or read out, for instance, optical properties, necessary signals and readout methods.
- Optical possibilities: Knowledge on optical components, for instance, coatings, diffractive structures and lasers.
- Mechanical possibilities: Constructions for mounting and adjustments, molding tolerances or new components, for instance, a new type of lens actuator.
- Electronic possibilities: Knowledge on electrical principles, like signal detection methods and low noise amplification.
- Dynamic/control possibilities: Assembly methods, which are feasible in the factory.
- Assembly methods: For instance, a new type of actuator or control principle.
- Process tolerances: A new type of actuator or control principle.

[*] The process in Fig. 5.1 is mainly represented from optical design point of view. This means that for the other disciplines the impact on the optical design is represented. The activities in the other disciplines mentioned are in fact more complicated than outlined here.
5.2.2 Constraints

Examples and explanation of the constraints are criteria on the subjects given below.

Required specification: Specifications numbers and features. For instance, the type of disks to be recorded or read out with required recording and read speeds or environment temperature or shock requirements.

Cost target: Cost target of the optical pick-up.

Environment: Environment requirements, for instance, lead free components.

Quality: Lifetime requirements in combination with climate requirements (temperature and humidity exposure).

Form factor: Mechanical dimensional requirements of the optical pick-up depending on or defining the mechanism and drive or recorder.

Required schedule: Timing of the milestones of the development project, for instance, the date of availability of the first samples and the planned mass production date.

Each of the inputs in the previous section also contains implicit information on the constraints.

5.2.3 The design steps

In the first design step, step 1, the inputs are incorporated in a few possible concepts: generation of a few alternatives by means of rough sketches and quick calculations. In order to have a quick view on the impact of several parameters, the analytical model described in the previous section can be applied. Also other quick calculations and estimations can be made, like electro-optical signals, rim intensities, laser powers and mechanical and optical tolerances.

A discussion of the alternatives and its pros and cons with the people of all relevant disciplines involved will ensure that a design will be chosen which is optimal from all aspects. For some sub-items a short feasibility study is necessary in order to get the necessary knowledge, e.g., a simulation, a small experiment or a discussion with a supplier about a component. Also a check on the constraints is performed. For instance, a calculation of the cost price of the design is compared with the cost target. With these inputs and discussions a choice is made for the optical design, with possibly one alternative.

When the outcome of the evaluations, discussions and checks is not satisfying, because one of the requirements is not fulfilled, it may be necessary that the process of step 1 must be repeated. Such a repetition can also be necessary for the next steps.

In step 2 the design is evaluated in detail, for instance, with a ray-tracing optical design program. In this phase the tentative specifications and drawings of the optical components are prepared, for detailed discussions with the suppliers. Extensive communication between the disciplines is necessary in this design phase. The electro-
optical signals are calculated in detail, in order to discuss with the electronic discipline for feedback and adaptation when necessary. The location of the IC’s on the pick-up and the electrical connections are made. The nominal dimensions of the light path and the dimensions of the optical pick-up are related. Hence, the drawing of the pick-up housing can be prepared and it may be possible that the optical design will be modified for mechanical reasons. The optical components are placed in the housing with limited accuracy. Tolerance calculations are necessary in order to find out the necessary accuracy. The effect of misalignments is estimated on the relevant parameters like optical aberrations, decentering of the spot on the detector and tolerances of radial tracking method. If the required accuracy is higher than what can be achieved with placement on mechanical references, the component is adjusted based on a measurement signal. The results are discussed with the people, who define the assembly equipment and the pick-up housing. No complete prototype is prepared in this phase. Some aspects, for instance, a new type of optical component can be evaluated in a separate test. The chance that total light path will work in practice is very high, when the total light is simulated by means of a ray-tracing program and other modelling tools, because result of calculations and simulations of optics and lens systems are in general very reliable.

When everything is satisfactory the design can be worked out in step 3. The modifications generated during the previous discussions are implemented. The final component specifications will be prepared. The tooling for assembly is defined. The drawings of the housing and the electronics on the pick-up will be finalized. A prototype will be made in order to verify the design.

After assembly and evaluation of the first models, some modifications may be necessary. This is step 4. When they are implemented and everything is OK the final design is ready.

The 4 steps are basically the “act-taste-act” steps of a design process [66]. Every step is evaluated (“taste”) and adapted (“act”) where necessary (Fig. 5.2).}

Fig. 5.2: Designing is an “act-taste-act” process.

From step 1 until step 4 the accuracy of the design description increases. Step 1 contains rough sketches, while step 4 is a final design with a lot of details. However, when going towards step 4 the room for changes, which is called the design space, decreases, because more and more people and money are involved, and the timing becomes more and more critical (see Fig. 5.3). The graphs have a non-linear shape, because the amount of described details, the amount of money and the amount people increase more than linear.

5.3 Considerations on constraints and inputs

The constraints and inputs are determining the design process and results to a large extent. In this section some general statements are made on how to deal with the constraints and inputs.

Use the latest feasible solutions

Using new solutions in a research environment will bring the desired new information and spin offs. However, during a product development the risks of failures should be minimized, which means that the approach of using new solutions is different.

Almost every development project has a tight planning. Therefore it is recommended to apply only feasible solutions and components. With the term feasible is meant that a solution has been technically proven in another product or by means of a separate investigation. If something unfeasible is incorporated in the design, the risk of project delay is very high, due to unforeseen problems. Before step 2 some feasibility studies can be performed.

On the other hand it is necessary to design in the latest feasible solutions, because they generally have an advantage in cost and/or specification. As a result, more value is created. For instance, when plastic lenses are feasible they will be used by all pick-up manufacturers, because of the advantage in cost price. Sticking to glass lenses will result in a too expensive design in comparison with the competitors.

Standard interface and standard components where possible

It is recommended to be unique if it results in a very obvious advantage. In all other cases it is recommended to use standard components and standard interfaces.

The mechanical and electrical interface of the pick-up to the drive preferably is according to the industry standards, in order to be able to sell the products to customers, which have other electronics sets and mechanics in the drive. It will result in constraints
for the mechanical outline, the position of the lens and bearings, the spot shape and the electro-optical signals.

It is recommended to use as much as possible standard optical components, which are off the shelf available at the suppliers, because of logistic and price advantages due to the large production quantities. These components are also tested by others and are therefore feasible. Consequently, less component evaluation and release work is necessary. Examples are lenses with a standard focal length, beamsplitters with standard coatings and standard detectors.

A difficulty is to define what the standard is going to be. When we enter the market very early, it is possible to set or influence the standard of an interface or a component.

In some cases a unique component can bring obvious advantages. Then it is worthwhile to use such a component in order to create extra value.

Reduction of components

A simple solution is very often a better one. Limiting the number of components is a way to make a design simpler. In general the elimination or combination of components will result in cost and manufacturing benefits. However, it is not always possible or beneficial to do so and sometimes integration may lead to very unique components.

High performance or low cost

A high performance can be a high speed of reading or recording, a high environment temperature, or reading or writing many types of disk. It can also be writing and reading a disk instead of only reading that disk. Low lost and high performance is of course ideal from business point of view. However, in most of the cases it is contradictory. A high performance means in general expensive components. Therefore it is important to set priorities on cost or on performance. On the other hand it is a challenge to get optimal result for a reasonable price.

Feasible processes and re-use of tooling

The factory will assemble the optical pick-up. Therefore it is very important to know what is possible in the factory and what is not. A total new process can only be designed in after a successful feasibility investigation.

It is even better, when a big part of the tooling of a previous product can be applied. This will result in a faster development time and a faster ramp up of the production volumes.

5.4 Summary

The way of working of designing a light path for an optical pick-up is explained. It is a multidisciplinary process in several steps. The relevant aspects have a technical nature like optics, electronics, mechanics and manufacturing, however, also a more general nature like cost, market trends development time and moment of product introduction. The process consists of several steps, which are alternations of generation and evaluation. Therefore, the design process is called an “act-taste-act process”. The approach in an industrial environment is different from a research environment. Some general statements are made on how to deal with the constraints and inputs.

In this chapter the general approach of a design process is discussed. The first light path design discussed in detail in this thesis is the DVD recorder with dual detector. This is the subject of the next chapter.
The dual detector light path design and optimization of the spot in the radial actuator stroke
6.1 Introduction

The design of the dual detector light path is treated in this chapter. This light path is applicable for a DVD recorder. A DVD recorder is expected to read or record CD-s as well. This requirement should be fulfilled with one objective lens. The requirement can be fulfilled with the "finite conjugate compatibility solution". Section 6.1 explains the principle of the finite conjugate compatibility solution. The total dual detector light path design is discussed in Section 6.2. A major issue of the finite conjugate compatibility solution is the coma due to the stroke of the objective lens, which is necessary for radial tracking. A novel solution for this unwanted coma is found and implemented in the dual detector light path design presented in this chapter. The solution is treated by analytical modeling and simulation with a ray-tracing program in Section 6.3. The summary of this chapter is found in Section 6.4.

6.2 The finite conjugate compatibility solution

As stated in Chapter 1 the CD cover layer has a thickness of 1.2 mm, while the DVD cover layer has a thickness of 0.6 mm. In most cases the aspherical objective lens of a DVD recorder is designed for a parallel beam towards the lens for DVD. This means that the design value of the spherical aberration for the DVD cover layer and the DVD wavelength is zero. The 0.6 mm thickness difference will cause spherical aberration, when the same lens is applied for DVD and CD in case of a parallel beam towards the objective lens. The RMS value in the approximation of primary spherical aberration can be expressed as follows [2]:

\[ W_{4 \omega \text{RMS}} = \frac{(n^2 - 1) \Delta D}{8 n r^2 \lambda^2} N A^4, \]

(6.1)

where \( \Delta D \) is the difference in cover layer thickness and \( n_r \) the refractive index of the cover layer. Reading out a CD disk results in \( \Delta D = 0.6 \) mm. When \( n_r = 1.57 \) and \( NA = 0.45 \) and \( \lambda = 785 \) nm, according to Equation (6.1), \( \Delta D \) will result in 110 m\( \lambda \). RMS spherical aberration, which is far beyond the Maréchal criterion.

The "finite conjugate compatibility solution" is a possibility to compensate for this spherical aberration. Spherical aberration will be generated in an objective lens when the beam is not parallel. This spherical aberration can be used to compensate for the spherical aberration generated by \( \Delta D \). This technique is used in the finite conjugate compatibility solution. Within the full clear aperture, a diffraction-limited focus is obtained on the DVD disk using a parallel laser beam. Within a reduced aperture a diffraction-limited spot is obtained on a CD disk by using a divergent laser beam towards the objective lens (Fig. 6.1). The numerical aperture of the divergent or pre-collimated beam towards the objective lens is defined as \( NA_d \). The spherical aberration, which arises due to the divergent beam, compensates the spherical aberration caused by the disk cover layer difference as will be shown later.

\[ H(\rho) = \sum \alpha_i \rho^i \]

(6.2)

where \( \alpha_i \) are the coefficients of the aspherical surface.

An example of a \( NA = 0.65 \) objective lens, which is designed for DVD is shown in Fig. 6.2. Its focal length is 2.75 mm. The lens is a plano-convex spherical glass lens with an aspherical correction layer by means of an UV curing lacquer, which is called the "replica layer".
The spherical aberration as a function of the magnification in the case of a 1.2 mm CD disk. The stop diameter of 2.6 mm is kept constant. The spherical aberration is obtained from situations with a ray-tracing program.

Fig. 6.3 shows a simulation with the ray-tracing program “Zemax” of the resulting spherical aberration as a function of the magnification of this lens. The aberration value is minimal for a magnification $NA/NA = 0.059$. The value of $NA = 0.026$ and distance from laser source towards the vertex of the aspherical surface of lens is 49 mm for this case.

The DVD beam is parallel and the CD beam is divergent. Consequently, the object distances of CD and DVD are different. Because the detector is located at the image of the laser spot, the distance from laser towards detector differs also. This makes it necessary to use two signal detectors for the finite conjugate compatibility solution: one for DVD and one for CD. In other words: the application of the finite conjugate compatibility solution results in a dual detector light path.

**6.3 The dual detector light path**

A dual detector light path was designed in 1998-1999 for the optical pick-up of the first generation Philips DVD video recorder [67]. The finite conjugate compatibility solution was at that time the only feasible solution for DVD recording with a single objective lens.

![Optical layout of the designed dual detector light path](image)

**Fig. 6.4: Optical layout of the designed dual detector light path.**

The optical layout of this dual detector light path is illustrated in Fig. 6.4 and Fig. 6.5. Fig. 6.4 shows a three-dimensional view and Fig. 6.5 shows the light path projected in one plane. This light path consists of two branches, which are located in two layers: the DVD branch at the bottom and the CD branch at the top.

Astigmatic focusing and differential push-pull radial tracking are applied in the DVD branch (see Section 3.5.2). The elliptical intensity profile of the DVD laser beam is circularized by means of a beam shaper. This beam shaper is a plastic lens element, which consists of two cylindrical and toroidal surfaces as proposed by Braat [46]. The laser power is measured by the forward sense diode. It detects the laser power just outside the beam that is coupled into the aperture. The three spots grating generates the three spots for the differential push-pull radial tracking method. The beam is made parallel by the collimator lens and is reflected by the folding mirror. It is transmitted by the dichroic beamsplitter, which splits the DVD and CD branch.
Fig. 6.5: Schematic representation of the designed dual detector light path.

Afterwards the beam passes the dichroic aperture and $\lambda/4$ plate and is focused on the disk by the objective lens. After reflection on the disk the polarization state of the laser beam is rotated 90° by the $\lambda/4$ plate and is therefore reflected by the PBS towards the servo lens and the detector. The servo lens has a cylindrical surface for generating astigmatism for the astigmatic focusing and a negative spherical lens, which is utilized for focus adjustment of the spots on the DVD detector (see Section 4.2.2 for the details). The light path parameters were calculated with the geometrical model given in Chapter 4. The light path parameters are as listed as "light path 4" in section 4.4.

The CD branch applies an LDGU (Laser Detector Grating Unit), which is explained in Section 3.6.2. It is suitable for CD- and CD-R(W) read. For focusing and radial tracking the Foucault and three spots central aperture method are applied, respectively. The numerical aperture of the beam coming out of the LDGU is reduced from $N_{Ac} = 0.103$ to $N_A$ by the (pre-)collimator. The numerical aperture of the CD objective lens is limited to 0.46 by the dichroic aperture. The dichroic aperture is a color sensitive aperture that is visible for CD and invisible for DVD. It can be a dielectric coating or a diffractive grating. The beam which is reflected by the disk goes via the dichroic beamsplitter back into the LDGU were it is diffracted towards the detector by the structure of the Foucault grating on the LDGU (Fig. 3.26).

The tilt sensor shown in Fig. 6.6 measures the disk tilt when reading or recording a DVD disk. It consists of LED (Light Emitting Diode), a lens and a split detector. The position of the imaged spot on the detector is depending on the disk tilt. The differential signal out of the split detector is as measure for the disk tilt. The radial tilt angle is corrected by tilting the total optical pick-up in the radial direction, which is perpendicular to the tracks on the disk.

Fig 6.7 shows cross-sections of the mechanical construction of the pick-up. The DVD and CD branch are located on top of each other and not next to each other in order to get a compact optical pick-up [68]. Photos of the final optical pick-up are presented in Fig. 6.8.

Fig. 6.6: Tilt sensor. The position of the spot on the split detector is depending on the disk tilt. The differential signal of the split detector is zero at a certain disk tilt.

Fig. 6.7: Two cross-sections of the dual detector optical pick-up. The components of the DVD branch are visible in the cross-section A-A on the left. Cross-section B-B shows the CD branch.

Fig. 6.8: Photos of the optical pick-up with the designed dual detector light path. The picture on the left shows the top view with the lens actuator and the tilt sensor. The picture on the right shows the bottom view with DVD branch. The connections of the LDGU are visible at the front of both pictures.
Measurement data [69] of the jitter with this light path as a function of disk tilt for CD and DVD are shown in Fig. 6.9a and 6.9b, respectively. (An explanation of jitter is given in Section 3.3.) The jitter is measured including an equalizer filter that boosts the shorter pits. Disk tilt generates coma, which causes this timing error of the RF signal. The results are comparable with the simulations of Fig. 3.10. From these graphs it is clear that DVD is more sensitive than CD despite the thinner cover layer of DVD. The DVD disk specification allows a tilt of the disk itself of 0.3° in tangential direction and 0.8° in radial direction. Because the disks can have this large tilt in the radial direction, the disk tilt is corrected in radial direction by means of tilting the optical pick-up in the drive mechanism of the DVD recorder as mentioned.

![Fig. 6.9: Jitter in % of c0 for DVD and CD as a function of disk tilt measured with the designed dual detector light path [69]. The curves are a parabolic fit of the measurement data.](image)

### 6.4 Reduction of the coma as a function of the radial stroke for CD

A major disadvantage of the dual detector light path and the finite conjugate compatibility solution is the coma due to the radial stroke of the objective lens required for radial tracking. This issue has been improved in this design in comparison with other dual detector designs.

#### 6.4.1 Coma in the radial stroke of the actuator

Fig. 6.10 shows the aberrations of the objective lens in Fig. 6.2 as a function of the image field radius for DVD and CD. The image field radius is the lateral deviation of the image point from the optical axis.

![Fig. 6.10: Aberrations of the objective lens as a function of the image field radius for CD (NAe = 0.027) and DVD (NAe = 0).](image)

The lens is designed for the best image field behavior for the DVD case. When this lens is applied for CD the coma coefficient \( A_{31} \) is dominant. This is mainly due to the thicker CD disk. For CD the lens does not fulfill the Abbe sine condition [37]. This means that coma will be generated in the image field of the objective lens for CD.

![Fig. 6.11: The objective lens generates coma in the radial stroke of the actuator.](image)
Due to the finite conjugate, the radial stroke of lens actuator results in image field use of the objective lens. These two effects introduce coma as a function of the radial stroke of the actuator (see Fig. 6.11). The maximum radial stroke is typically ±0.30 mm, while the stroke of the spot on disk is ±0.32 mm. The radial stroke problem is not present when reading or recording the DVD disk, because of the parallel beam.

One solution could be a lens with an image field, which is more balanced for DVD and CD as described in [68]. However, this compromise will affect the DVD performance.

### 6.4.2 Reduction theory

When extra spherical aberration is added into the beam towards the objective lens, the undesired coma can be reduced [69].

In order to understand this effect, the Zernike polynomials given in Section 3.3 can be applied [37]:

$$W(r, \phi) = A_m Z_m^m (r, \phi), \quad \text{(6.2)}$$

where $r$ is the normalized pupil radius and $\theta$ is the azimuth. The expression is in Cartesian coordinates with $x = r \cos(\phi)$ and $y = r \sin(\phi)$ is:

$$W(x, y) = A_m X_m^m (x, y), \quad \text{(6.3)}$$

where $X_m^m (x, y)$ is the Zernike coefficient in polar coordinates.

<table>
<thead>
<tr>
<th>n</th>
<th>m</th>
<th>Name aberration</th>
<th>$Z_m^m (r, \phi)$</th>
<th>$X_m^m (x, y)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>Tilt</td>
<td>$r \cos(\phi)$</td>
<td>$x$</td>
</tr>
<tr>
<td>1</td>
<td>-1</td>
<td>Tilt</td>
<td>$r \sin(\phi)$</td>
<td>$y$</td>
</tr>
<tr>
<td>2</td>
<td>0</td>
<td>Defocusing</td>
<td>$-1 + 2r^2$</td>
<td>$-1 + 2x^2 + 2y^2$</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>Astigmatism 0°</td>
<td>$r^2 \cos(2\phi)$</td>
<td>$x^2 - y^2$</td>
</tr>
<tr>
<td>2</td>
<td>-2</td>
<td>Astigmatism 45°</td>
<td>$r^2 \sin(2\phi)$</td>
<td>$2xy$</td>
</tr>
<tr>
<td>3</td>
<td>1</td>
<td>Coma 0°</td>
<td>$(-2r + 3r^3) \cos(\phi)$</td>
<td>$-2x + 3x^3 + 3xy^2$</td>
</tr>
<tr>
<td>3</td>
<td>-1</td>
<td>Coma 90°</td>
<td>$(-2r + 3r^3) \sin(\phi)$</td>
<td>$-2y + 3y^3 + 3xy$</td>
</tr>
<tr>
<td>4</td>
<td>0</td>
<td>Spherical aberration</td>
<td>$1 - 6r^2 + 6r^4$</td>
<td>$1 - 6x^2 + 6x^4 - 6y^2 + 6y^4 + 12x^2 y^2$</td>
</tr>
</tbody>
</table>

**Table 6.1:** Zernike coefficients in polar and Cartesian coordinates.

For the RMS value of each aberration type we obtain:

$$A_{\text{rms}} = \frac{1 + \delta_{\text{m}}}{2(n + 1)} A_m, \quad \text{(6.4)}$$

in which $\delta_{\text{m}}$ is the Kronecker delta symbol. The aberrations of interest for this subject are given in Table 6.1 in polar and Cartesian coordinates.

The parameter of decentering of the objective lens $\xi$ is defined as:

$$\xi = \frac{X_s}{R_p}, \quad \text{(6.5)}$$

where $R_p$ is the pupil radius and $x_s$ the decentering of the objective lens due to the radial stroke (both in mm). According to Table 6.1 the spherical aberration function is:

$$W_{\text{40b}}(x, y) = A_4 X_4^4 (x, y) = A_4 (1 - 6x^4 + 6y^4 - 6y^4 + 12x^2 y^2), \quad \text{(6.6)}$$

The residual spherical aberration $W_{\text{40b}}(x, y)$ is defined as the spherical aberration in the pre-collimated beam $W_{\text{40b}}(x, y)$ minus the spherical aberration of the objective lens $W_{\text{40b}}(x, y)$ which is not compensated by the divergent beam.

$$W_{\text{40b}}(x, y) = A_4 X_4^4 (x, y) = A_{\text{40b}} X_4^4 (x, y - \xi, y) \quad \text{(6.7)}$$

For $\xi = 0$, which is the situation on the optical axis, the spherical aberration should be zero, therefore $W_{\text{40b}}$ is compensated with a small increase of $N A_s$, therefore:

$$A_{\text{40b}} = A_{\text{40b}} \xi. \quad \text{(6.8)}$$

When the constant factors are disregarded we find:

$$W_{\text{40b}}(x, y) = A_{\text{40b}} (24\xi^2 x^2 - 12\xi^2 x - 36\xi^2 x^2 + 24\xi^2 x + 24\xi^2 y^2 - 12\xi^2 y^2), \quad \text{(6.9)}$$

which can be written as:

$$W_{\text{40b}}(x, y) = A_{\text{40b}} (8\xi X_1^1 (x, y) - 12\xi^2 X_2^2 (x, y) + 12\xi^2 X_3^3 (x, y) + 4\xi^2 + 24\xi^3) X_1^1 (x, y)). \quad \text{(6.10)}$$

Consequently:

$$A_{\text{40b}} = \frac{A_4}{8\xi}, \quad \text{(6.11)}$$

or with Equation (6.4):
\[ A_{\text{aberration}} = \frac{1}{2\sqrt{10}} \frac{A_{\text{rms}}}{\xi}. \]  

(6.11)

The conclusion of Equation (6.11) is: when objective lens generates coma proportional to the radial stroke, this coma can be reduced with spherical aberration in the beam.

However, Equation (6.10) has also some other terms. The astigmatism term results in:

\[ A_{\text{astigmatism}} = 12 \times \frac{A_{\text{rms}}}{\xi^2} A_{\text{aberration}}. \]

(6.12)

which can also reduce the quality of the spot. The other terms in Equation (6.10) are defocusing and tilt, which are compensated by the focus and radial servo system of the recorder.

### 6.4.3 Partial and full reduction

The graphs of Fig. 6.12 and 6.13 represent two examples of reduced coma as a function of the radial stroke of the actuator. Fig. 6.12 shows partial reduction. The coma at \( x_0 = 0.3 \) mm is reduced from 35 into 16 \( \text{mA RMS} \), which is more than 50% decrease. \( \text{NA}_e \) is increased from 0.026 to 0.031 in order to get no spherical aberration on axis. The astigmatism is raised a little according to Equation (6.12).

Fig. 6.12: The coma in the radial stroke of the actuator with and without spherical aberration in the pre-collimated beam. Partial reduction of the coma is obtained.

Fig. 6.13 shows almost full reduction: 35 into 4 \( \text{mA RMS} \). For this situation astigmatism becomes the dominant.

Fig. 6.13: The coma in the radial stroke of the actuator with and without spherical aberration in the pre-collimated beam. Almost full reduction of the coma is obtained.

The required spherical aberration is generated in an aspherical surface of the CD (pre-collimator) (see Fig. 6.14). It is a plastic lens made of COC (Cyclic Olefin Copolymer) with one aspherical and one flat surface.

Table 6.2 indicates the values of the spherical aberration in the beam for the two examples. The theoretical values are compared with the values calculated by means of a ray-tracing program "Zemax". The CD pupil radius is \( R_p = 1.3 \) mm, hence \( \xi \approx 0.23 \) at the maximum stroke. As stated \( \text{NA}_e \) will be increased. Therefore the corrected coma in the second column of Table 6.2 is a little higher, because of shorter object distance,
which increases the field angle in the actuator stroke. So a higher reduction is necessary in order to get the same result (see second column of Table 6.2). This value is larger for the full aperture of the (pre-)collimator, because the beam has to overfill the radial stroke with a rim of 0.3 mm.

<table>
<thead>
<tr>
<th></th>
<th>( A_{\text{31RMS}} ) to be reduced</th>
<th>( A_{\text{31RMS}} ) to be reduced including increased ( NA_e )</th>
<th>( A_{\text{40RMS}} ) beam (simulation)</th>
<th>( A_{\text{40RMS}} ) beam (theory)</th>
<th>( A_{\text{40RMS}} ) full aperture (theory)</th>
</tr>
</thead>
<tbody>
<tr>
<td>&quot;Partial&quot; reduction</td>
<td>19</td>
<td>22</td>
<td>17</td>
<td>15</td>
<td>35</td>
</tr>
<tr>
<td>&quot;Full&quot; reduction</td>
<td>31</td>
<td>40</td>
<td>33</td>
<td>28</td>
<td>64</td>
</tr>
</tbody>
</table>

Table 6.2: The values of \( A_{\text{31RMS}} \) and \( A_{\text{40RMS}} \) in m\( \lambda \) RMS for "partial" and "full" reduction of the coma at 0.3 mm actuator stroke (\( \zeta = 0.23 \)). The theoretical value \( A_{\text{40RMS}} \) of Equation (6.12) is compared with the value of the simulations with the ray-tracing program "Zemax".

### 6.4.4 The satellite spots

A point of attention in this method is the aberration level of the satellite spots. Based on some geometrical optics one can derive the following expression for the offset of the wave front of the satellite beam from the pre-collimator (Fig. 6.15):

\[
\Delta_e = l_c \cdot \frac{N_A}{N_A} \left( \frac{1}{f_e} \cdot \frac{N_A}{R_p} \right),
\]

where \( \Delta_e \) is the offset of the wave front of the satellite beam to the collimator, \( l_c \) the distance between collimator and the stop, \( s' \) the distance between the image of the main spot and the satellite spots at the source side, \( N_A \) the numerical aperture of the collimator and \( f_e \) the focal length of the objective lens.

The coma of a satellite spot is:

\[
A_{\text{31sat}} = 8 \Delta_e \cdot A_{\text{40RMS}},
\]

or in RMS:

\[
A_{\text{31sat RMS}} = 2 \sqrt{10} \cdot A_{\text{40RMS}}.
\]

For the values \( l_c = 10 \text{ mm}, s' = 71 \mu \text{m}, f_c = 2.75 \text{ mm}, N_A = 0.10, N_f = 0.46, R_p = 1.3 \text{ mm} \) and \( N_A = 0.028 \) or 0.031 we get \( \Delta_e = 0.054 \text{ mm} \). Table 6.3 shows the extra coma in the satellite spots. Coma in the satellite spot is less harmful than coma in the main spot, because these spots are only applied for the generation of the radial signal.

<table>
<thead>
<tr>
<th></th>
<th>( A_{\text{31RMS}} ) beam (theory)</th>
<th>( A_{\text{31RMS}} ) satellite spots due ( A_{\text{40RMS}} ) (theory)</th>
<th>( A_{\text{31RMS}} ) satellite spots total (simulation)</th>
<th>( A_{\text{31RMS}} ) satellite spots corrected for field/grating (simulation)</th>
</tr>
</thead>
<tbody>
<tr>
<td>50% reduction</td>
<td>15</td>
<td>5</td>
<td>33</td>
<td>7</td>
</tr>
<tr>
<td>90% reduction</td>
<td>28</td>
<td>10</td>
<td>39</td>
<td>13</td>
</tr>
</tbody>
</table>

Table 6.3: The values of \( A_{\text{31RMS}} \) in m\( \lambda \) RMS of the satellite spots for "partial" and "full" reduction. The satellite spots contain 26 m\( \lambda \) coma without spherical aberration in the beam. The theoretical value is according to Equation (6.15).

The resulting value of this extra coma is relative small because \( l_c \) is a small as possible. This is an argument to put the CD branch at the top for the light path configuration of Fig. 6.4 and 6.5. The value for partial reduction is smaller than for full reduction. We have chosen for partial reduction for this reason.
6.5 Summary

A dual detector light path is designed for DVD writing and CD reading. In order to achieve this, the finite conjugate compatibility solution is applied in this light path. Within the full clear aperture, a diffraction-limited focus is obtained on the DVD disk using a parallel laser beam. Within a reduced aperture a diffraction-limited spot is obtained on a CD disk by using a divergent laser beam towards the objective lens. The spherical aberration that arises due to the divergent beam compensates the spherical aberration caused by the difference in the thickness of the disk cover layer. This dual detector light path is designed in two layers: one for CD and one for DVD, which enables a compact optical pick-up unit. A major disadvantage of the dual detector light path and the finite conjugate compatibility solution is the coma due to the stroke of the objective lens, which is necessary for radial tracking. This effect is reduced by a factor of two by adding spherical aberration to the divergent beam between collimator and objective lens. A side effect of this measure is that the satellite spots get some extra coma, which is to a certain extent not harmful. In principle it would be possible to completely eliminate the stroke induced coma. However, in that case the coma of the satellites would become too large. Coma reduction with the mentioned factor of two appears to be the best compromise.

In this chapter we have discussed the designed dual detector light path with a solution for the coma due to the radial stroke of the actuator. The logical successor of the dual detector light path is the single detector light path, which is treated in the next section.

The single detector light path design
7.1 Introduction

The necessity of two detectors is a disadvantage of the finite conjugate compatibility solution. In this chapter we will discuss the design of the single detector light path suitable for DVD and CD recording. In this design the focus has been placed on maximum power efficiency in order to allow for a high rotation speed of the disk during recording, while not compromising on a low cost price and a good reliability.

The recording and read-out speed are the most important specification items for data drives. The higher the speed the more power is required in the diffraction-limited recording spot. For instance, a 8x DVD+R disk requires about 30 mW in the spot, while a 16x DVD+R disk needs 60 mW. The same holds for CD: 24x CD-R requires approximately 35 mW and 48x CD-R 60 mW. With a dual layer disk the capacity is almost doubled, however, a 4x dual layer DVD+R requires already 40 mW due to losses in the semitransparent layer. On the other hand, the required laser power is not always available in time. The efficiency of the power of a laser into the spot is approximately 20% to 30%, which means that, for a 16x DVD+R drive, a laser is required of roughly 200 mW to 300 mW. The laser manufacturers increase the laser power by means of improvement of their processes and designs.

The data drive and optical pick-up manufacturers have a speed race as shown in Fig. 2.4 and 2.5. The laser manufacturers have a laser power race in order to fulfill the laser power requirements for the speed race. In order to be the first one at a certain speed the optical pick-up should be as power-efficient as possible, in order to get maximum power into the recording spot with a certain laser. On the other hand, the cost price and reliability are very important. The designed single detector light path contains various new principles to combine these ambitious requirements.

In Section 7.2 the principle of infinite conjugate compatibility of the objective lens of the single detector light path is discussed. This lens enables a proper CD and DVD spot in case of two parallel beams. A pre-collimator is a lens that increases the coupling efficiency of the CD part of the single detector light path. This component is discussed in Section 7.3.

The light path concept is explained in Section 7.4. In Section 7.5 until 7.8 the novel technologies are discussed in order to improve the recording speed, cost and reliability, which are applied in the single detector light path design: a cheap and efficient CD beam splitter in Section 7.5 and 7.6, a cheap and reliable CD pre-collimator principle in 7.7 and an efficient DVD beamshaper in Section 7.8. These new principles are founded by analytical modeling and simulation. Information on the realization and implementation of the light path is given in Section 7.9. The summary of the chapter is found in Section 7.10.

7.2 The infinite conjugate compatibility solution

7.2.1 General

The single detector light path contains a lens, which is able to read and record a disk with different cover layer thickness with a parallel beam towards the objective lens. Such a lens has a wavelength selective structure on one surface in order to compensate for the difference in spherical aberration and dispersive effects between the DVD and CD lens as indicated in Fig. 7.1.

![Fig. 7.1: The structure on a compatible lens for a DVD and CD disk with a parallel beam.](image)

These structures can be made in the replica layer of a glass-replica-lens or in one surface of a plastic lens. This structure is located on the inner part of the lens diameter, which is used to make the numerical aperture of 0.5 for CD-R(W). Outside this aperture the rays are so aberrated that they will not reach the detector [72] and will not contribute to the recording spot.

One type of compatibility structure is the so called “non periodical phase structure”, which will be discussed briefly in the next session. Another way to make a wavelength selective structure is a (quasi) periodical diffractive structure that diffracts the beam for CD and DVD in a different way as described by [73]. This solution will not be discussed in this thesis in detail.

7.2.2 Non periodical phase structure

The non-periodic phase structure generates a phase correction which is visible for CD ($\lambda = 790$ nm) and invisible for DVD ($\lambda = 660$ nm), see [74] and [75]. The structure consists of steps with height $h_0$ which introduce an optical path difference of $\phi$ for DVD and CD according to:

$$\phi = h_0 \cos(\theta) (n_{\text{res}} - 1),$$

(7.1)

where $n_{\text{res}}$ is the refractive index of the lens and $\theta$ the angle of the cosine factor associated with the propagation vector of the wavefront in the non-periodic phase
structure. When $\phi$ is chosen in such a way that it is an integer times the wavelength for DVD, the structure will, in first approximation not be visible for DVD. The wavelength and the refractive index are different for CD, therefore the steps will influence the wave front with an aberration value $\Delta W_i$:

$$\Delta W_i = \frac{\phi - K\lambda}{\lambda}, \quad (7.2)$$

where $K$ is the largest integer so that $|\phi - K\lambda|$ minimized and $\Delta W_i$ is expressed in units of the wavelength of the light. The steps are chosen in such a way that they approximate the spherical aberration caused by the cover layer of the CD disk. The lowest order spherical aberration, given in a Zernike polynomial is, as a function of the normalized pupil radius $r$:

$$W(r) = A_{44}(6r^4 - 6r^2 + 1). \quad (7.3)$$

Fig. 7.2 shows how this curve, together with an offset, which can be approximated by the chosen discrete steps.

According to [74] a DVD-CD compatible objective lens can be made with 7 ring zones. The residual aberrations are higher order aberrations in the order of 40 m$\lambda$ RMS. These high order aberrations have a very limited effect on the read and recording performance.

### 7.3 Pre-collimator

As stated above, a single detector light path has two parallel beams directed towards the objective lens. Therefore, the coupling of efficiency of the CD beam towards the objective lens is limited, because of the relative small value of $NA$ for CD and the maximum allowed collimator numerical aperture for DVD due to the rim intensity requirements. The CD coupling efficiency can be enlarged by means of a pre-collimator. A pre-collimator is a lens, which decreases the divergence of a laser beam (see Fig. 7.3). The pupil diameters for CD and DVD are defined as $\phi_{CD}$ and $\phi_{DVD}$, respectively.

![Fig. 7.3: The pre-collimator enlarges the coupling numerical aperture from $NA_{CD}$ to $NA_p$.](image)

The coupling and collimator numerical aperture for DVD equals:

$$NA_{DVD} = \frac{\phi_{DVD}}{2f_c}, \quad (7.3)$$

where $f_c$ is the focal length of the collimator lens. For CD the collimator numerical aperture is:

$$NA_{CD} = \frac{\phi_{CD}}{2f_c}. \quad (7.4)$$

In case of parallel beams, the ratio of the CD and DVD pupil diameters is the ratio between the objective lens numerical apertures:

$$\frac{\phi_{CD}}{\phi_{DVD}} = \frac{NA_{CD}}{NA_{DVD}}. \quad (7.5)$$

The pre-collimator enlarges the coupling numerical aperture to $NA_p$:

$$NA_p = m_p NA_{CD}, \quad (7.6)$$

with $m_p$ the magnification of the pre-collimator, for which $|m_p| > 1$. $m_p$ is also the ratio between object distance $v_0$ and image distance $b_p$, so: $m_p = b_p / v_0$. 

![Diagram of pre-collimator](image)
7.4 The single detector light path configuration

The configuration of the designed single detector light path [76] [77] is discussed in this section.

7.4.1 The basic layout

Fig. 7.4 shows a schematic picture of the optical layout of the designed optical pick-up. This light path contains two high power lasers and one detector. The CD and DVD beam towards the objective lens are both parallel. The objective lens contains a wavelength selective structure as described in Section 7.1. The light path parameters are listed as light path 5 in Section 4.4.

![Fig. 7.4: Schematic representation of double writer light path with single detector.](image)

The intensity distribution of the DVD high power laser is circularised by means of a beamshaper similar to the dual detector light path in Chapter 6. This beamshaper is discussed in Section 7.8. The DVD grating generates three spots on the disk for the differential push-pull radial tracking. The DVD PBS (Polarizing Beam Splitter) transmits the DVD beam. The beams are parallel after the collimator lens. They are reflected by the folding mirror, which leaks a few percentages of the power towards the forward sense diode. The polarization state of the beam towards objective lens is changed into circular by means of the quarter wave plate. The beam is focused into the diffraction-limited spot on the disk by the objective lens. After reflection on the disk the polarization is rotated 90° with respect to the original state by the DVD PBS, the objective lens, the folding mirror and λ/4 plate to the objective lens, which focuses the spot on the disk. The DVD PBS is transparent for the CD beam with λ = 790 nm. The way back to the detector is the same as the DVD beam.

The composition of the DVD laser, the beamshaper, the DVD grating and the DVD PBS is called "the DVD laser branch" and the composition of the CD laser, the beamshaper, the CD grating and the CD beamsplitter is called "the CD laser branch". The DVD branch is located the closer to the collimator than the CD beam in order to generate room for the beamshaper and to make a PBS for the DVD branch possible. The choice of the beamsplitter types is such that the power on the disk and the detector are optimal for DVD+R(W). A PBS is most efficient for obtaining a high recording power on disk and on the detector.

A three-dimensional view of the designed light path is given in Fig. 7.5

![Fig. 7.5: A three-dimensional view of the designed light path.](image)
7.4.2 The light path orientation

In the light path orientation is chosen for a direction of the optical axis at 45° with the radial direction. This is shown in Fig. 7.4. This picture illustrates the housing of the light path. The bearings determine the radial direction. They are placed in the direction BB'. The axis AA' is given by the path of the light going from the folding mirror towards the detector.

The main reason for the 45°-orientation is efficient use of the footprint (space) for the optics. Secondly, astigmatism of the plane parallel plate fits to the desired direction for the astigmatic focusing and push-pull readout (see Section 7.6.2 for more detail). Without any additional components the orientation of the spot on the disk will be a DOS (Diagonal Oval Spot) for DVD and CD, because of the polarization state of the beams from the semiconductor lasers and the polarization sensitivity of the beamsplitters. The DVD beamsplitter is a PBS; the CD beam splitter is described in the next section.

In Fig. 7.7 the rim intensity in the pupil of the DVD and CD beam is given as a function of the azimuth for a Gaussian laser beam. The rim intensity is defined by Equation (3.47). The values of the rim intensity are typical for the CD-R(W) and DVD+R(W) recording spots.

Fig. 7.6: A 45° orientation of the optical axis with respect to the shafts.

Fig. 7.7: The RIM intensity as a function of the azimuth φ for the DVD+R(W) and CD-R(W).

It is clear that the spot orientation is not very important for DVD R(W), because this spot is made almost circular with a beamshaper. The two diamonds in Fig. 7.7a indicate the DVD+R(W) disk specification: between 45%-50%. This means that for a beamshaper the spot orientation can be at 45° with respect to the tracks on disk, while the spot still fulfills the disk specification. The change of intensity with the azimuth is rather large for CD-R(W) as shown in Fig. 7.7b. The DOS spot results in a good compromise between radial and tangential resolution and it is recommended by the CD-R(W) disk specification for high speed recording.

7.5 Partially polarizing optics

In this section we will discuss a low cost and efficient beamsplitter for CD that is implemented in the single detector light path design.

The DVD beamsplitter is a PBS with a multi layer-coating stack between two parts of glass. This PBS transmits the p-polarization component of the light intensity almost 100%. The reflectance of the s-polarization component is also close to 100%. This makes a PBS very efficient for obtaining a high recording power on the disk and on the detector. In order to make such a cube beamsplitter, various manufacturing steps are necessary, because it consists of two glass parts, which are glued together. Such a PBS is a standard component.

The CD beam splitter is a plane parallel plate. This plate is a simple component, which can be manufactured in significantly fewer steps than a cube. A plate has an air glass transition. It is hard to design and manufacture a PBS coating for an angle of incidence of 45°. Therefore most plate beamsplitters in used in optical pick-ups are non-polarizing, which means that the reflectance and transmittance of the p-component and the s-component are almost equal. In order to read out low-reflective disks on a high speed, a high efficiency of the light path towards the detector is required for a good signal to noise ratio. On the other hand high-speed disks ask a
high power in the diffraction-limited spot in order to be able to record on high speeds. When a non-polarizing plate beamsplitter is used, the percentage of power reflected towards the disk is theoretically 100% minus the power transmitted towards the detector. Consequently, when a large signal on the detector is required, it will be at the expense of the power towards the detector.

A good alternative is the application of a plate, which is partially polarizing in combination with a quarter wave plate as described in [78]. Partially polarizing means that the reflectance and the transmittance differ significantly for orthogonal states of polarization and are not very close to 0 or 100%. Two examples of these kinds of coatings are shown in Fig. 7.8.

![Fig. 7.8: Simulation of transmittance versus wavelength of a partially polarizing coating of a dielectric multi-layer coating of TiO₂ (H) and SiO₂ (L). The stack formula is (H)L/H. The coatings have both 19 layers in total on a B270 substrate. The coating of the graph on the left has higher transmission values for the CD laser than the one on the right.](image)

The coating on the plate is a dielectric multi layer stack, which acts as an interference filter. The intensity reflectance and transmittance can be calculated by means of the boundary conditions derived from the Maxwell equations as shown in [79]. Fig. 7.8 shows two coating stacks simulated for 19 layers by means of the coating simulation program "TFCalc". The substrate is B270 glass material. The materials of the stack consist of a material "H", TiO₂, with a high refractive index of 2.33 at λ=660 nm, and a material "L", SiO₂, with a low refractive index of 1.45 at λ=660 nm. The transmittance of the p-polarization component Tp is mostly larger than the transmittance of the s-polarization Ts. This effect is utilized to achieve the partially polarizing property of the beam splitter.

The CD wavelength is 790 nm. For the coating on the left the transmittance of the p-polarisation state is 50% for CD, which means a high transmission towards the detector, when this coating is applied in the designed single detector light path of Fig. 7.4 and 7.5. For the s-polarization the transmission is 20%, which means that 20% of the laser power towards the disk is lost. When the coating on the right of Fig. 7.8 is used in the path towards the disk only 5% is lost. On the way back 25% is transmitted towards the detector. This beam splitter is transparent for the wavelength of DVD: 660 nm.

### 7.6 The servo lens surface

In addition to the spherical and cylindrical power, the servo lens of the single detector light path also contains a correction for the unwanted coma generated by the plate beamsplitter on the detector. It is integrated with the cylindrical surface. When appropriate, the orientation of the astigmatism of the plate beamsplitter can also be rotated with this surface.

#### 7.6.1 Combination of coma correction and cylinder lens function in one surface

A disadvantage of a plane parallel plate is that next to astigmatism (see Equation (4.6)), also coma is generated on the detector. This can be expressed by means of Seidel coefficients according to [2]:

\[
W_{31, RMS\ plate} = -\frac{n_p^2}{2}\left(n_p^2 - 1\right)\sin(\alpha_p)\cos(\alpha_p) d_p NA_p^3. \tag{7.7}
\]

Reducing the plate thickness \(d_p\) will reduce the coma, however, the plate should have a certain minimum thickness, which is approximately 1 to 1.5 mm in order to avoid aberrations in the spot on the disk due to mechanical bending. The coma can be corrected with a surface profile on the servo lens. The correction is combined with the cylindrical surface used to generate extra astigmatism on the detector for the astigmatic focusing method. This servo lens is described in [80] (see Fig. 7.9).
The height $H(\rho_s, \theta)$ of the surface correcting for coma and introducing cylindrical power, fulfills the following expression:

$$H(\rho_s, \theta) = A_s \rho_s^3 \cos(\theta - \theta_1) + B_s \rho_s + C_s \rho_s^2 \cos^2(\theta - \theta_2),$$  \hspace{1cm} (7.8)

with $\rho_s$ the radius on the servo lens, $\theta$ the azimuth parameter, $\theta_1$ and $\theta_2$ fixed angles and $A_s$, $B_s$ and $C_s$ coefficients that have to be determined. When $\rho_{\text{max}}$ is the value of $\rho$ at the rim of the beam and $n_{\text{ave}}$ the refractive index of the lens material, the peak-to-valley value of the comatic contribution is:

$$W_{\text{st}} = \frac{A_s \rho_{\text{max}}^3 (n_{\text{ave}} - 1)}{\lambda},$$ \hspace{1cm} (7.9)

For the numerical aperture of the collimator also holds:

$$N_A = \frac{\rho_{\text{max}}}{d_s (n_{\text{ave}} - v_s)},$$ \hspace{1cm} (7.10)

where $d_s$ is the lens thickness, $v_s$ the distance object distance and $b_s$ the image distance. The substitution of Equation 7.10 in 7.9 yields:

$$A_s = \frac{W_{\text{st}} \lambda}{d_s^2 (n_{\text{ave}} - v_s)^3 N_A (n_{\text{ave}} - 1)} \lambda \sqrt{72} .$$ \hspace{1cm} (7.11)

$B_s$ is a coefficient for tilt, which has no impact on the aberration, when the angle of the surface with respect to the optical axis is small. For the cylindrical part of the surface holds:

$$\left(R_{\text{cyl}} - H(\rho_s, \theta)\right)^2 + \rho_s^2 \cos^2(\theta) = R_{\text{cyl}}^2.$$ \hspace{1cm} (7.12)

When $R_{\text{cyl}} >> H(\rho_s, \theta)$:

$$2R_{\text{cyl}}H(\rho_s, \theta) = \rho_s^2 \cos^2(\theta),$$ \hspace{1cm} (7.13)

Consequently:

$$C_s = \frac{1}{2R_{\text{cyl}}},$$ \hspace{1cm} (7.14)

or:

$$C_s = \frac{n_{\text{ave}} - 1}{2f_{\text{cyl}}}.$$ \hspace{1cm} (7.15)

When we consider light path 5 of Section 4.4 which is the DVD branch of the designed single detector light path, we find $n_p = 1.53$, $d_p = 1.41$ mm, $\alpha_p = 45^\circ$ and $N_A = 0.10$. From Equation 7.7, an amount of 42 m $\lambda$ RMS coma arises from the plane parallel plate. From Equation 7.11 and $n_{\text{ave}} = 1.58$, $d_s = 0.9$ mm and $v_s = -1.37$ we find $A_s = 0.055$ mm$^{-2}$. By means of optimizing in the ray-tracing program "Zemax", the coma is minimal for $A_s = 0.051$ mm$^{-2}$.

In Fig. 7.10 the geometrical spot on the detector is shown by means of Zemax simulations for a cylindrical servo lens with and without coma correction. Fig. 7.11 represents simulated spots on the detector with and without correction including diffraction by means of the simulation program "Diffract".
Fig. 7.10: Simulation (geometrical optics) of the light spot on the detector with a servo lens (a) without and (b) in the presence of coma correction.

Fig. 7.11: Simulation of the irradiance of spot on the detector including diffraction (a) with 42 m\(^2\) RMS coma and (b) without coma using a mirror disk. The bottom shows a cross-section trough the center of the spot.

Fig. 7.12 shows the focus error signals (the S-curves) of light path 5 and 2 of Section 4.4, with and without coma correction. The numerical aperture of light path 2 is larger than the value for larger than for light path 1. For \(N_A = 0.135, d = 1 \text{ mm}, \lambda = 790 \text{ nm}, c_p = 45^\circ\) and \(n_p = 1.52\), an amount of 82 mA RMS coma arises. From Fig. 7.12 it is clear that one of the peaks of the focus S-curve is affected by the coma on the detector, in particular when the coma is as large as in light path 2.

Fig. 7.12: "Zemax" simulations of the focus S-curve of light path 5 and 2 without and with coma correction. The focus error signal is normalized on the sum signal of the 4 segments of the quadrant detector shown in Fig. 3.15.

Other signal perturbations like crosstalk from the radial error signal into the focus error signal are influenced by coma on the detector. The effect on the wobble signal, which is necessary in order to read-out the address, will be shown in Chapter 9.
7.6.2 Rotation of the astigmatism of the plane parallel plate by the cylinder lens

As shown in Section 3.4.2, 3.5.1 and 4.2.6, the direction of the push-pull separation line on the detector and the direction of the focal line of the astigmatic beam should make an angle of 45° for proper push-pull and focus detection as shown in Fig. 7.13.

Push-pull detection: 1+2-3-4  Focus detection: 1+3-2-4

Orientation separation line for push-pull detection

Orientation focal lines for astigmatic focusing

Fig. 7.13: The orientation of the focal lines and the direction of the separation line of the push-pull detection make an angle of 45°.

When the light path is oriented as indicated in Fig. 7.6, which is AA' at 45° with respect to BB', the direction of the astigmatism generated by the plane parallel plate is in the desired direction. If this is not the case the astigmatism can be rotated by the servo lens surface as shown in [81].

One cylinder surface can rotate the astigmatism of the plane parallel plate and add extra astigmatism for the focus detection. The plane parallel plate generates a distance \( \Delta f_p \) between the focal lines, which is given by Equation (4.6). The cylinder surface generates a distance \( \Delta f_{ct} \) as given in Equation (4.8). This can be shown by means of Seidel coefficients. The Seidel coefficients of the astigmatism generated by the plate and the cylinder lens are in units of the wavelength of the light:

\[
W_{22p} = \frac{\Delta f_p}{2\lambda} N A_f^2 \quad \text{and} \quad W_{23ct} = \frac{\Delta f_{ct}}{2\lambda} N A_f^2. \tag{7.15}
\]

For the total wave front \( W_{tot} \), we obtain:

\[
W_{tot}(\rho, \theta) = W_{22p} \rho_2^2 \cos^2(\theta - \varphi_p) + W_{23ct} \rho_3^2 \cos^2(\theta - \varphi_{ct}) \tag{7.16}
\]

and

\[
W_{tot}(\rho, \theta) = W_{22ct} \rho_2^2 \cos^2(\theta), \tag{7.17}
\]

where \( \varphi_p \) is the angle of the astigmatism of the plane parallel plate with respect to the desired value, which is 45° with the separation line on the detector and \( W_{22ct} \) the total amount of astigmatism on the detector. \( \varphi_{ct} \) is the angle of the optical axis of the cylinder lens with the desired value. Using Equation (7.15), (7.16) and (7.17) and some goniometrical calculations one can find the following expression for the total distance \( \Delta f_{tot} \) between the focal lines:

\[
\Delta f_{tot} = \Delta f_p \cos(2\varphi_p) + \Delta f_{ct} \cos(2\varphi_{ct}) \tag{7.18}
\]

For \( \varphi_{ct} \) the following approximation is found:

\[
\varphi_{ct} = \frac{1}{2} \arcsin\left(\frac{\Delta f_p}{\Delta f_{ct}} \sin(2\varphi_p)\right). \tag{7.19}
\]

The angle of the cylindrical lens with the separation lines of the detector segments is -45° + \( \varphi_{ct} \). An example of values of \( \Delta f_p = 0.4 \) mm, \( \varphi_p = 45° \) and \( \Delta f_{ct} = 0.6 \) mm will result in \( \varphi_{ct} = 21° \) and \( \Delta f_{tot} = 0.45 \) mm. The angle of the cylinder axis with the separation lines of the detector segments is 66° for this case. When considering Equation 7.8, the orientation of the coma is determined by the orientation of the plate in front:

\[
\theta_2 - \theta_1 = \varphi_{ct} - \varphi_p. \tag{7.20}
\]

More extensive calculations on combining astigmatism of a cylinder lens and a plane parallel plate are found in [82].

7.7 Plastic pre-collimator with low temperature dependency

For a DVD/CD double writer light path with one objective lens, a pre-collimator is necessary in order to get enough power on the disk by a large coupling efficiency and sufficient RIM in intensity for DVD read-out (see Section 7.3). For cost reasons a plastic is very attractive. Examples of these plastics are COC (Cyclic Olefin Copolymer) or polycarbonate. A major problem of a plastic pre-collimator is defocusing on the disk due to shift of the focal length with temperature, because the plastic pre-collimator is located in the CD laser branch only and not in the detector branch, which is the path from beamsplitter towards detector. In this section two solutions for this problem are presented.
7.7.1 The focal length

Because the change of refraction index is the major part of the change in focal length with temperature, a good approximation of the change in focal length with temperature \( \frac{df_p}{dT} \) is:

\[
\frac{df_p}{dT} = \frac{f_p}{n_\rho - 1} \frac{dn_p}{dT},
\]

(7.21)

where \( f_p \) is the focal length of the pre-collimator and \( n_\rho \) is the refractive index of the pre-collimator. An expression for the sensitivity of the focus shift on the disk with temperature, \( \frac{dz_\rho}{dT} \), is:

\[
\frac{dz_\rho}{dT} = \frac{(1 - m_\rho^2) f_p}{2m_\rho^2(n_\rho - 1)} \frac{dn_p}{dT}.
\]

(7.22)

As defined in Section 7.3 and 4.2.1 the magnification of the pre-collimator is \( m_p \) and the magnification collimator/objective is \( m_e \). The focus shift \( \Delta z_\rho \) on the disk is:

\[
\Delta z_\rho = \frac{dz_\rho}{dT} \Delta T.
\]

(7.23)

Equation (7.22) illustrates that defocus due to a temperature change is proportional to the focal length of the pre-collimator. This is a reason to keep \( f_p \) very short for a plastic lens (see [83]). For example, with \( m_p = 1.7, dn/dT \approx -12.10^{-6}, n_\rho = 1.57, m_e = 6.54 \) the following table for \( \Delta T = 40 \) K can be filled in with:

<table>
<thead>
<tr>
<th>( f_p ) (mm)</th>
<th>( \Delta z_\rho ) on disk (( \mu )m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>0.29</td>
</tr>
<tr>
<td>9</td>
<td>0.43</td>
</tr>
<tr>
<td>14</td>
<td>0.68</td>
</tr>
<tr>
<td>32.5</td>
<td>1.57</td>
</tr>
</tbody>
</table>

For \( f_p = 6 \) mm the focus shift is only 0.37 \( \mu \)m, which results in a defocus of 18 \( \mu \)m RMS, while for \( f_p = 32.5 \) mm the Maréchal criterion, which is 70 \( \mu \)m RMS, is reached. Therefore it is recommended to design the focal length of the plastic pre-collimator as short as possible.

7.7.2 A wavelength sensitive structure

A property of semiconductor lasers is that the wavelength \( \lambda \) is dependent on the temperature \( T \) (see Table 7.2).

<table>
<thead>
<tr>
<th>Wavelength (nm)</th>
<th>( d\lambda/dT ) typical (nm/K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>790</td>
<td>0.25</td>
</tr>
<tr>
<td>660</td>
<td>0.20</td>
</tr>
<tr>
<td>405</td>
<td>0.07</td>
</tr>
</tbody>
</table>

It is possible to integrate a wavelength dependent structure on one of the surfaces of the pre-collimator lens, which compensates for the focus shift as a function of temperature due to the change of the refractive index with temperature of the plastic material [84]. In case of the light path shown in Fig. 7.5, the pre-collimator in front of a single laser only, which means that only one wavelength is relevant. An embossed structure will not significantly increase the manufacturing cost of a plastic lens, because the structure is put in the lens mold and not on every lens separately.

**Blazed grating**

Fig. 7.14: A blazed grating can be used as a wavelength sensitive structure in order to compensate for the temperature dependence of the focal length of the pre-collimator.

A possibility is using diffractive structures like a blazed grating. A blazed grating is a structure is shown in Fig. 7.14. For the angle of diffraction of the +1 order holds:

\[
p_\rho \sin(\alpha_e) = \lambda.
\]

(7.25)
For the angle of refraction $\alpha$, Snell's law yields:

$$n_{\text{low}} \sin(\psi_b) = \sin(\alpha_r)$$  \hspace{1cm} (7.26)

where $\psi_b$ is the blaze angle given in Fig. 7.14. When the blaze angle $\psi_b$ of the grating structure of $a$ is such that the angle of refraction is the same as the angle of diffraction, then simplified according to the scalar diffraction theory, 100% of the laser power will go into one order. With (7.25) and (7.26) and in the small angle approximation, this blaze angle is for the $+1$ order:

$$\psi_b \approx \frac{\lambda}{p_x(n_{\text{low}} - 1)}.$$  \hspace{1cm} (7.27)

For the height we obtain: $h_s = \lambda/(n_{\text{low}} - 1)$. An expression of the efficiency $\eta_{\text{order}}$ of the order $m$ of a blazed grating is:

$$\eta_{\text{order}} = \left( \sin \left( \frac{\pi h_s}{\lambda} \left( n_{\text{low}} - 1 \right) - \frac{\pi m}{\lambda} \right) \right)^2.$$  \hspace{1cm} (7.28)

Such a pre-collimator with wavelength-dependent structure consists of a functional refractive part and a functional diffractive part. The relation between the total focal length $f_{\text{p}}$ and the refractive part $f_r$ and the diffractive part $f_d$ of the pre-collimator is in thin lens approximation given by:

$$f_{\text{p}} = \frac{f_r f_d}{f_r + f_d}.$$  \hspace{1cm} (7.29)

For a lens grating the pitch $p_x$ changes as a function of the radius $\rho_s$ according to:

$$p_x(\rho_s) = \frac{\Delta f_d}{\rho_s}.$$  \hspace{1cm} (7.30)

For a diffractive lens the relation between the shift of focal length and temperature change is due to the wavelength change of the laser:

$$\frac{df_{\text{p}}}{dT} = \frac{f_r \Delta \lambda}{\lambda \Delta T}.$$  \hspace{1cm} (7.31)

When the focal length of the plastic structured pre-collimator is independent of the temperature, the first order requirement is:

$$\frac{df_{\text{p}}}{dT} = 0,$$  \hspace{1cm} (7.32)

which yields, together with (7.21), (7.28) and (7.30)

$$f_{\text{d}} = -f_r \left[ \frac{(n_{\text{p}} - 1) \Delta \lambda}{\lambda \Delta n} - 1 \right].$$  \hspace{1cm} (7.33)

For $dn/dT = -12.10^{-5}$, $n_p = 1.57$, $\lambda = 790$ nm and $\Delta \lambda / dT = 0.25$ nm°C we find:

$f_{\text{d}} = 15 f_r$. For $f_r = 9$ mm, $f_d = 135$ mm and a maximal value $\rho_s$ of $\rho_{\text{max}} = 2$ mm, the minimum pitch $p_x(\rho_{\text{max}}) = 53$ μm (see Equation (7.30)).

**Non-periodical phase structure**

Another possibility is to use a non-periodic phase structure described in Section 7.2. The steps of height $h_s$, resulting in an optical path difference $\Delta A = h_s (n_{\text{low}} - 1) = K A$, will modify the wave front by a change $\Delta W$, when $\lambda$ changes into $\lambda + \Delta \lambda$ due to wavelength shift induced by temperature change:

$$\Delta W = K \frac{\Delta \lambda}{\lambda}.$$  \hspace{1cm} (7.34)

where we finally have neglected the dispersion effect it the lens material. The steps are chosen in such a way that they approximate the defocus caused by the temperature induced $\Delta \lambda$. The steps $\Delta W$ should approximate $W(\rho_s)$ as a function of the radius $\rho_s$ on the pre-collimator:

$$W(\rho_s) = \left( \frac{d \psi}{dT} \right)^2 \frac{NA_p}{2 \lambda} \left( \frac{\rho_s}{\psi} \right)^2 \Delta T.$$  \hspace{1cm} (7.35)

with $\psi$, the object distance of the pre-collimator.

**Other effects**

Chromatic effects of the material of the pre-collimator and of other optical components, the temperature shift of other components that are in the non-common path and the expansion of the material of the optical pick-up are not taken into account in the previous considerations. The defocus shift due to these effects are in general smaller than the focus shift of the pre-collimator, however, one can take all these effect into account in the wavelength sensitive structure on the pre-collimator for CD or on another
component between a laser and beamsplitter. One example of such a component is discussed in the next section.

7.8 Beamshaper with pre-collimator function

When a beamshaper is applied, the coupling efficiency of the light into the path can be significantly higher, while having the same minimum rim-intensities as stated in Section 3.3.2. The beamshaper is described in principle in [46]. This beamshaper is modified for this single detector light path design. Fig. 7.15 shows cross-sections of a beamshaper in the x-z and y-z plane. The z-axis is the optical axis. The divergence of the beam in the x-z plane is increased in order to increase $\theta_1$ of the laser. The divergence of the beam in the y-z plane is decreased in order to decrease $\theta_j$ of the laser. The beamshaper magnifications in the two perpendicular cross-sections are respectively $m_x$ and $m_z$, with:

$$NA_x = m_x NA_j \quad \text{and} \quad NA_z = m_z NA_j.$$  \hspace{1cm} (7.36)

The advantage of a beamshaper including the pre-collimator function is an even higher coupling efficiency with the same value of $NA_c$. Increasing $NA_c$ instead of the pre-collimator function of the beamshaper would lead to less space for the optical components, more change in reflection and transmission due to angle sensitivity of the beam splitter coatings [85], a too thin plane parallel plate for obtaining the correct focus S-curve length.

In [47], the entrance and exit surfaces have a circular or flat cross-section in either the y-z or x-z-plane. In order to avoid too large values of the aberration coefficient $A_{\delta_{44}}$ all cross-sections of one of the surfaces should become a so-called “free form” surface [86].
7.9 Implementation of the design

The optical pick-up with the single detector light path is implemented in several DVD video recorders and DVD/CD writable data drives. The principles of a plane parallel plate with a partially polarizing coating, a cylindrical surface with coma correction, a plastic pre-collimator with short focal length, which results in a small temperature-induced focus shift on the disk, and a beamshaper with pre-collimator function are applied. Fig. 7.16 shows pictures of the first prototypes with milled housing and the final optical pick-ups. The optical components, the housing and the electrical connections are visible.

![Milled prototype side view](image1)
![Milled prototype bottom view](image2)

![Final pick-up side view](image3)
![Final pick-up bottom view](image4)

Fig. 7.16: The prototype with milled housing (pictures at the top), and the final product (pictures at the bottom) of the optical pick-up with the designed single detector light path. The connections to the CD- and DVD-laser and detector are visible in the side view. The bottom view shows the beamsplitter for CD and DVD, and the holders of the pre-collimator and the beamshaper.

The optical pick-up in the drive mechanism is given in Fig. 7.17. The eye pattern of the RF signal [69] [87] of one of the first prototypes reading a CD and DVD disk is shown in Fig. 7.18.

![Fig. 7.17: The drive mechanism with the optical pick-up (see also Fig. 3.31). The top of the optical pick-up with the objective lens actuator is visible.](image5)

![CD eye-pattern](image6)
![DVD eye-pattern](image7)

Fig. 7.18: The eye-pattern (see Fig. 3.1) of the first prototypes reading a CD and DVD [69] [87].

Due to the high efficiency of the light path, the first 16x DVD+R drive was introduced on the market with this optical pick-up in spring 2004. It is now capable to record 16x DVD+R, 16x DVD+R dual layer and 48x CD-R. This light path is now produced in quantities of several millions per year.
7.10 Summary

The designed single detector light path for a DVD and CD recorder has been discussed. The single detector light path has an objective lens with a wavelength sensitive structure that compensates the spherical aberration due to the difference in disk cover layer thickness between CD and DVD. The efficiency of the CD part is improved by increase of the CD coupling numerical aperture by means of a plastic pre-collimator. A plastic pre-collimator generates a focus shift on the disk as a function of temperature. This focus shift is limited by using a short focal length. An alternative is obtained by putting a wavelength-sensitive structure on the pre-collimator, where the wavelength shift of the laser due to temperature is used. A partially polarizing coating on a cheap plane parallel plate improves the power efficiency towards the disk and towards the detector in comparison with a non-polarizing coating. The unwanted coma of the plate beamsplitter is compensated by applying a corrective surface that is integrated with the cylinder lens surface used for the generation of astigmatism for the astigmatic focusing. The orientation of the astigmatism of the plate beamsplitter can also be rotated in the proper direction with this surface. The efficiency for DVD is maximized by the integration of a pre-collimator in the beamshaper. A PBS is applied by orientation of the laser far field at 45° with the track on the disk. The designed light path is applied in practice for DVD video recorders and DVD/CD recorder data drives.

In this chapter the design of the single detector light path is discussed. A possible next step is a light path with single detector and single laser. This is the subject of the next chapter.
8.1 Introduction

In order to reduce space, components and adjustments during the pick-up assembly dual wavelength lasers can be used. A dual wavelength laser is a laser device, which has two laser cavities that generate two beams with different wavelength.

There are two different types of dual wavelength lasers. The first type contains two separate laser chips in one package. The second type contains two laser cavities in one chip, which is called a "monolithic dual wavelength laser". The distance between the two emission points is defined as \( \Delta e \) (see Fig. 8.1). A typical value for \( \Delta e \) is 0.11 mm, both for the monolithic laser and the laser assembly with two separate chips.

![Fig. 8.1: A normal single wavelength laser (picture on the left), a dual wavelength laser with two separate chips in one package (picture in the middle) and a monolithic dual wavelength laser: two emission points from one chip (picture on the right).](image)

The subject of this chapter are the design choices one has to make in order to allow for the application of a dual wavelength laser in a single detector light path, which is suitable for high-speed DVD and CD recording. In this chapter we present principles about how to cope with the application of a dual wavelength laser in case of using a single detector array for astigmatic focusing and differential push-pull radial tracking as illustrated in Fig. 8.2. The layout with dual wavelength laser principles and dual detector is not discussed in detail in this thesis.

Applying a dual wavelength laser for DVD recording in combination with a single detector array creates several issues for the light path design. Design ideas to make the single detector light path with a dual wavelength laser suitable for high-speed DVD and CD recording are discussed by means of theoretical modeling.

8.2 Join grating

Of course, it is possible to join the two spots electrically by means of one detector device with two sets of detector segments: one for CD and one for DVD. Because a monolithic dual wavelength laser is made in a lithographic process the distance between the two lasers is known within an accuracy of 1 \( \mu \)m. This is also the case for the distance between two sets of detector segments. When the spherical part of the servo lens for the adjustment of the focus position of the light spot on the disk is not applied, it is possible to center the CD and DVD spots accurate enough on the detectors. However, as a result the detector must be aligned in three dimensions: one parallel to the optical axis for focusing of the spot on the disk and two directions perpendicular to the optical axis for the decentering of the spot on the detector. For a dual wavelength laser with two separate laser chips, the individual positions of the emission points are not accurate enough. The decentering of the CD and/or the DVD spot on the detector will be too large, when such a laser is applied without any measures.

A solution is to use a grating in the detector beam, which diffracts one beam towards the detector in the first order and transmits the other beam in the zero order. A possibility is a blazed join grating as described in [88]. The structure of such a grating is shown in figure 8.3.

![Fig. 8.2: The array of detector segments for astigmatic focusing and differential push-pull radial tracking with the three spots. \( \gamma \) is the power ratio between the main and the satellite spot, which is determined by the three spots grating.](image)
The structure of the blazed grating. The pitch is \( p_g \), the height of the structure is \( h_g \) and the blaze angle is \( \psi_b \). The duty cycle is 50%.

This structure can be molded in a plastic, for instance COC (Cyclic Olefin Copolymer). The pitch is determined by the object distance of the two lasers \( d_o \) and the optical distance \( g_h \) from the grating surface towards the detector or the object of the detector spot given by \( v_o \) in the case of a servo lens. The pitch of the grating is determined by:

\[
p_g = \frac{d_o}{p_g}.
\]

(8.1)

The wavelength \( \lambda \) is the wavelength of the beam that is diffracted in the first order. In order to get equal power in the first order and the zero order, the blaze angle \( \psi_b \) is such that the refraction angle is equal to the half the diffraction angle of the first order:

\[
\psi_b = \frac{\lambda}{2p_g (n_g - 1)}.
\]

(8.2)

\( n_g \) is the refractive index of the grating material. The depth \( h_g \) is such that its induced phase \( \phi_h \) for the wavelength equals \((2K+1)\pi\) for the first order beam and \(2K\pi\) for the zero order beam, where \( K \) is an integer. For \( \phi_h \) holds:

\[
\phi_h = \frac{2\pi h_g (n_g - 1)}{\lambda}.
\]

(8.3)

Suppose the zero order is used for DVD and the first order is used for CD, then a proper value of \( h_g \) is 3.8 \( \mu \)m with \( n_g = 1.52 \). This results in approximately \( \phi_h = 6\pi \) for DVD and \( \phi_h = 5\pi \) for CD. When the distance from the join grating to the spot on the detector is 3 mm and \( d_o = 0.11 \) mm the pitch \( p_g \) will be 34.5 \( \mu \)m. Therefore the blaze angle \( \psi_b \) is 1.26\(^\circ\). Practical values that can be reached with this grating structure without anti-reflection coating are 71\% in the zero order for DVD and 63\% in the first order for CD.

Fig. 8.4 shows a possible recorder light path with a dual wavelength laser and a blazed join grating [89]. This light path has no beamsheaper, which will result in a lower available power for DVD. Such a light path is still suitable for a DVD recording function and a CD read function as applicable for the DVD video recorder. The radial tracking of DVD can be differential push-pull and for CD differential phase detection. The grating can be a normal three spots grating for DVD and is described in Section 3.6.1. No grating is necessary for CD due to the single spot tracking method mentioned.

The two laser beams follow the same path via the grating, they reflect at the plate beam splitter, go through the collimator, the mirror, the \( \lambda/4 \) plate, and the objective towards the disk. The path towards the detector is via the objective, the \( \lambda/4 \) plate mirror, the collimator, the beamsplitter, the join grating and the servo lens. The DVD beam is diffracted in the zero order and goes straight on to the detector. The CD beam is diffracted in the first order in order to land on the same detector. The join grating is adjusted by a displacement along the optical axis and a rotation around the optical axis to get a decentering of the CD spot on the detector that is accurate enough (up to 1 \( \mu \)m). When the servo lens is adjusted along the optical axis in order to get the DVD spot on the disk in focus, the CD spot will also be accurately in focus, because the position of the two spots can differ about 5 \( \mu \)m along the optical axis on the laser side, which would mean a defocus of \( 5(2m^2) \) \( \mu \)m on the disk side, where \( m \) is the magnification from objective lens to collimator lens. For \( m = 6.54 \) according to light path 5 of Section 4.4, this results in a defocus of 0.06 \( \mu \)m, a small value in comparison with the focal depth for CD (1.9 \( \mu \)m). This means that only one focus adjustment is necessary instead of two.

The coating of the beamsplitter plate in Fig. 8.4 has 13 layers of TiO2 as material with a high index and SiO2 as material with a low index on a substrate of B270 glass [79]. Tp and Ts are approximately 35\% and 10\%, respectively.
When this coating is applied for both laser beams, 10% of the light is transmitted towards the forward sense diode, 90% is reflected towards the disk. On the way back about 35% is transmitted towards the detector for both DVD and CD.

As stated above this light path is still suitable for a DVD recording function and a CD read function. For a CD write function the power may be too low, because no precollimator for CD can be applied as shown in Section 7.3 due to the dual wavelength laser. The grating can be a normal three spots grating for DVD that is described in Section 3.6.1. A second reason for a difficulty with CD recording is that three spots push-pull radial tracking for both CD and DVD is not possible with a standard grating in front a dual wavelength laser. Solutions for these issues are given in the next sections.

8.3 Two-color grating

As shown in Section 3.5.3 differential push-pull radial tracking requires a value \( q' / 2 \) of distance of the satellite spot to the track that is followed by the main spot, where \( q' \) is the track pitch. The track pitch differs approximately a factor of two: 0.74 \( \mu \text{m} \) for DVD and 1.6 \( \mu \text{m} \) for CD. The angle of diffraction is inversely proportional to the wavelength. As a result the distance will not be \( q' / 2 \) for both CD and DVD, when the same grating is applied for both beams. This would mean that the grating should by adjusted in two different angles for CD and DVD, which is not very practical. Also the distance from main spot to satellite on the detector should fit for DVD and CD. The relations between the distances \( s \) between main spot and satellite for DVD and CD (\( \lambda_1 \) and \( \lambda_2 \) the wavelengths for and DVD and CD) is given by the following relation [90]:

\[
s_i(\lambda_i) = \frac{\lambda_1}{\lambda_2} s_i(\lambda_2).
\]  

(8.4)

A “two-color grating” is a possibility [91] to solve both issues mentioned above. In this two-color grating the satellite spots for CD and DVD are generated with a grating surface on both sides of a single component as illustrated in Fig. 8.6. When the depth \( h_g \) (Fig. 8.6) for one wavelength is chosen in such a way that optical path difference of the steps is \( K2\pi \), where \( K \) is an integer, this grating will generate no satellite spots for this wavelength. It is possible to meet the \( K^2 2\pi \) condition for the second wavelength with the structure on the other side.

In case of a 50% duty cycle binary grating, the power \( I_0 \) in the zero order is:

\[
I_0 = \frac{1}{2} I_0 \left[ 1 - \cos \left( 2\pi (n_i - 1) \frac{h_g}{\lambda_i} \right) \right].
\]  

(8.5)

\( I_0 \) is the power of the incoming beam. The energy in the first orders is (for a 50% duty cycle):

\[
I_i = \frac{1}{2} I_0 \left[ 1 - \cos \left( 2\pi (n_i - 1) \frac{h_g}{\lambda_i} \right) \right] \sin \left( \frac{\pi}{2} \right),
\]  

(8.6)

where:

\( \lambda_i = \) wavelength (\( i = 1, 2 \))

\( h_g = \) height grating structure

\( n_i = \) refractive index of the grating material at \( \lambda_i \)

For \( \lambda_1 = 660 \text{ nm} \) and \( \lambda_2 = 790 \text{ nm} \) and the plastic “Zeonex 480R” with \( n_1 = 1.5223 \) and \( n_2 = 1.4190 \) we get a ratio \( I_0 / I_1 \) as shown in Table 8.1.

<table>
<thead>
<tr>
<th>( h_g ) (( \mu \text{m} ))</th>
<th>( I_0 / I_1 ) at 660 (nm)</th>
<th>( I_0 / I_1 ) at 790 (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.244</td>
<td>5.88</td>
<td>992</td>
</tr>
<tr>
<td>1.498</td>
<td>998</td>
<td>5.68</td>
</tr>
</tbody>
</table>

Table 8.1: The grating ratio for \( \lambda = 660 \text{ nm} \) and \( \lambda = 790 \text{ nm} \).
In the example of Table 8.1, roughly 0.5% of light power will be generated on the satellite by the other grating surface, which part may impinge on the detector segment of the satellite.

The distance between the main spot and satellite on the detector $s_J$ in Fig. 8.2 must be the same for both wavelengths in order to get an equal light distribution on the segments $A_1$ and $A_2$ and on the segments $B_1$ and $B_2$ for CD and DVD. Therefore, the ratio of the grating pitches $p_i$ will be in a first approximation:

$$\frac{p_1}{p_2} = \frac{\lambda_2 g_1}{\lambda_2 g_2}$$  \hspace{1cm} (8.7)

where $g_i$ is the optical distance from the laser to the grating structure. The two grating structures will have a small difference in orientation of the azimuth angle with respect to the tracks $\Delta \theta$. This depends on the track pitch on the disk $q^m$, the magnification from disk to detector and on $s_J$. For the angle $\theta_i$ of the three spots with the tracks have the relation:

$$\theta_i = q^m m_{si} m_{gi}$$  \hspace{1cm} (8.8)

where $K$ is an integer that equals 2 in case of differential push-pull radial tracking, $m_e$ is the magnification from objective to collimator and $m_{sl}$ is the magnification of the servo lens in the circle of least confusion. When $q_1 = 0.74 \mu m$, $q_2 = 1.6 \mu m$, $m_e = 6.54$, $m_{si} = 1.39$ and $s_J = 150 \mu m$ (light path 5 of Section 4.4), $\Delta \theta$ is given by:

$$\Delta \theta = \theta_2 - \theta_1 = 1.49^\circ.$$  \hspace{1cm} (8.9)

The grating adjustment during the pick-up assembly can be performed for only one wavelength, which saves an extra adjustment. Disadvantages in comparison to a three spots grating are extra loss of recording power due to a lower grating ratio $I_1/I_0$ and a larger dependency of the grating ratio on the wavelength.

### 8.4 Holographic pre-collimator with join function

#### 8.4.1 Basic function

The function of a pre-collimator is the increase power on the disk by improved coupling efficiency for CD. A normal pre-collimator behind one laser as described in Section 7.2 is not possible, which means that the coupling numerical aperture can be too low to obtain enough power in the diffraction limited spot on the disk for CD recording. A possible solution is the application of two holograms [92] [93]. When two holograms are applied with a certain axial distance, a combination of a pre-collimator function and a function to join the spots on one detector can be designed. The situation shown in Fig. 8.3 is a positive pre-collimator function for the CD laser and a decentering of the CD beam.

![Two holograms](image)

*Fig. 8.7: Two holograms, which form a positive pre-collimator and a join function with symmetrical coupling. The CD beam is diffracted by hologram 1 and 2 in such a way that the coupling numerical aperture is increased from $NA_{CD}$ to $NA_{p}$. The CD beam is centered to the optical axis. The DVD beam is not influenced by the holograms.*

Both holograms act as decentered lenses. The optical power of both lenses accounts for the pre-collimator function, while the decentering of the lenses enables joining of the laser beams. The structure of the gratings is designed in such away that the DVD laser beam is diffracted in the zero order and the CD beam in the first order as will be explained in the next sections.

#### 8.4.2 Calculation of the pitch as a function of several design parameters

The holograms have a varying grating pitch. An estimation of the pitch of the two holograms is made in this paragraph. The pitches of the holograms are calculated by using Snell’s law, the grating equation and some geometrical considerations. The pitches $p_{h1}$ and $p_{h2}$ as a function of the position on the holograms 1 and 2 in the direction $A-A'$ of the separation of the emission points (Fig. 8.7) are:
\[ P_{h1} = \frac{\lambda d_b}{A n + \rho \left(g_a n + d_b \left(1 - \frac{N_{ACD}}{N_{Ap}}\right)\right)} \]  
(8.10)

and

\[ P_{h2} = \frac{-\lambda d_b}{A n + g_a n \rho \left(1 - \frac{N_{ACD}}{N_{Ap}}\right)} \]  
(8.11)

where \( \rho \) is the sine of the angle of incidence as a function of the position on the holograms, \( \lambda \) the wavelength of the CD-laser, \( n \) the refractive index of the material, \( g_a \) the distance of the lasers to the first hologram, \( d_b \) the thickness of the substrate, \( N_{Ap} \) the coupling numerical aperture for the CD-laser and \( N_{ACD} \) the numerical aperture at the exit or the collimator numerical aperture for CD. The detailed calculations of the pitch of the holograms are given in appendix C.

The pitches \( P_{h1} \) and \( P_{h2} \) of hologram 1 and 2 as a function of \( \rho \) are shown in Fig. 8.8 for the parameter values \( N_{Ap} = 0.135, N_{ACD} = 0.079, g_a = 1.5 \text{ mm}, d_b = 3 \text{ mm}, n = 1.52, \Delta_e = 0.11 \text{ mm} \). The sign of the pitch is determined by the sign of the blaze angle. The spatial frequencies \( Q_{h1} \) and \( Q_{h2} \) are defined as the reciprocal value of \( P_{h1} \) and \( P_{h2} \): 

\[ Q_{h1} = \frac{1}{P_{h1}} \quad \text{and} \quad Q_{h2} = \frac{1}{P_{h2}} \]  
(Fig. 8.9).

<table>
<thead>
<tr>
<th>( g_a ) (mm)</th>
<th>( d_b ) (mm)</th>
<th>( \rho = -N_{Ap} )</th>
<th>( \rho = 0 )</th>
<th>( \rho = N_{Ap} )</th>
<th>( \rho = -N_{Ap} )</th>
<th>( \rho = 0 )</th>
<th>( \rho = N_{Ap} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.5</td>
<td>3</td>
<td>-18.5</td>
<td>14.2</td>
<td>5.2</td>
<td>-60.0</td>
<td>-14.2</td>
<td>-8.0</td>
</tr>
<tr>
<td>1.5</td>
<td>4.5</td>
<td>-16.7</td>
<td>21.3</td>
<td>6.5</td>
<td>-90.0</td>
<td>-21.3</td>
<td>-12.1</td>
</tr>
<tr>
<td>3</td>
<td>3</td>
<td>-9.3</td>
<td>14.2</td>
<td>4.0</td>
<td>16.8</td>
<td>-14.2</td>
<td>-5.6</td>
</tr>
<tr>
<td>3</td>
<td>4.5</td>
<td>-10.5</td>
<td>21.3</td>
<td>5.3</td>
<td>40.3</td>
<td>-21.3</td>
<td>-8.4</td>
</tr>
</tbody>
</table>

Table 8.2: The pitches of hologram 1 and 2 for \( N_{Ap} = 0.135 \) and \( N_{ACD} = 0.079 \).  

One can conclude from Equation (8.10) and (8.11) and Table 8.2 the following. The grating pitch in the center of the CD beam (\( \rho = 0 \)) is only dependent on \( d_b \). The smaller the distance \( g_a \) the bigger the average grating pitch. The grating pitch increases when the distance \( d_b \) becomes larger. The pitches in the center of hologram 1 and 2 are equal, however, they have opposite blaze angle.
8.4.3 The grating structure

A double writer requires a structure, which results in an efficiency at least 80% in the first order for CD and in the zero order for DVD. A possible structure with a high efficiency is a blazed grating as shown in Fig. 7.14 of Section 7.7.2. In order to get the proper efficiencies for the different wavelengths it may have a stepped shape. Fig. 8.11 illustrates such a stepped blazed grating.

The optical path difference between the source and image points of the pre-collimated laser can be calculated by using geometric and optical relations. Treating both points as a source the interference between the two waves gives the appearance of the structure of the hologram. This was done for both holograms with the same parameters as used in of the graph shown in Fig. 8.8 (see Fig. 8.10).

The optical path difference introduced by one step with height $h_i$ must be an integer times one wavelength for DVD in order to enable maximum intensity in the zero order. The optical path difference introduced by the total step height $h_{tot}$ should be equal to half a wavelength for CD. The discrete steps decrease the intensity in the first order for CD. The efficiency of the diffracted first order is:

$$\eta_{1y} = \left( \frac{\sin \left( \frac{\pi}{N} \right)}{\frac{\pi}{N}} \right)^2,$$

where $N$ is the number of steps [94]. According to Equation (8.12) with four, five and six steps an efficiency of respectively 81%, 88% and 91% can be reached theoretically. For deriving of the blaze angle $\psi_b$ the angle of diffraction and refraction of the beam are equal, which is analog to (7.27) and yields in the approximate value:

$$\psi_b \approx \frac{\lambda}{p_t(n_g - 1)}.$$

For $\lambda=790$ nm and $n_g=1.52$, the blaze angle varies from $+16.7^\circ$ via $0^\circ$ to $-4.7^\circ$ on hologram 1 and from $-1.5^\circ$ to $-10.9^\circ$ on hologram 2, if we use the parameters of Fig. 8.8.

The hologram can be manufactured by injection molding. In practice, the tip radius of the diamond cutting tool, which is used to make the mold, limits the transmission of the gratings in case of diamond turning. Nowadays a reasonable minimum is 0.2 $\mu$m. The simplest estimation of the transmission is according to a one-dimensional model. The pitch of the hologram gratings is given by $p_t$. The loss is proportional to the ratio of the tip radius $\Delta$ and the pitch $p_t$, so proportional to $N\Delta/p_t$. The loss $L$ is calculated over the whole area from $-N\Delta_p$ to $+N\Delta_p$ and normalized to the total area $2N\Delta_p$.

*) The vague rings in the background have nothing to do with the holograms. It is an artifact of the digital discrete sampling of the pictures.
The results for various values of the number of steps $N$ are summarized in Table 8.3.

<table>
<thead>
<tr>
<th>Table 8.3: The loss as a function of the number of steps $N$ with a tip round-off of 0.2 μm, (parameters according to Fig. 8.8)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N$</td>
</tr>
<tr>
<td>-------------------------------</td>
</tr>
<tr>
<td>Loss hologram 1</td>
</tr>
<tr>
<td>Loss hologram 2</td>
</tr>
<tr>
<td>Total</td>
</tr>
</tbody>
</table>

8.4.4 Light path appearance with holographic pre-collimator and join function

The introduced principles can be applied in a light path configuration of a double writer single detector with dual wavelength laser shown in Fig. 8.12. The holographic pre-collimator enlarges the CD coupling efficiency and joins the DVD and CD beam on one detector. Differential push-pull for both CD and DVD is possible with the two-color grating as described in the previous section. This component can be adjusted in along or perpendicular to the optical axis, in order to tune the two spots exactly on the detector.

The laser wavelength is temperature-dependent as stated in Section 7.7.2. This leads to defocus under the influence of a temperature change of the light path. From this effect the wavelength dependence of the holographic lenses can be calculated. A calculation can be made for the expected defocus at, for instance, a temperature increase of 40 K. The defocus on the disk is 0.45 μm or 21 mλ RMS on disk for $\Delta T = 40$ K, $NA = 0.51$ for CD, $NA = 0.65$ for DVD and the parameters used for the calculations in Fig. 8.6. This is generously within the Maréchal criterion. The defocus appears to decrease with decreasing $g_b$ and increasing $d_b$. 

![Light path diagram](image)
8.5 Summary

New ideas enabling a single detector light path with a dual wavelength laser suitable for high-speed DVD and CD recording have been proposed. A dual wavelength laser is a laser device that has two laser cavities in order to generate two beams with different wavelength. Applying a dual wavelength laser saves a beamsplitter, a laser package and several adjustments during assembly of the pick-up. A grating element can be used to join the DVD and CD beam to one detector. The depth and the blaze angle determine the power of the two beams towards the detector. Differential push-pull for CD and DVD with the same detector is possible with the introduced two-color grating. For CD and DVD this grating has a separate grating surface with different pitch, depth and orientation with respect to the tracks. It works for CD and DVD almost independently, while both beams pass this component. A normal pre-collimator is not possible in combination with a dual wavelength laser. A pre-collimator, suitable for a dual wavelength laser, is designed by using two hologram surfaces on one component. This component also has a join function. The average pitch of the holograms is depending on the thickness and the distance of the component towards the laser. A stepped and blazed grating has been introduced as structure of the holograms. The CD efficiency is depending on the number of steps of the structure. In practice, the DVD and CD efficiency also depends on the tip radius of the diamond cutting tool, which is used for the manufacturing of the molds for providing the holograms.

This chapter dealt with proposals to apply a dual wavelength laser in single detector light path suitable for DVD and CD recording. In the next chapter we will discuss a specific system aspect in more detail.
9.1 Introduction

As stated in Section 2.1.3 the recorder needs several signals on an empty recordable and rewritable disk: a tracking signal, a signal that determines the pit lengths and rotation speed of the disk and a signal that gives information on the disk properties like the type of disk and required recording power.

The tracking signal is generated by means of the pre-groove. The wobble in the pre-groove results in a push-pull signal of the main spot that determines the pit lengths and rotation speed in a DVD+R(W) disk. It is a slightly meandering pre-groove with small amplitude. Fig 9.1 illustrates the wobble of an empty and written DVD+R(W) disk. The signal that is retrieved from the wobble is called "Address in Pre-groove" (ADIP). It contains the address information. The wobble is present on the disk in the complete recordable area. The wobble period is $32c_b$ or $4.26 \, \mu m$, which is very close to the period of the longest pit $28c_b$, $c_b$ is the channel bit length, which is defined as the covered distance on a track corresponding to one bit. The short wobble period results in a feature of DVD+R(W) system: to link the pits of individual written parts very accurately (within a limit of about 5 channel bits). The amplitude of the wobble is $0.03 \, \mu m$.

DVD-R(W) uses "pre-pits" for time and address information in combination with a longer period of the wobble: $186c_b$. The pre-pits are pits, which are located between the pre-grooves ("land pre-pits"). Fig. 9.2 gives a schematic view of the wobble and the pre-pits of a DVD-R(W) disk. The signal generation from the pre-pits is also based on push-pull readout.

Fig. 9.2: The wobble and the pre-pits of a DVD-R(W) disk: empty on the left and written on the right.

The pits of a written disk will have impact on the wobble and pre-pit signal. Optical imperfections like aberrations and detracking will enhance the impact of the pits on the wobble and pre-pit signal. The crosstalk of the RF signal into the wobble signal can lead to the problem that the wobble and the pre-pits cannot be read out properly. A low pass filter does not solve the problem, because the RF signal and the wobble signal are in the same frequency range. It was not fully understood which of the aberrations or other deviations are most significant. Therefore, the effect of these imperfections on the wobble signal [95] and the pre-pit signal is explored by simulation and theoretical modeling.

Simulations on wobble signal are discussed in Section 9.2. Section 9.3 describes analytical calculations with diffraction theory on the wobble signal. Measurements on the wobble signal are shown in Section 9.4. Simulations and measurements on the pre-pit signal are given in Section 9.5. This chapter will be summarized in Section 9.6.
9.2 Wobble simulations

9.2.1 Simulations of the disk and light path parameters in the pupil

The effect of the optical disturbances are calculated by means of the optical simulation program “Diffrac” [96] and [97]. The Fraunhofer diffraction calculations are performed in the scalar approximation. This means that vector diffraction effects are not taken into account. For the simulation the following light path parameters were used (according to light path 4 of Section 4.4): \( N_A = 0.65, \lambda = 660 \text{ nm}, f_r = 2.75 \text{ mm} \) and \( f_e = 12.79 \text{ mm} \).

With the use of a beamshaper, the far field of the laser was reshaped to \( \theta_f = 14.9^\circ \) and \( \theta_r = 17.7^\circ \). As explained in Section 3.3.2, the orientation of the spot with respect to the track on disk is ROS (Radial Oval Spot). Fig. 9.3 shows the pupil with the intensity distribution of beam towards the disk and the spot on the disk for the aberration free situation.

![Fig. 9.3: The pupil of the Gaussian laser beam towards the disk (left) and the spot on the disk (right).](image)

The DVD+RW disk parameters that are applied are based on measurements [98] on a typical written DVD+RW disk. The parameters of the groove and pit geometry were chosen in such a way that the RF and push-pull signals from the disk in the simulations match the measured disk. Fig. 9.4 shows a schematic representation of the pit and pre-groove geometry. Fig. 9.5 illustrates the disk with the pits and the pre-groove for three different pit lengths: \( 4c_b \), \( 7c_b \) and \( 14c_b \).

![Fig. 9.4: The geometry of the pits and the pre-groove. The dimensions are in \( \mu \text{m} \). The height is exaggerated with respect to the width. The refractive index of the cover layer is 1.57. The reflection coefficient of the pits is 0.4. The track pitch is 0.74 \( \mu \text{m} \).](image)

![Fig. 9.5: The disk with the pre-groove and pits with a length of \( 4c_b \), \( 7c_b \) and \( 14c_b \).](image)

9.2.2 The wobble signal

The wobble signal is measured in the recorder as a push-pull signal \( (PP) \) of the main spot. In order to get a signal that is independent on the disk reflection and the power in the spot, the push-pull signal is normalized by the central aperture signal \( CA \) of the main spot. Therefore the normalized signal equals \( PP/CA \). The \( PP \) and \( CA \) signals are shown in Fig. 9.6.

![Fig. 9.6: Definition of the push-pull signal \( (PP) \) and the central aperture signal \( (CA) \) of the main spot on the detector. The wobble is read out as a push-pull signal. The RF signal is read out as \( CA \) signal.](image)

![Fig. 9.7: Simulation of the pupil from the disk with a pre-groove as a function of the spot position with respect to the groove. The intensity in the overlap areas of the diffractive orders of the disk is low in the bottom and high in the top for position (a). In position (b) the intensity in the overlap areas are equal. Position (c) is opposite from position (a). This change in intensity in the overlap areas generates the push-pull signal of the wobble.](image)
The pupil of an empty disk with pre-groove is shown in Fig. 9.7. The peak-to-peak wobble amplitude of the empty disk normalized with the central aperture signal is \( PP/CA \). The simulation yields \( PP/CA = 0.40 \), a value which is almost equal to the measured value. When the spot is on the track, the overlap areas of the zero and +1 and -1 order of the reflected beam from the disk have equal intensity. Consequently, the push-pull wobble signal is zero. When the wobble is at its maximum amplitude of 0.03 \( \mu m \), the overlap areas differ clearly in intensity. This difference in intensity generates the wobble signal.

### 9.2.3 The effect of aberrations in the pupil

The calculations on aberrations in the spot on disk are discussed first. Fig. 9.8 shows the effect of 50 m\( \lambda \) RMS of individual aberrations on the crosstalk between the signal of pits and the wobble. The signal of the pits, which is normally detected as the central aperture signal, is detected in the push-pull signal due to the aberrations. The crosstalk is also a push-pull signal normalized by the central aperture signal \( (PP/CA) \). It is calculated with the spot in the middle of the pre-groove.

![Crosstalk and effect of different aberrations of 50 m\( \lambda \) RMS](image)

**Fig. 9.8:** The crosstalk between the signal of the pit and the wobble and effect of different individual aberrations of 50 m\( \lambda \) RMS.

The amount of individual aberrations is 50 m\( \lambda \) RMS. The pits have a length of 7C\( b \), which is the average of the RF signal. A summary of the aberrations relevant for this chapter is given in Table 9.1. As usual, the aberrations are compensated by aberrations of a lower order in order to get the minimum total RMS value (Equation (3.39), (3.40) and (3.41)). For instance, spherical aberration is compensated with defocusing according to

\[
W(r, \phi) = W_{40}r^4 - W_{20}r^2 \quad \text{with} \quad W_{20} = -W_{40}.
\]

In Fig. 9.8 the orientation angle \( \phi \) is indicated with a second number. For instance, astigmatism at 45° with the tracks on the disk is indicated with \( W_{22,45} \).

<table>
<thead>
<tr>
<th>m \ n</th>
<th>Name aberration</th>
<th>Aberration coefficient</th>
<th>Expression aberration ( S_{ab}(r, \phi) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 0</td>
<td>Defocusing</td>
<td>( W_{20} )</td>
<td>( r^2 \cos(\phi - \Phi) )</td>
</tr>
<tr>
<td>2 2</td>
<td>Astigmatism</td>
<td>( W_{22} )</td>
<td>( r^2 \cos(\phi - \Phi) )</td>
</tr>
<tr>
<td>3 1</td>
<td>Coma</td>
<td>( W_{31} )</td>
<td>( r^2 \cos(\phi - \Phi) )</td>
</tr>
<tr>
<td>3 3</td>
<td>Clover</td>
<td>( W_{33} )</td>
<td>( r^2 \cos(\phi - \Phi) )</td>
</tr>
<tr>
<td>4 0</td>
<td>Spherical aberration</td>
<td>( W_{40} )</td>
<td>( r^4 )</td>
</tr>
<tr>
<td>4 2</td>
<td>Higher-order astigmatism</td>
<td>( W_{42} )</td>
<td>( r^4 \cos(\phi - \Phi) )</td>
</tr>
<tr>
<td>5 1</td>
<td>Higher-order coma</td>
<td>( W_{51} )</td>
<td>( r^4 \cos(\phi - \Phi) )</td>
</tr>
<tr>
<td>6 0</td>
<td>Higher-order spherical aberration</td>
<td>( W_{50} )</td>
<td>( r^6 \cos(\phi - \Phi) )</td>
</tr>
<tr>
<td>6 2</td>
<td>Higher-order astigmatism</td>
<td>( W_{62} )</td>
<td>( r^6 \cos(\phi - \Phi) )</td>
</tr>
</tbody>
</table>

**Table 9.1:** An overview of the aberrations relevant for this chapter. In this table, the aberrations are listed according to expansion in Seidel coefficients (Equation (3.37)), because it results in simple expressions with one term per aberration type. \( r \) is the normalized pupil radius and \( \phi \) the azimuth. The orientation is defined as \( \Phi \).

From Fig. 9.8 it is obvious that astigmatism oriented at 45° with respect to the tracks on disk \( (W_{22,45}) \) is the dominant aberration in the disturbance of the wobble. Orientation at 45° with respect to the tracks means that the focal lines make an angle of 45° with the tracks. The amplitude of the crosstalk perturbation is for 50 m\( \lambda \) RMS even higher than the wobble amplitude: 0.45/40 = 1.1. Other aberrations with impact are radial coma \( (W_{31,0}) \) and different higher order aberrations. Radial coma means here that the coma tail is pointing perpendicular to the tracks. Coma at 45° with respect to the tracks \( (W_{31,45}) \) also has impact. The mentioned higher order aberrations are higher order astigmatism at 45° \( (W_{42,45}, W_{62,45}) \), clover \( (W_{31,0}, W_{53,45}) \) and higher order coma \( (W_{51,0}, W_{31,45}) \).

Defocusing \( (W_{20}) \), spherical aberration \( (W_{40}) \), astigmatism at 0 or 90° \( (W_{22,0}, W_{22,90}) \), \( W_{22,45} \) and tangential coma \( (W_{51,0}, W_{51,90}) \) were investigated by simulation also, but no crosstalk from the pits into the wobble channel was found without presence of other aberrations.

In Fig. 9.9 the intensity distribution of the readout pupil of the disk without aberrations is given as a function of the position of the spot with respect to the pits. In Fig. 9.9 (a) and (e) the spot is located on the middle of the land, for (b) and (d) on the transition pit-land, and (c) is on the middle of the pit. The intensity in the pupil is low when the spot is on the pit and high when the spot is on the land. The push-pull overlap areas of the pre-groove are clearly visible. The push-pull direction is the vertical direction in this picture. No difference in the two overlap areas between zero and first order is observed.
Crosstalk and astigmatism at 45° with the track on disk

The effect of astigmatism at 45° is illustrated in Fig. 9.10. Fig. 9.10** shows an opposite push-pull signal, when the Fig. 9.10 (b) and (d) are compared.

The crosstalk curve shows rather steep peaks. The phase shift between the RF signal and the crosstalk signal is 90°. When the astigmatism makes an angle of -45° the signal has a similar shape, however, the positive peak becomes negative and the negative peak becomes positive.

*) The dots in Fig. 9.9c are due to a graphical artifact and should be neglected.

**) Fig. 9.10c shows clearly also crosstalk from the pits into diagonal direction, which is used for the astigmatic focus detection. In the practical situation a low pass filter will eliminate this signal for the wobble readout.
The relation between the peak-to-peak amplitude of the crosstalk perturbation as a function of the amount of astigmatism at $45^\circ$ is given in Fig. 9.12. The relation is almost linear. The shape of the crosstalk with lower values of astigmatism was exactly the same as in Fig. 9.11. A realistic value of astigmatism on a DVD recorder is 20 mλ RMS.

**Crosstalk and radial oriented coma**

The aberration coma in the radial direction (comet tail directed in the radial direction) also has effect. This is illustrated in more detail in Fig. 9.13 and 9.14. When the spot is exactly on the pit, the top of the push-pull signal of Fig. 9.12 (c) is much darker than the bottom. The crosstalk signal is in phase with the RF signal for radial coma as shown in Fig. 9.13 and 9.14.

![Fig. 9.13: Simulation of the pupil with the disk information as a function of the spot-pit position (50 mλ RMS radial coma).](image)

**Crosstalk and several higher order aberrations**

The intensity profiles of the pupils in case of higher order aberrations that have impact on the wobble signal are shown in Fig. 9.15. For $W_{33}$ (clover) the position (c) has the maximum amplitude. For $W_{42}$ and $W_{62}$ it is (b) and (e).

![Fig. 9.15: Simulation of the pupil as a function of the spot-pit position for higher order aberrations with effect on wobble crosstalk.](image)

**The effect of different pit lengths**

In order to calculate the effect of different pit lengths the wobble crosstalk is also calculated for 4Cb and 14Cb. The effect of 45° astigmatism and radial coma is shown in Fig. 9.16. The peak-to-peak crosstalk signal is maximal for 7Cb for both astigmatism and coma.

![Fig. 9.16: Crosstalk and effect of three pit lengths and astigmatism (left) and coma (right).](image)
Fig. 9.17 and 9.18 illustrates the shape of the crosstalk for a scan of one pit length for 4c₆, 7c₆, and 14c₆. The 4c₆ shapes are more rounded than the 7c₆ and 14c₆. The double frequency arises for radial coma at 14c₆ pits.

![Fig. 9.17: Three pit lengths and the shape of the crosstalk signal for astigmatism at 45°.](image)

One can conclude that the amplitude of the crosstalk curve is a slightly dependent on the pit length and that the 7c₆ pit has the largest amplitude.

9.2.4 Pupil filling

The effect of pupil filling error is also investigated. Pupil filling error is decentering of the maximum intensity in the pupil. The decentering in this calculation was set to 20% of the pupil radius \(A_r = 0.2\), which means a value of 0.36 mm. The effect of pupil filling error is made visible in the pupil given in Fig. 9.19 and as signal given in Fig. 9.20. It obvious that the pupil filling error also generates a DC offset. In the practical situation this will be compensated during the photo diode adjustment procedure when the spot is centered on the detector.

![Fig. 9.19: Simulation of the pupil from the disk with radial pupil filling error (7c₆ pits).](image)

![Fig. 9.20: The crosstalk due to a radial pupil filling error of a decentering of 20% of the pupil radius with 7c₆ pits.](image)

If the shape of the coma crosstalk and the pupil filling crosstalk are compared (see Fig. 9.14 and 9.20), it is expected that they can compensate each other. So, crosstalk due to pupil filling it can compensate crosstalk due to radial coma, when their signs are opposite.
9.2.5 Detracking and satellite spot orientation

Tracking offset during recording results in pits, which are not written in the middle of the pre-groove. Fig. 9.21 and 9.22 show that this offset of the pits with respect to the groove will introduce increase of the crosstalk.

Fig. 9.21: The pupil with the disk information as a function of the spot-pit position in case of 0.1 µm offset of the pits with respect to the pre-groove.

Fig. 9.22: Crosstalk caused by pits, which are written 0.1 µm next to the middle of the pre-groove.

For a differential push-pull system the spot has two possible spot orientations as given in Fig. 9.23. In orientation 1 the satellites A and B are located next a written track and an unwritten track. In orientation 2 satellite A is located between two written tracks and satellite B is between two unwritten tracks. The phase of the crosstalk signal with respect to the pit position has a similar behavior as for pupil filling error and coma as shown in Fig. 9.22, 9.20 and 9.14. As a result, the effect of tracking offset can be compensated by pupil filling and/or coma.

Orientation of the satellite spots with respect to the written tracks

Fig. 9.23:
Two different orientations of the satellite with respect to the written tracks.

A picture of the satellite spots in orientation 1 and 2 during a 7c0 pit crossing is shown in Fig. 9.24. In orientation 1 the satellites clearly show an offset. In orientation 2 there is no offset visible. The central aperture signal from satellite A is lower than from satellite B.

Fig. 9.24: Simulation of the pupil of the satellites A and B at 7c0 pit crossing for orientation 1 and 2.

Orientation 1 results in a tracking offset of 0.10 µm, while orientation 2 generates almost no offset in the simulations (0.0013 µm). The tracking offsets value of 0.1 µm in case of orientation 1 was also found by measurements [98]. Orientation 2 showed no offset in the measurements.

9.2.6 Simulations including detector

The signals of the spot on the detector are also investigated by simulation with the parameters of light path 4 as described Section 4.4. In case of a light path with astigmatic focusing, the spot on the detector is the circle of least confusion. Including the effects of diffraction it has a more square shape (see also Fig. 7.11 (b)). The spots on the detector as a function of the pit position for the 7c0 pits without aberration in the spot on disk are shown in Fig. 9.25. The spots are rotated 90° to the pupil as shown in Section 4.2.6.
Fig. 9.25: Simulation of the spot on the detector as a function of the spot position for 7c₈ pits and no aberrations.

Wobble crosstalk in case of aberrations in the forward path

The effect of aberrations in the pupil and on the detector is comparable. Fig. 9.26 shows an example with astigmatism at 45° in the path towards the disk. The shape and amplitude of the crosstalk signal in the pupil and on the detector is the same.

Fig. 9.26: Crosstalk in the pupil and on the detector in case of 50 mλ RMS astigmatism at 45° for 7c₈ pits.

Pictures of the spots on the detector in case of astigmatism at 45° and radial coma are shown in Fig. 9.27. The coma of the spot on disk is compensated by the way back towards the detector. As a result no coma shape is visible in the picture of Fig. 9.27.

Fig. 9.27: Simulation of the spot on detector for 50 mλ RMS astigmatism at 45° (top) and radial coma for 7c₈ pits (bottom).

Effect of coma correction on the detector

For light path 2 and 5 of Section 4.4 the plate generates respectively 82 and 42 mλ RMS coma on the detector. When this coma is not corrected by a coma correction plane as described in Section 7.6.1, the shape of the detector spot is like the ones shown in Fig. 9.28. The shape is similar to 7.11 (a).

Fig. 9.28: The spot on the detector as a function as the spot position with 42 mλ coma on the detector due to the plane plate of light path 5 (4c₈ pits no aberrations).

Without aberrations in the spot on the disk, the coma on the detector can generate a small amount of crosstalk. For 42 mλ and 82 mλ RMS coma on the detector the peak-to-peak crosstalk value normalized by the central aperture signal CA is 0.037 and 0.048 respectively. This is an increase in comparison with the coma free detector spot of 16-50%. In case of 50 mλ RMS astigmatism at 45° in the spot on disk the coma on the detector has a relatively small effect: < 5%.
9.2.7 Simulations on a recordable disk

The effects of astigmatism at 45° with the tracks on disk are also investigated on a DVD+R or DVD-R like disk. The pits of a recordable disk are in general a little narrower than for a rewritable disk and have less absorption. The value of the pit width (see Fig. 9.4) is decreased from 0.56 to 0.41 μm. The reflection coefficient of the pits is increased from 0.4 to 0.9. The shape of the crosstalk of the wobble into the wobble channel for astigmatism at 45° with the tracks for the two disk types is given in Fig. 9.29. The amplitude and the shape of the crosstalk signal are equal.

![Fig. 9.29: The crosstalk of a 76° pit in the radial push-pull channel with 50 mRMS astigmatism at 45° with respect to the tracks on disk for a DVD-R disk (left) and a DVD-RW disk (right).](image)

The detracking due to the satellite spot orientation as treated in Section 9.2.4 is also investigated for an R disk. The detracking due to the pits for orientation 1 was approximately a factor of 10 smaller for the R disk in comparison with the RW disk. Apparently, written wider amplitude pits disturb the tracking signal more than narrower phase pits.

9.3 Analytical model of the crosstalk between the pits and the wobble signal

9.3.1 Analytical model with amplitude pits and aberrations

**Theory**

Using scalar diffraction theory as treated in Section 3.2 and [1], an analytical approach of the impact of aberrations on the crosstalk will be given in this section.

The optical signal of an optical disk is described in Section 3.2.5, Equation (3.26), as follows:

\[ e_p(x,y) = \sum_{m} \sum_{n} r_{mn} \exp \left( \frac{2\pi i (m u_0 + n v_0)}{p q} \right) f \left( \frac{x-m}{p}, \frac{y-n}{q} \right) \]

(9.1)

where \( e_p \) is the electro-magnetic field in the pupil, \( x \) and \( y \) are the positions in the pupil normalized by pupil radius, \( p \) and \( q \) are the periods of the pits in two directions normalized by \( \lambda/NA \), \( m \) and \( n \) are the diffracted orders in two directions, \( f(x, y) \) is the pupil function and \( u_0 \) and \( v_0 \) are the relative positions of the pits with respect to the spot on the disk normalized by \( \lambda/NA \).

\( r_{mn} \) is the inverse Fourier transform of a pit period on disk as shown in Equation (3.33):

\[ r_{mn} = \frac{1}{p \cdot q} \int_{-\frac{p}{2}}^{\frac{p}{2}} \int_{-\frac{q}{2}}^{\frac{q}{2}} \tilde{R}(u, v) e^{- \frac{2\pi i (m u_0 + n v_0)}{p q}} du dv \]

(9.2)

where \( \tilde{R}(u, v) \) is the reflection function on disk and the pupil function and \( u \) and \( v \) are the positions of the pits on disk normalized by \( \lambda/NA \).

The pits are simplified into one-dimensional pits in this model, and the \(+1\) and \(-1\) diffracted order will be considered only. Therefore Equation (9.1) is reduced to:

\[ e_p(x,y) = \sum_{m} r_{m0} \exp \left( \frac{2\pi i m u_0}{p} \right) f \left( \frac{x-m}{p}, y \right) \]

(9.3)

For the Fourier transform \( r_{m0} \) we obtain:

\[ r_{m0} = (a_p e^{i\psi} - 1) \frac{P_l}{p} \sin c \left( \frac{2\pi m P_l}{p} \right) \quad \text{for} \ m \neq 0 \]

(9.4)

and

\[ r_{00} = 1 + (a_p e^{i\psi} - 1) \frac{P_l}{p} \quad \text{for} \ m = 0 \]

(9.5)
where \( p_1 \) is the pitch dimension normalized by \( \lambda/NA \), \( a_p \), the reflection coefficient in the pits and \( \nu \) the phase depth of the pits. When the pits are amplitude pits with a duty cycle of 50\% the expressions (9.4) and (9.5) look like:

\[
r_{\text{top}} = (a_p - 1) \frac{1}{2} \sin \left( \frac{\pi m}{2} \right), \tag{9.6}
\]

and

\[
r_{\text{bottom}} = \frac{1}{2} + \frac{a_p}{2}, \tag{9.7}
\]

respectively. The \(-1\) diffracted order on the left (I + III) and the \(+1\) diffracted order on the right (II + IV) is shown in Fig. 9.30.

![Diagram of pupil with diffracted orders](image)

Fig. 9.30: The pupil with diffracted orders.

The electro-magnetic fields in the overlap areas in the left \( e_{\text{PL}} \) and right \( e_{\text{PR}} \) are:

\[
e_{\text{PL}} = r_{\text{top}} e^{-2\pi i p x} f(x + \frac{1}{p}, y) + r_{\text{bottom}} f(x, y) \tag{9.8}
\]

and

\[
e_{\text{PR}} = r_{\text{top}} e^{-2\pi i p x} f(x - \frac{1}{p}, y) + r_{\text{bottom}} f(x, y). \tag{9.9}
\]

When a homogenous pupil is considered, \( f(x, y) \) is defined as follows:

\[
f(x, y) = e^{2\pi i \Phi(x, y)} \quad \text{for} \quad x^2 + y^2 \leq 1 \tag{9.10}
\]

and

\[
f(x, y) = 0 \quad \text{for} \quad x^2 + y^2 > 1, \tag{9.11}
\]

with \( \Phi(x, y) \) the pupil aberration function given in Section 3.3. Consequently, the fields in the left and right overlap area are:

\[
e_{\text{PL}} = \frac{a_p - 1}{\pi} e^{-2\pi i \frac{\pi}{p} \Phi(x, y)} \left[ 1 + a_p e^{2\pi i \Phi(x, y)} \right] \tag{9.12}
\]

and

\[
e_{\text{PR}} = \frac{a_p - 1}{\pi} e^{-2\pi i \frac{\pi}{p} \Phi(x, y)} \left[ 1 + a_p e^{2\pi i \Phi(x, y)} \right]. \tag{9.13}
\]

In order to find the irradiance \( e_{\text{PL}} \) and \( e_{\text{PR}} \) are multiplied with its complex conjugate:

\[
e_{\text{PL}}^2 = e_{\text{PL}}^* e_{\text{PL}} \quad \text{and} \quad e_{\text{PR}}^2 = e_{\text{PR}}^* e_{\text{PR}}. \tag{9.14}
\]

When constant factors are neglected, because they are not relevant for the pit crosstalk the result is:

\[
e_{\text{PL}}^2 = 2 e_p^* e_p \cos \left[ 2\pi \left( W(x + \frac{1}{p}, y) - W(x, y) - \frac{\eta_0}{p} \right) \right] \tag{9.15}
\]

and

\[
e_{\text{PR}}^2 = 2 e_p^* e_p \cos \left[ 2\pi \left( W(x - \frac{1}{p}, y) - W(x, y) + \frac{\eta_0}{p} \right) \right]. \tag{9.16}
\]

where:

\[
y_p = \frac{a_p - 1}{\pi} \quad \text{and} \quad \xi_p = \frac{1 + a_p}{2}. \tag{9.17}
\]

For \( p \leq 1 \), the crosstalk signal is now the difference of the power in the top I + II minus the bottom II + IV as illustrated in Fig. 9.30. So for the crosstalk signal \( X_{\text{cros}} \) holds:

\[
f(x, y) = e^{2\pi i \Phi(x, y)} \quad \text{for} \quad x^2 + y^2 \leq 1 \tag{9.10}
\]

and

\[
f(x, y) = 0 \quad \text{for} \quad x^2 + y^2 > 1, \tag{9.11}
\]
\[ X_{\text{crosstalk}} = \int_{\text{I}} e_{\text{L},x}^2 \, dx \, dy + \int_{\text{II}} e_{\text{L},y}^2 \, dx \, dy - \int_{\text{III}} e_{\text{L},x}^2 \, dx \, dy - \int_{\text{IV}} e_{\text{L},y}^2 \, dx \, dy \quad (9.18) \]

Conclusions that can be drawn from the Equations (9.15), (9.16), and (9.18) are that asymmetric aberrations in the radial direction \( y \) will result in crosstalk from the pits into the push-pull wobble channel.

The power will be integrated over the areas I, II, III and IV in order to calculate the crosstalk. Fig. 9.31 shows the left overlap area.

The integration over area I results in:

\[ \int_{-\frac{1}{2p}}^{\frac{1}{2p}} \int_{0}^{p} e_{\text{L},x}^2 \, dx \, dy + \int_{-\frac{1}{2p}}^{\frac{1}{2p}} \int_{0}^{p} e_{\text{L},y}^2 \, dx \, dy \quad (9.19) \]

The areas II, III and IV are calculated in the same way.

**Results**

By means of Equation (9.14), (9.15), (9.17), (9.18) and (9.19) for area I and similar for the areas II, III and IV, the crosstalk is calculated. 4c\textsubscript{s} pits are considered, because for this pit length \( p \) equals approximately 1 and Fig. 9.16 shows that the impact of the pit length is limited. Fig. 9.32 shows the crosstalk generated by astigmatism at 45° with respect to the tracks. The calculations are carried out by means of "Mathcad".

Fig. 9.32: The shape of the crosstalk of the model for 50 m\( \lambda \) RMS astigmatism at 45°.

Fig. 9.32 resembles Fig. 9.11 of the simulations. The peak-peak value of the crosstalk is 57% of the RF peak-peak. The effect of various aberrations calculated with this model is summarized in Table 9.2.

<table>
<thead>
<tr>
<th>Aberration</th>
<th>Orientation</th>
<th>Relative effect</th>
</tr>
</thead>
<tbody>
<tr>
<td>( W_{30} )</td>
<td>-</td>
<td>0</td>
</tr>
<tr>
<td>( W_{22} )</td>
<td>0°</td>
<td>0</td>
</tr>
<tr>
<td>( W_{22} )</td>
<td>45°</td>
<td>100%</td>
</tr>
<tr>
<td>( W_{22} )</td>
<td>90°</td>
<td>0</td>
</tr>
<tr>
<td>( W_{31} )</td>
<td>0°</td>
<td>0</td>
</tr>
<tr>
<td>( W_{31} )</td>
<td>45°</td>
<td>29%</td>
</tr>
<tr>
<td>( W_{31} )</td>
<td>90°</td>
<td>41%</td>
</tr>
<tr>
<td>( W_{40} )</td>
<td>-</td>
<td>0</td>
</tr>
</tbody>
</table>

The results in Table 9.2 confirm the results obtained earlier, however, the difference between the effect of astigmatism at 45° and radial coma is smaller than for the "Diffract" simulations. So, also according to this model astigmatism at 45° with the track has the largest impact on crosstalk between the RF signal of the pits and the wobble signal.
9.3.2 Analytical model with phase and amplitude pits, pupil filling and aberrations

The expression

A more general approach of the reflection function of the disk also contains a phase depth. The pupil function is based on a Gaussian laser beam including decentering of the pupil filling. After some mathematics, the power in the left and right overlap areas yields the following expression:

\[
\begin{align*}
e_{\text{pm}}^2 &= \frac{1}{\pi} e^{-\sigma^2(x+y^2)} \left( \sigma_{\text{pm}}^2 - 1 \right) \cos \left( 2\pi \left( W(x+\frac{1}{p},y) - W(x,y) - \frac{u_0}{p} \right) \right) \\
+ \frac{1}{\pi} e^{-\sigma^2(x+y^2)} 2\sigma_{\text{pm}} \sin(y) \sin \left( 2\pi \left( W(x+\frac{1}{p},y) - W(x,y) - \frac{u_0}{p} \right) \right),
\end{align*}
\]

(9.19)

and

\[
\begin{align*}
e_{\text{pa}}^2 &= \frac{1}{\pi} e^{-\sigma^2(x+y^2)} \left( \sigma_{\text{pa}}^2 - 1 \right) \cos \left( 2\pi \left( W(x-\frac{1}{p},y) - W(x,y) + \frac{u_0}{p} \right) \right) \\
+ \frac{1}{\pi} e^{-\sigma^2(x+y^2)} 2\sigma_{\text{pa}} \sin(y) \sin \left( 2\pi \left( W(x-\frac{1}{p},y) - W(x,y) + \frac{u_0}{p} \right) \right),
\end{align*}
\]

(9.20)

where \( \psi \) is the phase depth of the pits, \( \sigma(x,y) \) the Gaussian pupil filling in Cartesian coordinates with decentering \( \Delta_x \) and \( \Delta_y \) normalized on the pupil radius:

\[
\sigma(x,y) = \sigma_x (x-\Delta_x)^2 + \sigma_y (y-\Delta_y)^2.
\]

(9.21)

Results

The crosstalk of the model generated for a Gaussian laser beam with a radial pupil filling error according \( \sigma_x = 0.6, \sigma_y = 0.8 \) and \( \Delta_x = 0.3 \) is shown in Fig. 9.33. They are similar to the calculations in Section 9.2.4: The shape of Fig. 9.33 resembles the shape of Fig. 9.20, apart from the irrelevant polarity and offset.

![Crosstalk](image)

Fig. 9.33: The shape of the crosstalk of the model in case of radial pupil filling error.

Table 9.3 shows the effect of pupil filling error, astigmatism at 45° and radial coma in case of the Gaussian beam for an amplitude pits in the right column and a phase pit in the left column. The ratio of the effect of astigmatism at 45° and radial pupil filling is also not so large as for the “Diffract” simulations. Tangential pupil filling error has no impact. The phase pits generate a crosstalk, which is 16% smaller than the amplitude pits, because in this model the amplitude of RF signal of the phase pits is also 16% smaller than the RF signal of amplitude pits.

<table>
<thead>
<tr>
<th>Aberration or pupil filling error</th>
<th>Relative effect</th>
</tr>
</thead>
<tbody>
<tr>
<td>( a_{\text{pm}} = 0 )</td>
<td>100%</td>
</tr>
<tr>
<td>( a_{\text{pm}} = 0.4 )</td>
<td>84%</td>
</tr>
<tr>
<td>( \Phi = 45^\circ )</td>
<td></td>
</tr>
<tr>
<td>( \Delta_x = 0.3 ) (tangential)</td>
<td>87%</td>
</tr>
<tr>
<td>( \Delta_y = 0.3 ) (radial)</td>
<td>74%</td>
</tr>
<tr>
<td>( \Phi = 90^\circ ) (radial)</td>
<td>26%</td>
</tr>
<tr>
<td>( \psi = 0.3 ) rad</td>
<td>22%</td>
</tr>
</tbody>
</table>

Table 9.3: The relative effect on the crosstalk of aberrations of 50 mλ RMS and pupil filling error and the phase/amplitude of the pits for 4cb pits according to the model.
9.4 Measurement of the crosstalk between the pits and the wobble signal versus 45° astigmatism

The sensitivity for astigmatism at 45° with the tracks is also determined by experiments [99]. The amplitude of the wobble crosstalk was measured of several DVD recorder optical pick-ups. The wavefront aberration of the beam and the objective lens was measured by an interferometer in order to determine the aberration value of the spot on disk. The optical pick-ups had a cocktail of several aberrations. They were selected on different values of the wobble crosstalk and equal values of the other electro-optical signals like jitter, RF signal amplitude or radial signal amplitude. Fig. 9.34 shows the relation between the amount of crosstalk and the amount of 45° astigmatism. The crosstalk and the 45° astigmatism correlate very well despite the other aberrations of the spot and the other differences between the individual optical pick-ups.

![Graph showing measurement of crosstalk and astigmatism at 45° on the spot on disk](image)

Fig. 9.34: The crosstalk and the wave front of several of several optical pick-ups was measured. The graph shows that the larger the amount of astigmatism at 45° with respect to the tracks is, the larger crosstalk will be. The crosstalk was measured at a pit length of approximately 70 Why? [99].

9.5 The Pre-pit signal

9.5.1 The pre-pit signal of an empty and written disk

As shown in Section 9.1, DVD-R and DVD-RW disks contain in addition to the wobble pre-pits. The pre-pit signal of the DVD-R disk is also investigated by means of simulations. The length of the pre-pit is 2c. Fig. 9.35 illustrates the push-pull signal of a pre-pit as a function of the spot position of a DVD-R and a DVD-RW disk in case of an empty and a written disk. When the spot passes the pre-pit a peak arises in the push-pull signal. The pits of the written disks are 14c long. The signals are normalized on the central aperture signal CA. The DVD recorder only recognizes the signal of the pre-pits with a particular polarity: the “valid pre-pits”. Pre-pits are located on both sides of the tracks. The valid pre-pits are located at the side of the track that is closest to the rim of the disk. The written pits change the amplitude of the pre-pit signal. The pre-pit signal amplitude of the written part is smaller than for the unwritten part for the DVD-R disk. For the DVD-RW disk it is just the opposite. The amplitude of the pre-pits next to the written pit can be larger than next to a land due to the normalized signal. The division by the CA signal lowers the pre-pit signal more in case of a land than in case of a pit.

![Graphs showing pre-pit signal](image)

Fig. 9.35: The pre-pit signal of an empty and written part on a DVD-R disk (left) and a DVD-RW disk (right).

The pupil as a function of the spot position is given in Fig. 9.36. The pictures (c) correspond to the peak of the pre-pit signal. The pupils in the top of Fig. 9.36c are brighter than the in the bottom. This causes the peak of the pre-pit signal to occur, when the spot passes the pre-pit. The effect of pits can be seen on the various positions of the spot with respect to the pit and pre-pit. The top and bottom of the pupils of Fig. 9.36a and d are equal, which results in the zero push-pull signal before and after passing the pre-pit. The pupil in Fig. 9.36c of the written part of the RW disk is very dark, which can explain the increase of the peak in Fig. 9.35 due to the normalizing by CA.
9.5.2 The pre-pit signal and aberrations

The effect of aberrations is also investigated for the pre-pit signal. Fig. 9.37 shows the effect of various aberrations with an amount of 50 mλ RMS on the pre-pit signal. Defocusing and astigmatism affects the pre-pit amplitude to some extent. The sign of the defocusing and the orientation of the astigmatism is relevant.

The impact of various aberrations with a value of 50 mλ RMS on the pre-pits signal of a DVD-R disk is shown in Fig. 9.38. The ratio of the pre-pit signal amplitude of the empty and written disk is shown. Astigmatism and defocusing have the largest impact on this ratio. The orientation of the astigmatism and the sign of the defocusing are relevant.

![Pre-pit ratio and effect of different aberrations of 50 mλ RMS](chart)

Fig. 9.37: The amplitude of the pre-pit signal of an unwritten disk and various aberrations.

![Pre-pit amplitude empty disk and effect of different aberrations of 50 mλ RMS](chart)

Fig. 9.38: The ratio of the amplitude of the pre-pit signal of an empty and a written part of the disk and various aberrations.

The pupil as a function of the spot position for the written and unwritten DVD-R disk is shown in Fig. 9.39 for 50 mλ RMS astigmatism parallel to the tracks. In Fig. 9.39c the light distribution in the pupil of the written part is not homogeneous anymore. This results in a decrease of the pre-pit signal.

![Fig. 9.39: The pupil as a function of the spot position for an empty disk and a written R disk in case of 50 mλ RMS astigmatism parallel to the tracks.](chart)
When written pits are present at the position where the pre-pit is read out, the pre-pit signal can vary strongly in particular in case of aberrations. This makes the readout of the pre-pit signal of a written disk very difficult in practice. From Fig. 9.37 and 9.38 we can conclude that astigmatism parallel or perpendicular to the tracks has the largest impact on the pre-pit signal. Fig. 9.37 shows that 50 \( \mu \text{RMS} \) defocusing or astigmatism can change the pre-pit signal of the empty part with approximately 20 to 40 \%. However, Fig. 9.38 shows that the ratio of the pre-pit signal of the empty and written part can change according to these simulations with approximately a factor of 5.

When aberrations are combined, for instance, astigmatism and defocusing or spherical aberration and defocusing the result is different. The impact of, e.g., astigmatism parallel to the tracks can be enhanced or weakened to a certain extend by means of defocusing. This can be used in a practical player. However, the maximum defocusing during recording is limited, because it enlarges the diffraction-limited recording spot.

A pupil filling error also has a small effect on the pre-pit signal ratio of the empty and written disk. A pupil filling error of 10\% of the pupil diameter results in a change of the ratio of approximately 10\%. Tracking offset has a larger impact. This will be explained in the next section.

9.5.3 The pre-pit signal and detracking

The impact of a small radial tracking error of 0.033 \( \mu \text{m} \) on a DVD-R disk is illustrated in Fig. 3.40. The signal of an unwritten part is not sensitive for this tracking error as shown in the picture on the left. However, the pre-pit signal ratio of an empty and unwritten part is strongly changed by the detracking as shown in picture on the right. A detracking error, which results in a spot position towards the pre-pit, increases the pre-pit signal on the written part. When the detracking error is in the opposite direction, the pre-pit signal on the written part is decreased. This means that the tracking offset also is a possible parameter to improve the pre-pit signal of a written disk.

9.5.4 Measurement of the pre-pit signal with different astigmatism orientation

Fig. 9.37 and 9.38 show that the pre-pit amplitude is dependent on the astigmatism orientation. In a measurement setup the pit amplitude signal of a written pit is measured in a flexible optical pick-up. An amount of 26 \( \mu \text{RMS} \) astigmatism is generated by means of a tilted plate in the path towards the disk. The orientation can be changed by rotation of the plate around the optical axis. The disk was a DVD-R disk.

![Pre-pit amplitude and Orientation of astigmatism](image)

Fig. 9.41: Relative pre-pit amplitude as a function of the orientation angle \( \Phi \) in case of 26 \( \mu \text{RMS} \) astigmatism. 0\(^\circ\) orientation means that the focal line which is the closest to the lens is parallel the tracks [100].

Fig. 9.41 shows that the pre-pit amplitude signal is dependent on the orientation of the astigmatism. The defocusing was optimized for optimum jitter. When the focal line closest to the objective lens oriented at 0 or 180\(^\circ\), the pre-pit amplitude is maximal. Comparison of larger amounts of optical pick-ups showed also very different results for 0 and 90\(^\circ\) astigmatism.

The impact of the track error was measured in the same setup. The pre-pit amplitude can be increased with a factor of 2 with a tracking offset difference of approximately 50 \( \mu \text{m} \), when tracking offset was such that the spot displacement is towards the rim of the disk. This is also the direction were the valid pre-pits are located. This is in agreement with Fig. 3.40.
9.6 Summary

DVD+R(W) disks contain high frequency wobbled track for address and timing information. A DVD-R(W) disk contains a wobble in combination with small pre-pits on the land between the grooves. Simulations have been carried out in order to investigate the effect of optical disturbances on the wobble and the pre-pit signal. The pits of a written disk affect the wobble and the pre-pit signal.

Aberrations in the spot on the disk with radial asymmetry in the spot on disk are the main reason for crosstalk of the pits into the wobble signal. Astigmatism at 45° with respect to the tracks has the largest impact on the crosstalk of the pits into the wobble signal. Other aberrations with a noticeable effect are radial coma, clover and higher order astigmatism at 45°.

A radial pupil filling error also causes wobble crosstalk. The amplitude of the wobble crosstalk is not strongly dependent on the pit length. When the satellites are oriented symmetrically to the written track pits, the pits on disk will get an offset with respect to the pre-grooves, which results in a higher crosstalk. An analytical model with one-dimensional pits is derived for wobble crosstalk in the pupil. The results of the model are similar to the simulation results. Coma generated by a plane parallel plate on the detector causes a small increase of the wobble crosstalk.

The amplitude of the pre-pit signal on a written part of the disk is changed by the written pit. The pre-pit signal of an empty disk is not very dependent on aberrations. The pre-pit signal of a written part is highly affected by aberrations. Defocusing and astigmatism parallel and perpendicular the tracks changes the pre-pit signal most. Detracking also has a large effect. Detracking can increase and decrease the signal next to a written pit.

The system of the recorder appeared to be very sensitive for the critical aberrations, discussed in this chapter. These aberrations should be controlled in particular. Measures can be taken in the signal processing to make the system more robust against these perturbations of the wobble [101] and the pre-pit signal. Also, defocusing and radial tracking can be used to improve the pre-pit detection.

By the investigations, described in this chapter a description is given of which of the aberrations and other imperfections particularly enhance the wobble and pre-pit signal perturbations.
10.1 Light path design for optical disk systems

The light path or the optics of a DVD recorder consists of the lasers, the detectors, the lenses and the other optical components. It generates the diffraction-limited light spot on the disk and the electro-optical signals from the disk. Several light paths for DVD recordable and rewritable systems have been designed. This is the main subject of this thesis. A number of novel principles have been applied in these light path designs. These principles are outlined below.

A geometrical model of the light path with three spots radial tracking and astigmatic focusing is developed. This model can be used as design tool for evaluation of the light path parameters during the light path design. Results of this model are compared with results of the ray-tracing program "Zemax". The results of the model and Zemax agree. Several relations between the light path parameters are found. The smaller the pupil diameter, the larger the 90° rotated displacement of the spot on the detector due to the actuator stroke will be. The focus S-curve is a signal generated by the light path, which is a measure for the amount of defocusing of the spot on the disk. The minimum distance of the satellite spots on the disk depends on the focus S-curve length: the shorter the S-curve, the shorter this distance can be. The smaller the magnification from the objective to the collimator is, the smaller the S-curve from the same plate thickness will be. A large magnification from objective to collimator lens results in a smaller distance of the main spot to the satellite on the disk for the same grating pitch and optical distance from laser to grating. The model and the simulations with Zemax both show that the angle of the satellites depends on the distance between collimator and objective lens. Identical S-curve lengths and amounts of astigmatism on the detector can be achieved with a cylinder lens with a long focal length and a long distance to the detector or with a more powerful cylinder lens with a short distance to the detector. The rotation of the satellites and the increase of their mutual distance on the detector are larger for the latter case. The S-curve is less symmetrical for the situation with the powerful cylinder lens. The S-curve of a plate is symmetrical. The shift of the radial beams in the pupil increases with a decreasing grating pitch and an increasing distance between collimator and pupil. This model is used during the design of the light paths described in this thesis.

The way of working when designing the light path of an optical pick-up is explained by means of a multidisciplinary design process. The light paths described in this thesis are designed according to this process. The input for this process is information from various sides for instance: own developments, component suppliers and competition and various disciplines, for instance: optics, electronics, mechanics and manufacturing. The constraints are the specification, the cost target, the quality, the development time and the moment of product introduction. The process consists of several steps, which are alternations of generation and evaluation. Therefore, the design process is called an "act-taste-act process".

One of the requirements of a DVD recorder light path is that it is also suitable for reading or writing a CD or CD-R(W). Designs have been made of a dual and a single detector light path.

The dual detector light path has a separate signal detector for CD and DVD. A major disadvantage of the dual detector light path is the coma due to the stroke of the objective lens, which is necessary for radial tracking. This effect is reduced by a factor of two by adding spherical aberration to the divergent beam between collimator and objective lens. A side effect of this measure is that the satellite spots get some extra coma, which is to a certain extent not harmful. In principle it would be possible to completely eliminate the stroke induced coma. However, in that case the coma of the satellites would become too large. Coma reduction with the mentioned factor of two appears to be the best compromise. This dual detector light path is designed in two layers: one for CD and one for DVD, which enables a compact optical pick-up unit.

In the design of the single detector light path the focus has been put on maximum power efficiency in order to allow for a high rotation speed of the disk during recording, while not compromising on a low cost price and a good reliability. The efficiency of the light path towards the disk and the detector is optimized by application of a partially polarizing plate beamsplitter and a plastic pre-collimator. The function of a pre-collimator is to increase the coupling efficiency of the laser. A plastic pre-collimator generates a focus shift on the disk as a function of temperature. This focus shift is limited by using a short focal length. An alternative is obtained by applying a wavelength-sensitive structure on the pre-collimator, where the wavelength shift of the laser due to temperature is used. A partially polarizing coating on a plane parallel plate improves the power efficiency towards the disk and towards the detector in comparison with a non-polarizing coating. The unwanted coma of the plate beamsplitter is compensated by applying a correction surface, which is integrated with the cylinder lens surface that is used for the generation of astigmatism for the astigmatic focusing. The orientation of the astigmatism of the plate beamsplitter can also be rotated in the proper direction with this surface. A pre-collimator function can be integrated in the beamshaper. The efficiency for DVD is maximized by the integration of a pre-collimator in the beamshaper. A PBS (polarizing beamsplitter) is applied by orientation of the laser far field at 45° with the track on the disk.

In a possible next generation light path a dual wavelength laser can be used. A dual wavelength laser is a laser device that has two laser cavities in order to generate two beams with different wavelength. Applying a dual wavelength laser saves a beamsplitter, a laser package and several adjustments during assembly of the optical pick-up. The issue is how to integrate a dual wavelength laser in a single detector light path that is suitable for high-speed DVD and CD recording. A grating element can be used to join the DVD and CD beam to one detector. The depth and the blaze angle determine the power of the two beams towards the detector. Differential push-pull for CD and DVD with the same detector is possible with the introduced two-color grating. For CD and DVD this grating has a separate grating surface with different pitch, depth and orientation with respect to the tracks. It works almost independently for CD and DVD, while both beams pass this component. A normal pre-collimator is not possible in combination with a dual wavelength laser. A dedicated pre-collimator is designed by using two holographic surfaces on one component. This component also has a join function. The average pitch of the holograms is depending on the thickness and the density of the component towards the laser. A stepped and blazed grating has been introduced as structure of the holograms. The CD efficiency is depending on the number of steps of the structure. In practice, the DVD and CD efficiency depends on the tip radius of the diamond cutting tool, which is used for the manufacturing of the molds for providing the holograms. These proposed new ideas enable a single detector light path with dual wavelength laser suitable for high-speed DVD and CD recording.
In this thesis an overview is given of the most important optical principles applied for reading or writing a disk, including a brief description of the rest of the system of a recorder. Technologies from different fields are combined in an optical disk recorder: optics, mechanics, dynamics, servo electronics, high-frequency electronics, digital signal processing and firmware. The opto-mechanical tolerances become tighter when going from CD to DVD. The maximum allowable tilt angle between objective lens and disk is decreased significantly despite of the smaller disk cover layer. The requirements on the stability of the differential push-pull radial tracking signal reduce the tolerances of the disk eccentricity and alignment failures in the recorder with a factor of two due to the smaller track pitch.

In order to be able to record a writable DVD disk, the recorder needs timing or address signals and information about the disk properties. The information and signals are stored on a DVD+R(W) disk by means of a high-frequency wobbled track. A DVD-R(W) disk contains a lower frequency wobble in combination with small pre-pits on the land between the grooves.

The wobble and pre-pit signals have been evaluated in terms of optical tolerances. Simulations have been carried out in order to investigate the effect of optical imperfections on the wobble and the pre-pit signal. The pits of a written disk appear to affect the wobble and the pre-pit signal. Aberrations in the spot on the disk with asymmetry in the radial direction are the main reason for crosstalk of the pits into the wobble signal. Astigmatism at 45° with respect to the tracks has the largest impact on crosstalk. Other aberrations with noticeable effect are radial coma, clever and higher order astigmatism at 45°. A radial pupil filling error also causes crosstalk. The amplitude of the wobble crosstalk is very dependent on the pit length. When the satellites are oriented symmetrically to the written track pits, the pits on disk will get an offset with respect to the pre-grooves, which results in a higher crosstalk. An analytical model with one-dimensional pits is derived for wobble noise in the pupil. The results of the model are similar to the simulation results. Coma on the detector generated by the plane parallel plate causes a small increase of the wobble crosstalk. The written pits change the amplitude of the pre-pit signal. The pre-pit signal of an empty disk is not very sensitive for aberrations. However, the pre-pit signal of a written part is highly affected by aberrations. Defocusing and astigmatism parallel and perpendicular to the tracks have the largest impact on the pre-pit signal. Detracking has also a significant effect. It can increase or decrease the pre-pit signal next to a written pit. By these evaluations, a description is given of which of the aberrations and other imperfections particularly enhance the wobble and pre-pits signal perturbations.

10.2 Implementation of the designs

The main part of the work is carried out over a period of approximately 5 years in the time frame from 1998 until 2003. The design of the single detector light path contributed to the introduction of the first Philips DVD recorder in August of 2001 and it was applied in various other first generation DVD recorders. The designed single detector light path is applied in the current data drives and video recorders of Philips and other brands. The data drive with this light path was the first in the market, which reached a DVD+R recording speed of 16x in spring 2004.

10.3 Perspectives

After the DVD recorders and data drives, the blue laser drives will come up with a storage capacity of 25 to 50 GB in case of the Blu-ray Disc format. A possible next generation optical disk after Blu-ray Disc with again serious capacity enlargement can be reached by different methods. Decrease of the laser wavelength towards deep-UV is not very likely, because this wavelength excludes the application of plastic and most glass types, which makes a cheap player, recorder or drive difficult. A further increase of the numerical aperture beyond a value of 1 is possible with the Solid Immersion Lens technology, which can result in a capacity increase of roughly a factor of 6 with respect to the Blu-ray Disc format. A principle to increase the disk capacity towards very high values is holographic data storage, by using the volume of the disk. However, disadvantages of holographic data storage for non-professional applications are the rather complex optics and the totally different disk technology in comparison with the current disks. Therefore, it is expected that the increase in capacity will also come from the utilization of more than two layers in combination with the Blu-ray Disc numerical aperture.
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Name</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A_{act}$</td>
<td>Amplitude lens actuator</td>
<td>m</td>
</tr>
<tr>
<td>$A_s$</td>
<td>Coefficient surface description</td>
<td>mm$^{-2}$</td>
</tr>
<tr>
<td>$a_{3j}$</td>
<td>Aspherical coefficient for description of a lens surface</td>
<td>mm$^{(2)}$</td>
</tr>
<tr>
<td>$A_{3_{,rev}}$</td>
<td>Zernike coefficient of coma in the satellite spots</td>
<td></td>
</tr>
<tr>
<td>$A_{40km}$</td>
<td>Zernike coefficient of spherical aberration in the pre-collimated beam</td>
<td></td>
</tr>
<tr>
<td>$A_{nnRMS}$</td>
<td>RMS value of a Zernike coefficient</td>
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</tr>
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<td>Zernike coefficient</td>
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</tr>
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<td>$A_I$</td>
<td>Overlap area zero and first diffracted orders of the disk normalized by the pupil area</td>
<td></td>
</tr>
<tr>
<td>$A_{II}$</td>
<td>Overlap area zero and first diffracted orders of the disk normalized the pupil area</td>
<td></td>
</tr>
<tr>
<td>$a_p$</td>
<td>Amplitude reflection coefficient of the pit</td>
<td></td>
</tr>
<tr>
<td>$B$</td>
<td>Magnetic field</td>
<td>T</td>
</tr>
<tr>
<td>$B_s$</td>
<td>Coefficient surface description</td>
<td></td>
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<td>Image distance pre-collimator</td>
<td>mm</td>
</tr>
<tr>
<td>$b_{pu}$</td>
<td>Image distance pupil with respect to collimator lens</td>
<td>mm</td>
</tr>
<tr>
<td>$b_s$</td>
<td>Image distance with respect to sensor lens first focal line</td>
<td>mm</td>
</tr>
<tr>
<td>$b_{sc}$</td>
<td>Image distance with respect to sensor lens second focal line</td>
<td>mm</td>
</tr>
<tr>
<td>$b_{sl}$</td>
<td>Image distance with respect to sensor lens circle of least confusion</td>
<td>mm</td>
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<tr>
<td>$C_s$</td>
<td>Coefficient surface description</td>
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<tr>
<td>$CA$</td>
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<tr>
<td>$CA_{A,B,C}$</td>
<td>Central aperture signal of spot A, B or C</td>
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<tr>
<td>$C_{act}$</td>
<td>Spring constant of the actuator</td>
<td>N/m</td>
</tr>
<tr>
<td>$c_p$</td>
<td>Channel bit length</td>
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<tr>
<td>$C_e$</td>
<td>Coupling efficiency of the laser beam in the aperture/pupil</td>
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<tr>
<td>$D$</td>
<td>Cover layer thickness</td>
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<td>Damping constant of the actuator</td>
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<tr>
<td>$d_c$</td>
<td>Thickness of an optical component</td>
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<td>$d_h$</td>
<td>Thickness of the substrate of a hologram component</td>
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<td>Length arbitrary optical component</td>
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<td>Thickness plane parallel plate</td>
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<tr>
<td>$d_{pu}$</td>
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<td>$d_{pu}$</td>
<td>Distance between cylinder lens and image pupil including shift plate</td>
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<td>$D_s$</td>
<td>Spacer layer thickness dual layer disk</td>
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<td>$d_s$</td>
<td>Thickness servo lens</td>
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<td>$E_d$</td>
<td>Energy exposed on the disk during recording</td>
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<td>Function proportional to the electro magnetic field in a overlap</td>
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<td>Function proportional to the electro magnetic field on the disk</td>
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<td>$e_{pl}$</td>
<td>Function proportional to electro-magnetic field the right overlap</td>
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<td>$e_{pr}$</td>
<td>Function proportional to electro-magnetic field the left overlap</td>
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<tr>
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<tr>
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<td>$g$</td>
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<td>$g_{dis}$</td>
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<tr>
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<td>Relative intensity distribution or irradiance of the spot on disk</td>
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<td>$I_{act}$</td>
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<td>A</td>
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<tr>
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<td>$k$</td>
<td>Wave number: $2\pi/\lambda$</td>
<td>$m^{-1}$</td>
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<td>Length coil of the actuator</td>
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<tr>
<td>$m_{act}$</td>
<td>Moving mass of the actuator</td>
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<td>Magnification objective lens collimator lens</td>
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<td>$m_{CA}$</td>
<td>Central aperture radial modulation</td>
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<tr>
<td>$m_r$</td>
<td>Magnification pre-collimator</td>
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<tr>
<td>$m_{pp}$</td>
<td>Push-pull radial modulation</td>
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<td>$m_s$</td>
<td>Magnification collimator lens servo lens</td>
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<td>$m_d$</td>
<td>Magnification sensor lens for detector</td>
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<td>$MTF_{CA}$</td>
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<td>Modulation transfer function for push-pull detection</td>
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<td>$m_r$</td>
<td>Magnification satellites without sensor lens in $y-z$-plane</td>
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<tr>
<td>$m_s$</td>
<td>Magnification beamshaper in the $\theta_r$ direction</td>
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<td>$m_{pp}$</td>
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<td>Number of steps of a stepped grating structure</td>
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<td>$N_A$</td>
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<td>$N_{cD}$</td>
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<td>$N_{cD,D}$</td>
<td>Numerical aperture collimator lens DVD</td>
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<td>$N_A$</td>
<td>Numerical aperture of the divergent beam towards the objective lens on case the finite conjugate compatibility solution</td>
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<td>Numerical aperture servo lens</td>
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<tr>
<td>$n_{c}$</td>
<td>Refractive index cover layer disk</td>
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<td>$n_{d}$</td>
<td>Refractive index dye layer recordable disk</td>
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<td>$n_{g}$</td>
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<td>Refractive index beamshaper in the</td>
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<td>$n_{i}$</td>
<td>Refractive index of a material at $\lambda_i$</td>
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<td>Refractive index of a lens</td>
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<td>$n_{p}$</td>
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<td>Refractive index servo lens</td>
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<tr>
<td>$O$</td>
<td>Distance between cylinder lens and undisturbed focus</td>
<td>mm</td>
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<td>$O_p$</td>
<td>Distance cylinder lens and undisturbed focus including shift of the plate</td>
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<td>Period disk reflection function along the tracks normalized by $2\pi/NA$</td>
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<tr>
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<td>$p_i$</td>
<td>Pitch of a grating with index $i$</td>
<td>$\mu m$</td>
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<td>$P_{i,IV}$</td>
<td>Function proportional to the power in a detector segment</td>
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<td>$p_i$</td>
<td>Pit length normalized by $\lambda/NA$</td>
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<td>$PP$</td>
<td>Push-pull signal</td>
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<tr>
<td>$PP_{A,B,C}$</td>
<td>Push-pull signal of spot A, B or C</td>
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<td>$P_{PP}$</td>
<td>Function proportional to the power of the push-pull signal</td>
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<tr>
<td>$P_{e}$</td>
<td>Write power in spot on disk</td>
<td>mW</td>
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<tr>
<td>$q$</td>
<td>Period disk reflection function perpendicular to the tracks or track pitch normalized by $\lambda/NA$</td>
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<tr>
<td>$q'$</td>
<td>Track pitch or period disk reflection function perpendicular to the tracks</td>
<td>$\mu m$</td>
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<tr>
<td>$Q_{hi}$</td>
<td>Spatial frequency of hologram with index $i$</td>
<td>$\mu m^{-1}$</td>
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<td>Track pitch for disk with index $i$</td>
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<td>$q_{t}$</td>
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<td>$R$</td>
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<td>Normalized pupil radius or Fourier transform of the reflection function of the disk</td>
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<td>$r_{dp}$</td>
<td>Distance point in the pupil to point in the observation plane</td>
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<td>$r_{d}$</td>
<td>Vector point in the pupil to point in the observation plane</td>
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<td>$R_{act}$</td>
<td>Resistance actuator coil</td>
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<td>Radius of the tracks on disk</td>
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<td>Amplitude and phase of the diffracted orders of the disk</td>
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<td>$s$</td>
<td>Distance main spot to the satellite spots on disk</td>
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<td>$s'$</td>
<td>Image height virtual satellite spot generated by three spots grating</td>
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<tr>
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<td>$S_{p}$</td>
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<td>$T$</td>
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<td>$u$</td>
<td>Coordinate in disk plane normalized by $\lambda/NA$</td>
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<td>Position in the disk plane normalized by $\lambda/NA$</td>
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<td>$v$</td>
<td>Coordinate in disk plane normalized by $\lambda/NA$</td>
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<td>Position in the disk plane normalized by $\lambda/NA$</td>
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<td>Linear velocity of the disk during recording</td>
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<td>RMS value of coma generated by a plane parallel plate</td>
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<td>Aberration coefficient with orientation angle with azimuth at $45^\circ$</td>
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<td>Aberration coefficient with orientation angle with azimuth at $90^\circ$</td>
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<td>Distance of the satellites with respect to the track followed by the main spot</td>
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<td>$x_{so}$</td>
<td>Coordinate in the observation plane</td>
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<td>$x_{ol}$</td>
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<td>$x_{obs}$</td>
<td>Actuator stroke</td>
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<tr>
<td>$x_{dc}$</td>
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<tr>
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<tr>
<td>$z_{d}$</td>
<td>Distance second focal line and circle of least confusion without sensor lens</td>
<td></td>
</tr>
<tr>
<td>$\phi$</td>
<td>Focus shift on the disk</td>
<td>mm</td>
</tr>
<tr>
<td>$Z_{r}$</td>
<td>Zernike polynomials in polar coordinates</td>
<td></td>
</tr>
<tr>
<td>$\alpha$</td>
<td>Half cone angle of the focused beam towards the disk</td>
<td>$\circ$</td>
</tr>
<tr>
<td>$\alpha_{pl}$</td>
<td>Angle of the plane parallel plate with the optical axis</td>
<td>$\circ$</td>
</tr>
<tr>
<td>$\alpha_{s}$</td>
<td>Angle satellite beams generated by three spots grating</td>
<td>$\circ$</td>
</tr>
<tr>
<td>$\alpha_{g}$</td>
<td>Angle satellite beams between collimator and objective lens</td>
<td>$\circ$</td>
</tr>
<tr>
<td>Symbol</td>
<td>Name</td>
<td>Unit</td>
</tr>
<tr>
<td>--------</td>
<td>----------------------------------------------------------------------</td>
<td>------</td>
</tr>
<tr>
<td>$\beta$</td>
<td>Angle of the laser far field distribution with respect to the tracks</td>
<td>°</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>Ratio of the zero and first diffractive order of a grating</td>
<td></td>
</tr>
<tr>
<td>$\delta_{x}$</td>
<td>Displacement spot on detector due to actuator stroke</td>
<td>$\mu m$</td>
</tr>
<tr>
<td>$\delta_{x_{1}}$</td>
<td>Displacement spot on detector due to actuator stroke without sensor lens</td>
<td></td>
</tr>
<tr>
<td>$\delta_{x_{90}}$</td>
<td>Component displacement spot on detector parallel to the first focal line due to actuator stroke without sensor lens</td>
<td>$\mu m$</td>
</tr>
<tr>
<td>$\delta_{x_{900}}$</td>
<td>Component displacement spot on detector perpendicular to the first focal line due to actuator stroke without sensor lens</td>
<td>$\mu m$</td>
</tr>
<tr>
<td>$\Delta_{0}$</td>
<td>Offset wave front satellite beam to the collimator</td>
<td>mm</td>
</tr>
<tr>
<td>$\Delta D$</td>
<td>Difference in cover layer thickness between disk types</td>
<td>mm</td>
</tr>
<tr>
<td>$\Delta d$</td>
<td>Extension by arbitrary optical component</td>
<td>mm</td>
</tr>
<tr>
<td>$\Delta e$</td>
<td>Distance emitting point of a dual wavelength laser</td>
<td>mm</td>
</tr>
<tr>
<td>$\Delta f_{1}$</td>
<td>Distance focal lines generated by cylinder lens</td>
<td>mm</td>
</tr>
<tr>
<td>$\Delta f_{2}$</td>
<td>Distance focal lines on the detector</td>
<td>mm</td>
</tr>
<tr>
<td>$\Delta f_{p}$</td>
<td>Distance focal lines generated by plane parallel plate</td>
<td>mm</td>
</tr>
<tr>
<td>$\Delta f_{s}$</td>
<td>Distance focal lines without sensor lens</td>
<td>mm</td>
</tr>
<tr>
<td>$\Delta$</td>
<td>Shift satellite beams in pupil</td>
<td>mm</td>
</tr>
<tr>
<td>$\Delta h$</td>
<td>Mechanical height of written effect on a disk</td>
<td>mm</td>
</tr>
<tr>
<td>$\Delta x_{0}$</td>
<td>Error in distance of the satellites with respect to the track followed by the main spot</td>
<td>$\mu m$</td>
</tr>
<tr>
<td>$\Delta y_{0}$</td>
<td>Error of the course of the objective lens for three spots radial tracking</td>
<td>$\mu m$</td>
</tr>
<tr>
<td>$\Delta y$</td>
<td>Decentering maximum Gaussian laser beam normalized to the pupil radius in the y direction</td>
<td>°</td>
</tr>
<tr>
<td>$\Delta T$</td>
<td>Temperature difference</td>
<td>K</td>
</tr>
<tr>
<td>$\Delta W_{x}$</td>
<td>Difference in aberration value</td>
<td></td>
</tr>
<tr>
<td>$\Delta W_{y}$</td>
<td>Decentering maximum Gaussian laser beam normalized to the pupil radius in the x direction</td>
<td>°</td>
</tr>
<tr>
<td>$\Delta z$</td>
<td>S-curve peak to peak</td>
<td>$\mu m$</td>
</tr>
<tr>
<td>$\Delta z_{1}$</td>
<td>S-curve peak half 1</td>
<td>$\mu m$</td>
</tr>
<tr>
<td>$\Delta z_{2}$</td>
<td>S-curve peak half 2</td>
<td>$\mu m$</td>
</tr>
<tr>
<td>$\Delta z_{d}$</td>
<td>Defocusing of the spot on the disk</td>
<td>$\mu m$</td>
</tr>
<tr>
<td>$\Delta \theta$</td>
<td>Difference in angle of the three spots</td>
<td>°</td>
</tr>
<tr>
<td>$\Delta \Theta$</td>
<td>Error in position in control loop</td>
<td>mm</td>
</tr>
<tr>
<td>$\eta_{\text{obs}}$</td>
<td>Scale factor between of pupil coordinates $x_{a}$ and $x_{b}$</td>
<td>mm</td>
</tr>
<tr>
<td>$\eta_{x}$</td>
<td>Lateral shift servo lens</td>
<td>mm</td>
</tr>
<tr>
<td>$\theta$</td>
<td>Azimuth in the disk plane or on an optical surface</td>
<td>°</td>
</tr>
<tr>
<td>$\theta_{i}$</td>
<td>Angle of the three spots with a track of a disk type with index $i$</td>
<td>°</td>
</tr>
<tr>
<td>$\theta_{p}$</td>
<td>Phase depth of the pit</td>
<td>°</td>
</tr>
<tr>
<td>$\theta_{1}$</td>
<td>Orientation with respect to the azimuth of a surface</td>
<td>°</td>
</tr>
<tr>
<td>$\theta_{2}$</td>
<td>Angle associated with the propagation vector of the wave front relevant for a non-periodical phase structure on a curved surface</td>
<td>°</td>
</tr>
<tr>
<td>$\theta_{x}$</td>
<td>Far field Gaussian laser perpendicular to the stripe (FWHM)</td>
<td>°</td>
</tr>
<tr>
<td>$\theta_{z}$</td>
<td>Far field Gaussian laser parallel to the stripe (FWHM)</td>
<td>°</td>
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</table>

### Symbol Table

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Name</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\lambda$</td>
<td>Wavelength</td>
<td>nm</td>
</tr>
<tr>
<td>$\lambda_{i}$</td>
<td>Wavelength with index $i$</td>
<td>nm</td>
</tr>
<tr>
<td>$\nu$</td>
<td>Image distance from the pupil to the observation plane</td>
<td>mm</td>
</tr>
<tr>
<td>$\nu_{i}$</td>
<td>Image distance from the pupil to the observation plane index $i$</td>
<td>mm</td>
</tr>
<tr>
<td>$\xi$</td>
<td>Decentering spot on detector</td>
<td>mm</td>
</tr>
<tr>
<td>$\xi_{p}$</td>
<td>Decentering of the objective lens normalized by $\lambda/NA$</td>
<td>mm</td>
</tr>
<tr>
<td>$\xi_{0}$</td>
<td>Wavelength with index $i$ nm</td>
<td></td>
</tr>
<tr>
<td>$\phi$</td>
<td>Optical path difference introduced step $i$ of a structure</td>
<td>$\mu m$</td>
</tr>
<tr>
<td>$\rho$</td>
<td>Radius in disk plane normalized by $\lambda/NA$</td>
<td>mm</td>
</tr>
<tr>
<td>$\rho_{0}$</td>
<td>Radius radial beam on cylinder lens</td>
<td>mm</td>
</tr>
<tr>
<td>$\rho_{s}$</td>
<td>Sine of the angle of incidence of a ray</td>
<td>°</td>
</tr>
<tr>
<td>$\rho_{r}$</td>
<td>Radius at the rim of a surface</td>
<td>mm</td>
</tr>
<tr>
<td>$\sigma$</td>
<td>Parameter Gaussian laser beam</td>
<td></td>
</tr>
<tr>
<td>$\sigma_{x}$</td>
<td>Parameter Gaussian laser beam in x direction</td>
<td>°</td>
</tr>
<tr>
<td>$\sigma_{y}$</td>
<td>Parameter Gaussian laser beam in y direction</td>
<td>°</td>
</tr>
<tr>
<td>$\sigma_{x_{0}}$</td>
<td>Parameter Gaussian laser beam in the pupil perpendicular to the stripe</td>
<td>°</td>
</tr>
<tr>
<td>$\sigma_{y_{0}}$</td>
<td>Parameter Gaussian laser beam in the pupil parallel to the stripe</td>
<td>°</td>
</tr>
<tr>
<td>$\phi_{p}$</td>
<td>Azimuth in the pupil plane</td>
<td>°</td>
</tr>
<tr>
<td>$\phi_{o}$</td>
<td>Angle of optical axis of a cylinder lens with the desired value</td>
<td>°</td>
</tr>
<tr>
<td>$\phi_{r}$</td>
<td>Angle astigmatism of a plate in comparison with the desired value</td>
<td>°</td>
</tr>
<tr>
<td>$\phi_{s}$</td>
<td>Rotation angle satellite spots</td>
<td>°</td>
</tr>
<tr>
<td>$\phi_{1}$</td>
<td>Orientation with respect to the azimuth for an arbitrary aberration</td>
<td>°</td>
</tr>
<tr>
<td>$\phi_{2}$</td>
<td>Orientation with respect to the azimuth for astigmatism</td>
<td>°</td>
</tr>
<tr>
<td>$\phi_{CD}$</td>
<td>Orientation with respect to the azimuth for coma</td>
<td>°</td>
</tr>
<tr>
<td>$\phi_{l}$</td>
<td>Pupil diameter CD</td>
<td>mm</td>
</tr>
<tr>
<td>$\phi_{h}$</td>
<td>Spot diameter on detector or diameter circle of least confusion on detector</td>
<td>$\mu m$</td>
</tr>
<tr>
<td>$\phi_{D}$</td>
<td>Diameter circle of least confusion without sensor lens</td>
<td>$\mu m$</td>
</tr>
<tr>
<td>$\phi_{D_{V}}$</td>
<td>Diameter circle of least confusion without sensor lens DVD</td>
<td>$\mu m$</td>
</tr>
<tr>
<td>$\Psi$</td>
<td>Phase between zero and first diffractive order of the disk</td>
<td>°</td>
</tr>
<tr>
<td>$\Psi_{b}$</td>
<td>Blaze angle</td>
<td>°</td>
</tr>
<tr>
<td>$\omega$</td>
<td>Angular frequency</td>
<td>Hz</td>
</tr>
</tbody>
</table>
Terminology and abbreviations

Aberration Deviation from the perfect spherical wave front
Actuator Linear Lorentz motor that can move the objective lens in focus and radial direction
Astigmatic focusing Focusing method where an astigmatic spot on the detector is applied
Astigmatism Primary aberration of the wave front that generates two focal lines instead of one focal point
Basic engine of the recorder Part of the recorder that contain the optics, read channel, write channel and the servo channel including motors/actuators
Beam splitter Optical component that splits a laser beam whether or not depending on wavelength or polarization
Blazed grating Grating that boosts one diffractive order by means of a tilted surface
Byte Unit for storage capacity = 8 bits
CAV Constant Angular Velocity (of the disk)
CCD Charge Coupled Device
CD Compact Disc: optical disk generation with capacity of 680 MB for data use and 815 MB in the case of CD-Audio",)
Cd-i Compact Disk interactive
CD-R Compact Disk Recordable
CD-ROM Compact Disc Read Only Memory
CD-RW Compact Disk Rewritable
Central aperture signal Signal detected of the entire pupil from the disk
Circle of least confusion Circle between the two focal lines in case of astigmatism
CLV Constant Linear Velocity (of the disk)
CMOS Complementary Metal Oxide Semiconductor
COC Cyclic Olefin Copolymers: type of plastic
Collimator lens Lens to transfer the divergent laser into a parallel laser beam
Comb/combo player Player with DVD-read and CD-R(W) recording
Cover layer Plastic layer that protects the information layer of the disk
Cylinder lens Lens with cylindrical surface in order to generate the astigmatism on the detector for astigmatic focusing
DC Direct Current
Defocusing Deviated lateral position of the diffraction limited spot with respect to the information layer of the disk
Detector Set of photo diodes to transfer the light power into current or voltage in order to generate the RF signal and other electro optical signals from the disk
Dichroic aperture Color sensitive aperture/stop
Dichroic beamsplitter Color sensitive beamsplitter

Differential push-pull radial tracking Radial tracking method where the push-pull signals of the main spot and satellite spots are applied (same as three spots push-pull)
DOS Differential Oval Spot
DPD/DTD Differential Phase Detection or Time Differential Phase Detection: method for radial tracking using the (1,±1)-orders of the disk
Drive mechanism Mechanism that rotates the disk and moves the optical pickup for the large radial stroke
Dual wavelength laser Laser device with two laser cavities that generate two beams with different wavelength
DVD Digital Versatile Disc: optical disk generation with capacity a of 4.7 GB single layer and 8.5 GB dual layer
DVD+R Type of recordable DVD
DVD+R DL, DVD+9 Type of rewritable DVD
DVD+RW Type of recordable DVD
DVD-R Type of rewritable DVD
DVD-RAM Type of rewritable DVD
DVD-RW DVD Random Access Memory: type of rewritable DVD
EFM Eight to Fourteen Modulation: type of coding
FiFO First In First Out: buffer memory
Focal line Focused line instead of focused point due to by astigmatism
Focus error signal Signal generated by the optical pickup, which is a measure for the amount of defocusing on disk
Focus S-curve Shape of the signal generated by the optical pickup, which is a measure for the amount of defocusing on disk
Detector that measures the power of the laser
Focus method where pupil obscuration is applied
Foucault grating for Foucault focusing
FWHM Grating
HD-DVD Optical component with a diffractive structure
Holographic pre-collimator High Density DVD: optical disk with capacity a of 15 to 20 GB single layer using a blue laser
Pre-collimator that consist of two holograms that can be used for a dual wavelength laser
Integrated Circuit
IEC International Electro-technical Commission
IEC Timing error of the RF signal
IF Light Amplification by Stimulated Emission of Radiation
IC Laser Detector Grating Unit
IC Light Emitting Diode
IC Composition of optical components, lasers and detectors that generates the diffraction-limited light spot on the disk and the RF signal, servo signals and other electro-optical signals
MB Mega Byte = 10^6 Bytes, unit for storage capacity
MB Mega byte = 10^6 bits
MD Mini Disk: small MO-disk with compressed audio
MO-disk Magneto-Optical disk: disk with magnetic domains written out with the Kerr effect
Spherical aberration
Primary aberration of the wave front, where the marginal rays cross the optical axis at a different position than the paraxial rays.

s-polarization
s means “senkrecht” (German): E vector perpendicular to the plane of incidence.

Spot size detection
Three spots central aperture radial tracking
Three spots grating
Three spots push-pull radial tracking

Remote Sensing Thermography (TOS)
Transmittance of p-polarization
Transmittance of s-polarization

Track
Spiral on the disk, which is followed by the spot. It can be a sequence of pre-recorded pits or a pre-groove.

Ts
Transmittance of s-polarization

Two color grating
Grating that works for two wavelengths almost independently

USB
Universal Serial Bus

UV
Ultra Violet

VCD
Video-CD: CD with compressed digital video

VLP
Video Long Play: disk with analog video (used in the past)

WO
Write Once: disk that can be written only once

Wobble
Slightly meandering pre-groove that contains the signals of an empty recordable/rewritable disk

Write channel
Part of the basic engine of the recorder that converts the raw data to be stored on the disk into laser pulses

*) The origin of the name “byte” is the expression “by eight”. A byte is generally 8 bits. There is confusion about the capacity of kilobyte. It cannot be 1000 bytes (kB) or 1024 bytes (KB). This is also the case for megabyte (MB) that can be 1024² bytes or 1000² bytes or even 1000-1024 bytes (floppy disk). A gigabyte (GB) can be 1000³ bytes or 1024³ bytes. The IEC has decided in 1998 to use the factors of 1000. Therefore, for the capacity of an optical disk in this thesis, 1 MB is considered as 10² bytes and 1 GB as 10³ bytes.

**) A 74-minutes CD-Audio disk has a capacity of 0.815 MB. However, a CD data disk (for instance, CD-ROM) contains a storage capacity of 0.680 MB typically due to the used capacity, which is needed for the extra error correction.
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Appendix A:

An overview of the CD and DVD standards

The specifications of the disk types are described in the so-called disk standards. Relations between the various CD and DVD disk standards are summarized in two diagrams.

A schematic overview of the Compact Disc standards is shown in Fig. A.1 (see also [7]). The various disk specifications are described in books indicated with a color. The first CD standard was CD Digital Audio (CD-DA). The required disk properties are described in the "Red Book". The name "Red Book" arose, because the draft papers of the CD-Audio standard were put in a red colored portfolio. So, in their communication, Philips and Sony used the name "red book" [10].

Fig. A.1: The relation between CD standards. The standards are written in several books. Some of them are identified with a color name.
Next to CD-ROM, which was described in the yellow book, CD-i ("Green Book") was launched. The CD-ROM XA (eXtended Architecture) was generated in order to play these applications on a regular PC. The bridge disk was defined for Photo-CD and Video-CD ("White Book"). CD-extra or enhanced music CD ("Blue book") is set to combine a CD-Audio and a CD-ROM XA disk. DDCD (Double Density CD) is a CD disk with a factor of two more capacity than a normal CD (to be readout with $\lambda = 780$ nm read $N_A = 0.5$), which has almost disappeared. Super Audio CD is essentially a CD/DVD disk (see Section 2.2.2.).

CD-MO (magneto-optical CD) was around 1988 the candidate for a writable CD system. The disk format was equal to CD read-only, however, the pits were written in magnetic domains. The writable CD-s are described in the orange book; part 1 for MO, part 2 for CD-R and part 3 for CD-RW. CD-R and CD-MO started at 1x speed ("x" refers to the reference velocity $v_{ref}$). The CD-R was set as a standard in 1990. For CD-R a 2x and 4x version were added in 1994 and 1998, respectively. Real high-speed is described in the CDR multi-speed standard (Orange Book part 2, volume 2). CD-RW started with 2x. The 4x speed was added in 1998 (1-4x). High-speed upgrades of CD-RW are specified in the high-speed standard (4-10x), the ultra speed standard (8-24x) and the ultra speed+ standard (8-32x).

Next to Philips and Sony, other companies were also involved in the standards. The Photo-CD standard was set together with the Eastman Kodak Company. Video-CD was set together with JVC and Matsushita. The companies Taiyo Yuden, Philips and Sony set the CD-R standard.

An overview of the most relevant DVD standards is given in Fig. A.2. DVD was jointly developed by 10 companies: Hitachi, JVC, Matsushita, Mitsubishi, Philips, Pioneer, Sony, Thomson, Time Warner and Toshiba. The DVD standard started with DVD-video and DVD-ROM. DVD-RW is derived from DVD-R. DVD+RW and DVD+R started independently. DVD+R(W) was launched by 8 companies: Dell, HP, Mitsubishi, Philips, Ricoh, Sony, Thomson and Yamaha. Analogously to CD, speed-upgrades for recordable and rewritable disk are also introduced. For instance, for DVD+RW with a capacity of 4.7GB, the 2.4x standard was introduced in 2000, the 4x standard in 2002 and the 8x standard in 2005.

Fig. A.2: The most important DVD standards and their relationships.
Appendix B:

The focus s-curve calculation

In order to calculate the focus S-curve on the disk the two focal lines on the detector will be imaged on the disk. In this calculation we will “look for” the object distance for image on the detector (in focus the circle of least confusion) on the detector in the y-z-plane and in the x-z-plane (Chapter 4).

The position of the spherical sensor lens with respect to the collimator is defined as:

\[ l_n = f_c + v_n. \]  
(B.1)

The object distance in the diode plane of the spherical sensor lens is:

\[ v_n = \frac{f_b}{b_n - f_s}. \]  
(B.2)

For the x-z-plane the image in the collimator is:

\[ b_{cy} = l_n - v_n, \]  
(B.3)

which results in an object distance for the collimator lens \( v_{cy} \):

\[ v_{cy} = \frac{f_c b_{cy}}{b_{cy} - f_c}, \]  
(B.4)

and an image distance \( b_{oy} \) for the objective lens:

\[ b_{oy} = l_c - v_{cy}. \]  
(B.5)

The object distance for the objective lens is

\[ v_{oy} = \frac{f_o b_{oy}}{b_{oy} - f_o}. \]  
(B.6)

The half-length of the S-curve on disk is now:

\[ \Delta z_1 = \frac{v_{oy} - f_o}{2}. \]  
(B.7)
The factor of 2 is due to the mirror function of the disk. Now, we can do the same in the y-z-plane. In this situation the power of the cylinder lens is incorporated.

\[ V_n \text{ and } L_n \text{ are the same as in the x-z-plane.} \]

The image distance for the cylinder lens is:

\[ b_{\text{cyl}} = d_{\text{a}} - V_{\text{cyl}} , \quad \text{(B.8)} \]

with \( d_{\text{a}} \) is the optical thickness of the servo lens:

\[ d_{\text{a}} = \frac{d_{\text{s}}}{n_s} \quad \text{(B.9)} \]

The object distance for the cylinder lens \( V_{\text{cyl}} \) is:

\[ V_{\text{cyl}} = \frac{f_{\text{s}} b_{\text{cyl}}}{b_{\text{cyl}} - f_{\text{cyl}}} \quad \text{(B.10)} \]

The image distance for the collimator lens is:

\[ b_{\text{c}} = f_{\text{c}} + V_{\text{c}} - d_{\text{a}} - V_{\text{cyl}} . \quad \text{(B.11)} \]

The object distance in the collimator lens is influenced by the plane parallel plate:

\[ V_{\text{c}} = \frac{f_{\text{c}} (b_{\text{c}} - A'_{\text{p}})}{b_{\text{c}} - f_{\text{c}} - A'_{\text{p}}} . \quad \text{(B.12)} \]

The image distance for the objective lens is:

\[ b_{\text{m}} = -V_{\text{m}} + t_{\text{e}} , \quad \text{(B.13)} \]

and its object distance:

\[ V_{\text{m}} = \frac{f_{\text{m}} b_{\text{m}}}{b_{\text{m}} - f_{\text{m}}} . \quad \text{(B.14)} \]

The other half of the S-curve is represented as:

\[ \Delta z_2 = \frac{V_{\text{m}} - f_{\text{m}}}{2} . \quad \text{(B.15)} \]

The total S-curve length is the combination of Equation (B.7) and (B.15):

\[ \Delta x = \Delta z_1 + \Delta z_2 . \quad \text{(B.16)} \]

---

**Appendix C:**

**Calculation of the pitch of the holograms**

In order to calculate the pitch of the holograms the grating formula is used [37].

\[ \sin(\theta_1) - \sin(\theta_2) = m \frac{\lambda}{P_{\text{w}}} , \quad \text{(C.1)} \]

**Fig. C.1:**

Definition of the angles.

\[ m \text{ is the diffracted order. The definition of the angles is shown in Fig. C.1.} \]

With Snell's law:

\[ \sin(\theta_1) = n \sin(\theta_2) , \quad \text{(C.2)} \]

Equation (C.2) leads to:

\[ n \sin(\theta_1) - \sin(\theta_2) = m \frac{\lambda}{P_{\text{w}}} . \quad \text{(C.3)} \]

**Fig. C.2:**

The element, the laser sources, the virtual image and the relevant rays.
A ray can be traced through both holograms as shown fig C.2.

For \( \varepsilon \) we obtain:

\[
\varepsilon = d\sin(\theta_0). \tag{C.4}
\]

The virtual images of lasers 1 and laser 2 must coincide and this leads to:

\[
\left(\frac{d}{n} + g_s\right)\sin(\theta_2) = g_s \sin(\theta_0) + A_\varepsilon + \varepsilon, \tag{C.5}
\]

so:

\[
\varepsilon = -A_\varepsilon - g_s \sin(\theta_0) + \left(g_s + \frac{d}{n}\right)\sin(\theta_0). \tag{C.6}
\]

For hologram 1, (C.3) yields when \( m = -1 \) with pitch \( p_{h1} \):

\[
\frac{n\varepsilon}{d_s} - \sin(\theta_0) = -\frac{\lambda}{p_{h1}}. \tag{C.7}
\]

The combination of (C.6) and (C.7) yields:

\[
\frac{n}{d_s} \left(-A_\varepsilon - g_s \cdot \sin(\theta_0) + \left(g_s + \frac{d}{n}\right) \cdot \sin(\theta_0)\right) - \sin(\theta_0) = -\frac{\lambda}{p_{h1}}, \tag{C.8}
\]

which results in:

\[
p_{h1} = \frac{-\lambda d_s}{A_n + (g_s n + d_1) \sin(\theta_0) - \sin(\theta_2)}. \tag{C.9}
\]

With \( p_3 = \sin(\theta_0) \), the expression for the pitch on hologram 1 becomes:

\[
p_{h1} = \frac{-\lambda d_s}{A_n + p_3(g_s n + d_1) \left(1 - \frac{NA_{c,0}}{NA_p}\right)}. \tag{C.10}
\]

For hologram 2 with pitch \( p_{h2} \), (C.3) yields:

\[
\sin(\theta_2) - n\sin(\theta_1) = \frac{m\lambda}{p_{h2}}. \tag{C.11}
\]

For \( m = -1 \):

\[
p_{h2} = \frac{-\lambda}{\sin(\theta_1) - n\sin(\theta_1)}. \tag{C.12}
\]

With (C.4) and (C.6), (C.12) yields the following expression:

\[
p_{h2} = \frac{-\lambda}{\sin(\theta_1) - \frac{n}{d_s} \left(-A_\varepsilon - g_s \sin(\theta_0) + \left(g_s + \frac{d}{n}\right) \sin(\theta_0)\right)}. \tag{C.13}
\]

or:

\[
p_{h2} = \frac{-\lambda d_s}{A_n + g_s n \left(\sin(\theta_0) - \sin(\theta_1)\right)}. \tag{C.14}
\]

As a result, the pitch of hologram 2 is given by:

\[
p_{h2} = \frac{-\lambda d_s}{A_n + g_s n \left(1 - \frac{NA_{c,0}}{NA_p}\right)}. \tag{C.15}
\]
Summary

This thesis deals with the design of several generations of light paths for DVD video recorders and data drives, in which a number of new principles have been applied.

DVD stands for "Digital Versatile Disc". It is the current generation optical disk with a storage capacity of 4.7 or 8.5 GB. The history of the optical disk started in the late nineteen-sixties and lead to the introduction of the Video Long Play disk (VLP) in 1978 and the Compact Disc (CD) in 1983. The CD was later broadly accepted as audio carrier and storage medium for 680 MB of computer data. The DVD with 7 to 13 times more storage capacity than the CD was introduced in 1995. The DVD is being used for digital video or audio recording and data storage. Recently the capacity of an optical disk is even more increased towards 25 or 50 GB with the introduction of the next generation: "Blu-ray Disc".

An overview is given of the most important optical principles applied for reading or writing a disk. In addition to this, the other parts of the system of a recorder are described briefly. The light path is the composition of lasers, detectors, lenses and other optical components that generates the diffraction-limited spot on the disk. Additionally, the information from the disk is converted into several electro-optical signals.

A DVD recorder should be suitable for CD reading or recording as well. Furthermore, for computer drives, the efficiency of the light path towards to disk and the detector should be as high as possible in order to be able to read or write the disk as fast as possible. Other constraints are a low cost price and a high reliability. Within this framework several light paths for DVD recorders were designed, in which a number of new principles have been applied.

The parameters of a light path with astigmatic focusing and three spots radial tracking are described with a geometrical model, which is used during the light path design. With this model relations between the light path parameters have been found.

The multi-disciplinary design process of a light path is described. The relevant aspects partially have a technical origin like e.g. optics, electronics, mechanics and manufacturing issues. However, also more general aspects play a role like product cost, market trends, development time and moment of product introduction.

Designs have been made for dual and single detector light paths. An important disadvantage of the single detector light path is the coma due to the stroke of the objective lens. This stroke is necessary for radial tracking. This is solved by adding spherical aberration to the divergent beam between the collimator and the objective lens. The light path is designed in two layers: one for CD and one for DVD.

The efficiency of the single detector light path for CD is maximized by application of a partially polarizing plate beamsplitter and a plastic pre-collimator. The function of the pre-collimator is to increase the coupling efficiency of the laser. The disadvantage of
focus drift due to temperature change is limited by using a short focal length of the pre-collimator. An alternative could be the implementation of a diffractive structure on this lens. The unwanted coma of the plate beamsplitter is compensated by applying a corrective surface, which is integrated with the cylinder lens surface. This cylindrical surface is used for the generation of astigmatism which is needed for the astigmatic focusing method. The orientation of the astigmatism of the plate beamsplitter can also be rotated in the proper direction with this surface. The efficiency for DVD is maximized by integration of a pre-collimator in the beamshaper. A PBS (polarizing beamsplitter) is applied by orientation of the laser and the beamshaper at 45° with the track on the disk.

In next generation light paths, a dual wavelength laser can be used. This laser generates two laser beams just next to each other with two different wavelengths: an infrared one for CD and a red one for DVD. Application of a dual wavelength laser leads to reduction of components and adjustments in the light path. In order to implement a single detector light path, a special grating can be used in order to join the two beams on the detector. Three spots radial tracking for CD and DVD is possible with a two-color grating, which works for CD and DVD almost independently, while both beam pass this component. A pre-collimator combined with a function to join the two beams is designed. This component consists of two holographic surfaces. The transmission for CD and DVD is optimized by using a stepped and blazed grating structure.

Typical signals of a writable DVD disk have been evaluated in terms of optical tolerances. The addresses and other information needed on a DVD+R(W) are stored on the disk by means of a slightly wobbling track: the "wobble". DVD-R(W) disks contain, in addition to the wobble, pits between the tracks: the "pre-pits". The written pits disturb the wobble and the pre-pit information. In order to understand these effects, simulations have been carried out and a model has been set up.

The written pits disturb the wobble and the pre-pit information. In order to understand these effects, simulations have been carried out and a model has been set up. It appears that particular aberrations considerably amplify the effect of the written pits. The wobble appears most sensitive for astigmatism at 45° with the track on the disk, while the pre-pit signal appears most sensitive for astigmatism perpendicular to or parallel with the track on the disk.

The designed dual detector light path is applied in the first generation DVD recorder of Philips. The design of the single detector light path is applied in the current Philips data drives and video recorders.

Samenvatting

Dit proefontwerp gaat over het ontwerp van verschillende generaties lichtwegen voor DVD-videorecorders en DVD data drives, waarin een aantal nieuwe principes zijn toegepast.

DVD staat voor “Digital Versatile Disc”, hetgeen betekent: digitale veelzijdige plaat. Dit is de huidige optische plaat met een opslagcapaciteit van 4.7 of 8.5 GB. De geschiedenis van de optische plaat begon eind jaren zestig en monde uit in de introductie van de beeldplaat (VLP: Video Long Play) in 1978 en de Compact Disc (CD) in 1983. De CD werd later algemeen geaccepteerd als geluidsdrager en opslagmedium voor 680 MB aan computer data. In 1995 werd de DVD geïntroduceerd met 7 tot 13 maal meer opslagcapaciteit dan de CD. DVD wordt gebruikt voor digitale video- of geluidsopnames en dataopslag. Recent is de capaciteit van optische platen verder vergroot tot 25 of 50 GB door de introductie van de volgende generatie: "Blu-ray Disc".

Er wordt een overzicht gegeven van de belangrijkste optische principes zoals die worden toegepast bij het uitlezen of beschrijven van de plaat. Daarnaast wordt de rest van het systeem van de recoder kort beschreven. De lichtweg is het samenstel van lasers, detectoren, lenzen en andere optische componenten dat de buigingsbegrensde spot op de plaat genereert waarmee de plaat uitgelezen of beschreven wordt. Daarnaast wordt de informatie afkomstig van de plaat omgezet in verschillende elektro-optische signalen.

Een DVD-recorder moet ook geschikt zijn om een CD te kunnen lezen of schrijven. Verder is het belangrijk voor computerdrives dat de efficiëntie van de lichtweg naar de plaat en de detector toe zo hoog mogelijk is. Dit om de plaat zo snel mogelijk te kunnen beschrijven of uitlezen. Andere randvoorwaarden zijn een lage kostprijs en een hoge betrouwbaarheid. Binnen dit kader zijn verschillende lichtwegen ontworpen voor DVD-recorders, waarin een aantal nieuwe principes toegepast worden.

De parameters van een lichtweg met astigmatische focussering en driespots radiale volging zijn beschreven met een geometrisch model, dat gebruikt is tijdens het lichtwegontwerp. Met dit model zijn relaties gevonden tussen de lichtwegparameters onderling.

Het multidisciplinaire ontwerpproces van een lichtweg is beschreven. De relevante aspecten zijn enerzijds technisch van aard, zoals optiek, elektronica, mechanica en fabricagetechniek, maar anderzijds spelen ook algemener e zaken een rol zoals kosten, markttrends, ontwikkeling en moment van productintroductie.

Er zijn ontwerpen gemaakt van lichtwegen met een dubbele en een enkele detector. Een belangrijk nadeel van de lichtweg met de dubbele detector is de coma die wordt veroorzaakt door de uitslag van de objectief lens die nodig is voor de radiale volging. Dit is opgelost door sferische aberratie toe te voegen aan de divergente bundel tussen de collimator en het objectief. De lichtweg is ontworpen in twee lagen boven elkaar: één voor CD en één voor DVD.
De typische signalen van een beschrijfbare DVD plaat zijn op optische toleranties van de pre-pits het meest gevoelig voor astigmatisme loodrecht of evenwijdig met het oppervlak. Hierdoor worden tevens de twee bundels samengevoegd. De transmissie voor geevalueerd. De adressen en andere benodigde informatie van DVD+R(W) staan door detector mogelijk te maken kan gebruik gemaakt worden van een speciaal raster om de DVD is mogelijk met een tweekleurenraster, dat voor CD en DVD nagenoeg

In een volgende generatie lichtwegen kan gebruik gemaakt worden van een tweegolfenlenzelaar. Deze laser genereert twee laserbundels vlak naast elkaar met twee verschillende golflengtes: een infrarode voor CD en een rode voor DVD. Toepassing van een tweegolfenlenzelaar leidt tot een lichtweg met minder componenten en afregelingen. Om met een tweegolfenlenzelaar een lichtweg met slechts een enkele detector mogelijk te maken kan gebruik gemaakt worden van een speciaal raster om de twee bundels op de detector bij elkaar te voegen. Driespots radiale volging voor CD en DVD is mogelijk met een tweekleuren raster, dat voor CD en DVD nagenoeg onafhankelijk werkt, terwijl beide bundels er wel door heen gaan. Het ontwerp van de pre-collimator bestaat uit een plaat die aan beide zijden is voorzien van een holografisch oppervlak. Hierdoor worden tevens de twee bundels samengevoegd. De transmissie voor CD en DVD is geoptimaliseerd door gebruik te maken van een gestapte rasterstructuur met een blaze.

De typische signalen van een beschrijfbare DVD plaat zijn op optische toleranties geëvalueerd. De adressen en andere benodigde informatie van DVD+R(W) staan door middel van een licht slingerend spoor op de plaat: de "wobble". DVD-R(W) platen hebben daarnaast ook nog putten tussen de sporen: de "pre-pits". De geschreven putten verstoren de informatie opgeslagen in de wobble en de pre-pits. Om deze effecten te begrijpen zijn simulaties gedaan en is er een model gemaakt. Het blijkt dat bepaalde aberraties in de spot deze effecten fors versterken. De wobble blijkt het meest gevoelig voor astigmatisme georiënteerd onder 45° met het spoor op de plaat, terwijl het signaal van de pre-pits het meest gevoelig blijkt voor astigmatisme loodrecht of evenwijdig met het spoor op de plaat.

De ontworpen dubbele detector lichtweg is toegepast in de eerste generatie DVD-recorder van Philips. Het ontwerp van de enkele detector lichtweg wordt toegepast in de huidige Philips DVD data drives en DVD-recorders.

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I want to thank Jack van den Eerenbeemd, Rene Verbeuque, Ronald Drenten, Peter Coops and Joris Vreheen for the cooperation in generating several new ideas and for their allowance to use them in this thesis. I thank Edgar van Gool, Arthur van der Put, Henk 't Lam, Hans Spruit and Richard de Gruyl, who permitted me to publish their measurement results in this thesis. I want to express my appreciation to president Seichiro Katagawa and senior engineer Kouei Hatade of the company Nalux, who jointly developed the beamshaper with integrated pre-collimator with Philips Optical Storage and who permitted me to mention it in this thesis. I am also grateful to Jan Tatosek for his contribution on the market information and his permission to use it in this thesis.

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Peter Jutte was born on December 29\textsuperscript{th}, 1958 in Bergen op Zoom, the Netherlands. In 1978 he obtained his VWO certificate at the John F. Kennedy Atheneum in Dongen. In 1986 he finished his study Applied Physics at the Eindhoven University of Technology, where he obtained his Ir. degree. In 1986 he joined Royal Philips Electronics. Currently he is optical system architect at Philips Optical Storage at the innovation department of the BL-OPU (Business Line Optical Pick-up Unit). Peter Jutte is married and has three children: one daughter of 9 years old and two sons of 5 and 4 years old.
Stellingen

Behorende bij proefontwerp

Light Path Design for Optical Disk Systems

van

Peter Jutte
De coma die bij lichtweg wordt veroorzaakt met de dubbele detector door de radiale uitslag van de objectieflens kan aanzienlijk worden verminderd door sferische aberratie toe te voegen aan de divergente bundel tussen de collimator en het objectief.

Dit proefontwerp, Hoofdstuk 6

Het focusverloop op de plaat veroorzaakt door temperatuurverandering van een plastic pre-collimator is recht evenredig met de brandpuntsafstand. Dit focusverloop kan daarom worden beperkt door gebruik te maken van een korte brandpuntsafstand van de pre-collimator.

Dit proefontwerp, Hoofdstuk 7

Astigmatisme georiënteerd onder $45^\circ$ met het spoor op de plaat is de aberratie die de overspraak tussen het signaal van de putten en het signaal van de slingering van het spoor op een beschrijfbare DVD het meest versterkt.

Dit proefontwerp, Hoofdstuk 9

Gelijke mate van astigmatisme op de detector kan worden opgewekt door een sterke cilinderlens met een korte afstand tot de detector en met zwakke cilinderlens met een lange afstand tot de detector. In het eerste geval is de rotatie van de satellietspots op de detector en de toename van hun onderlinge afstand door de cilinderlens groter dan in het tweede geval. Dit is van belang voor het ontwerp van de detector.

Dit proefontwerp, Hoofdstuk 4

Een wetenschappelijk probleem wordt in een research-omgeving over het algemeen gezien als goed, gewenst, leuk en uitdagend, terwijl een wetenschappelijk probleem in een industriële omgeving ervaren wordt als slecht, ongewenst, vervelend, een risico en iets dat te vermijden is.

Dit proefontwerp, Hoofdstuk 2

Tijd is voor veel mensen kostbaarder dan geld. Tijd is over de landen van deze wereld eerlijker verdeeld dan geld.