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Ultrafast optical signal processing applying electroabsorption modulators as a pulse source and four-wave mixing in semiconductor optical amplifiers as a gating device

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Ultrafast optical signal processing applying
electroabsorption modulators as a pulse source
and
four-wave mixing in semiconductor optical
amplifiers as a gating device

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Master of Science Thesis
carried out from November 2001 to July 2002

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Foreword

The research described in this report is the result of my master thesis project in electrical engineering at the University of Technology in Eindhoven, the Netherlands. The research was carried out at the Advanced Technology labs of the Optical Networks department of the Information and Communication Networks (ICN) business unit of the Siemens AG in Munich, Germany, under the supervision of Dr. Mario Heid. Supervision from the University of Technology in Eindhoven was provided by associate professor Huug de Waardt and professor Djan Khoe. The master thesis project, which was conducted from November 5th 2001 to July 31st 2002, was conducted within the framework of the Information Society Technology project FASHION (IST-2000-28765). This IST project is a collaboration between Siemens, the University of Technology in Eindhoven, and the British Telecom Exact research labs. A brief overview on the contents of the FASHION project is given in section 1.1. In this report many acronyms are used. Each acronym is defined the first time it appears. As a further help, all acronyms are listed in appendix I on page 67 in alphabetical order.
Summary

The research for my thesis was focused on two topics related to creating and demultiplexing an optical time-division multiplexed signal. On each topic a summary is given.

Pulse generation using electroabsorption modulators

The next generation telecommunication systems will most likely be based on optical time-division multiplexing (OTDM). In these systems stable and compact return-to-zero (RZ) pulse sources are required. At this point mode locked fiber lasers (MLFL) are the prevalent pulse source used in the laboratory. The MLFLs produce pulses with a small pulse width and high extinction, but are not stable enough for system applications. In the FASHION project RZ pulse sources with an extinction ratio of more than 30 dB and a pulse width of less than 2 ps are required. In this work the possibility is investigated as to whether an electroabsorption modulator (EAM) could be used as an alternative RZ pulse source to a MLFL in the FASHION project. The EAM is small in size, integratable and very stable in its operation. Although several EAM configurations exist, the two most common setups are considered here: the single and the cascaded EAM configuration.

Using a static characterization method the performance of the EAM was simulated. In these simulations the pulse width and the extinction ratio have been determined as a function of the working parameters. Experiments have been performed with the single EAM configuration. The measurements showed that due to nonlinear effects and a high electrical reflection coefficient the pulses produced by the EAM were longer than simulated. Even though the performance of the cascaded configuration is expected to be significantly better than the performance of the single EAM configuration, in both, the single and the cascaded EAM configuration, the EAM under study is not capable of producing the quality of pulses required in the FASHION project. A possible way to improve the pulse quality is to employ re-amplification and re-shaping regeneration in combination with pulse compression.

It can be concluded that since an EAM is a compact, cost effective and stable device it would be very suitable for system applications. However up to now the pulses the EAM generates do not comply with the demands for a pulse source in a 160-Gbit/s OTDM
Summary

system. If the performance of the EAM improves it will be able to compete with other RZ pulse sources like the MLFL.

Optical time-division channel demultiplexing using four-wave mixing in semiconductor optical amplifiers

In communication systems with a channel data rate of over 100 Gbit/s optical demultiplexers are needed because of speed limitations of the electrical circuit. In the FASHION project a 160-Gbit/s optical time-division multiplexed (OTDM) signal needs to be demultiplexed to base rates of 10 or 40 Gbit/s. So far a Mach-Zehnder interferometer was used for this purpose. In this thesis research, the possibility was investigated to which extend four-wave mixing (FWM) in a semiconductor optical amplifier (SOA) can be used as alternative demultiplexer to a Mach-Zehnder interferometer.

In this paper several demultiplexing techniques are presented and compared. Demultiplexing applying FWM in a SOA is extensively studied. As a result several working conditions are given for realizing a strong FWM signal with a high optical signal-to-noise ratio after demultiplexing. Using these conditions error-free demultiplexing of a 160-Gbit/s OTDM data stream to a base rate of 10 Gbit/s and 40 Gbit/s is demonstrated. Both setups proved to be stable in operation.

FWM in a SOA is due to its simplicity a very stable and reliable technique for demultiplexing an OTDM signal. A big advantage is that the device is very compact which means that it is ideal for integration on a small print. Compared to the Mach-Zehnder interferometer the performance at high base rates is significantly better. However, applying FWM in a SOA, the demultiplexed data channel will still be present in the transmitted channel; hence add-drop multiplexing is not possible.
1 Introduction

In next generation communication systems it is anticipated that optical time-division multiplexing (OTDM) will be a key technology to cope with the increasing demand for transmission capacity. The OTDM technique is the main topic of the FASHION project. The research for my thesis took place within the framework of this project.

1.1 The FASHION project

'FASHION' is the abbreviation for 'ultraFast All-optical Switching for HIgh speed OTDM Networking'. The FASHION project is an Information Society Technology project (number: IST-2000-28765). It is a collaboration between Siemens, the University of Technology in Eindhoven, and British Telecom Exact. In the FASHION project the general objective is to set up a high-speed flexible optical network. In this network single-channel data rates of 160 Gbit/s and higher are to be realized by using optical time-division multiplexing (OTDM), exceeding the electrical time domain multiplexing possibilities to 40 or 80 Gbit/s. In the first stage of the project a 160-Gbit/s point to point connection will be established. The second step is to realize add and drop functionalities and thereby realizing an optical OTDM network.

1.2 Research objectives

My master thesis describes two research topics related to the FASHION project:

1. Pulse generation using electrical absorption modulators (EAMs)

In today's telecommunication net non-return-to-zero (NRZ) pulses are much more commonly used than RZ pulses. In the FASHION project an OTDM network will be realized. Since an OTDM network requires RZ pulses, a good and stable RZ pulse source is needed. The RZ pulse source that is mostly used at this moment is the mode locked fiber laser (MLFL) [28]. Although the MLFL produces very short pulses (~1 ps) at very high extinction ratio (~70 dB), the device cannot be used in system applications due to its sensitivity to temperature changes, inability to operate at all frequencies and its bulky size. Since stability and integratability are crucial factors for implementing a pulse source in system applications, a stable and small (in size) alternative RZ pulse source has to be found. In this research the possibilities for using an EAM as a pulse source are considered. The EAM is very small in size, works at all frequencies and also does not need special alignment. Another big advantage of the EAM is that it is a
Chapter 1. Introduction

relatively cheap device (compared to the MLFL). Over the last few years EAMs proved to be capable of producing high quality pulses; pulses with pulse widths of 1.8 ps and extinction ratios of to 35 dB [24], [27]. The goal of this research is to create an EAM pulse generator that generates pulses with an extinction ratio of at least 30 dB and pulse widths of 2 ps or less. These are the minimum requirements for a pulse source to be used in the FASHION project.

2. Optical time-division channel demultiplexing using four-wave mixing (FWM) in semiconductor optical amplifiers (SOAs)

In the FASHION project demultiplexing of an OTDM signal is one of the main issues that need to be realized. Several OTDM demultiplexing techniques have been reported so far [23], [30]. Up to now in the FASHION project the Mach Zehnder interferometer is used as demultiplexer. In this research, the possibility is examined as to whether four-wave mixing (FWM) in a SOA is a good alternative demultiplexer to a Mach-Zehnder interferometer. For system applications semiconductor optical amplifier (SOA) based switches are particularly promising because they feature superior stability and low switching energies. Using FWM in SOAs demultiplexing up to 200 Gbit/s (32 x 6.3 Gbit/s) has been reported by Morioka et al [26]. The highest base rate reported until now is 20 Gbit/s [29]. The objective of this research is to first obtain similar results using FWM by demultiplexing a 160-Gbit/s data stream into 16 x 10 Gbit/s. Thereafter the 160-Gbit/s signal will be demultiplexed into 4 x 40 Gbit/s.

This report addresses the topics 'Pulse generation using electrical absorption modulators' and 'optical time-division channel demultiplexing using four-wave mixing in SOAs' separately, and thus is separated into two parts:

The first part deals with the topic 'pulse generation using electrical absorption modulators'. In chapter two the operational principle of the EAM is described. Chapter three explains the principle of generating pulses using an EAM and gives simulational and experimental results of pulse generation at 40 GHz. In chapter four the first research subject is concluded.

In the second part of the report, the second topic 'optical time-division channel demultiplexing using four-wave mixing in SOAs' is discussed. In chapter five the concept of OTDM is explained and several demultiplexing methods are described. Chapter six focuses on the origin and ways to optimize FWM in a SOA. Chapter seven then deals with the demultiplexing of a 160-Gbit/s data stream in which the
experimental setup is described and then the experimental results are given. In chapter eight the conclusion of the second part of the research is given.
Section 1: Pulse generation using electroabsorption modulators (EAMs)

2 The electroabsorption modulator

2.1 The operational principle

The device structure of an EAM is comparable to a semiconductor laser as they are both waveguide devices. It uses an electric field to produce optical intensity modulation by shifting the semiconductors absorption edge. Two types of EAMs exist; the bulk and the multiquantum well (MQW) EAM. Compared to bulk EAM, the MQW EAM can absorb the input signal better. The disadvantage however is that the performance depends on the state of polarization and the wavelength of the input signal [34]. Hence, MQW EAMs are in general more suitable for wide bandwidth applications. In the next two subchapters the operation principle of both the bulk and the MQW EAM is described. In section 2.2 the EAM used in the experiments will be discussed.

2.1.1 The bulk EAM

In Figure 2.1 a diagram of a basic GaAlAs bulk EAM structure is given [14]. The optical light is coupled into the waveguide on the left side of the structure and the optical output emerges on the right side. The optical signal is modulated inside the EAM by varying the band-edges of the substrate by applying a negative electrical voltage on the voltage input.

![Diagram of a basic GaAlAs bulk EAM](image)

Figure 2.1: Basic structure of a GaAlAs bulk EAM
Chapter 2. The electroabsorption modulator

The modulation in the bulk EAM is based on the Franz-Keldysh effect. Figure 2.2 (a) and (b) depict the energy band diagram of the semiconductor inside the EAM with (b) and without (a) an external bias voltage applied. In these figures x is the distance from the surface of the semiconductor; the left-hand side of Figure 2.2 (a) and (b) represent the surface of the semiconductor at which a Schottky barrier contact or shallow p-n junction has been attached.

![Energy Band Diagram](image)

**Figure 2.2: Effect of applying a negative bias voltage to the semiconductor in a bulk EAM**

When no voltage is applied (Figure 2.2 a) the conduction and valence band-edges are flat. A photon can only be absorbed if it has enough energy to lift an electron across the band-gap (at arrow a1 and a2). With an external voltage applied (Figure 2.2 b), the bands are bent by the electric field. Outside of the depletion layer, the bands are flat (b2). In the depletion layer, closer to the surface, a transition can also occur when the photon energy is less than the band-gap energy since the applied electric field effectively broadens the states of the conduction band (b1). Therefore there is a finite probability of an electron state in the gap which reduces the effective band-gap and thereby shifts the absorption edge towards longer wavelengths. This wavelength shift affects the absorption coefficient.
Chapter 2. The electroabsorption modulator

2.1.2 The multiquantum well EAM

Similar to the bulk EAM, in a MQW EAM the absorption edge of the semiconductor is also shifted to longer wavelengths by applying an external bias voltage, inducing a strong electric field. The mechanism behind the device is however not based on the Franz-Keldysh effect, but the quantum confined Stark effect (QCSE) [25]. In Figure 2.4 the diagram of a basic MQW EAM structure is shown.
Chapter 2. The electroabsorption modulator

Figure 2.4: Basic structure of a MQW EAM

The basic MQW EAM shown in Figure 2.4 has an InGaAs/InAlAs MQW structure [18]. The MQW, where the optical signal is coupled into, consists of small layers of InAlAs and InGaAs. The well can be n- or p- type (usually has a light doping). The energy band diagram corresponding with the MQW structure, when no external voltage is applied, is given in Figure 2.5 (a). For simplicity the band diagrams are drawn for an intrinsic material (outside the wells). The reduced electron energy (increased hole energy) in the wells produce a local confinement for electrons and holes hence we see that the probability densities of the electrons ($P_{el}$) and holes ($P_{h}$) are high in the wells and low elsewhere.

Figure 2.5: Effect of applying a negative bias to the semiconductor in a MQW EAM

\[ P_{el} \] Probability density of the electrons
\[ P_{h} \] Probability density of the holes
Compared to the MQW, the n and the p layer are perfect conductors; therefore the bias voltage applied to the EAM will be equal to the voltage difference over the quantum well (Figure 2.5 b). Due to the electric field produced by the voltage difference both the conduction and the valence band are tilted inside the quantum well structure. As a result the effective band-gap energy is reduced. The absorption edge is now shifted towards longer wavelengths. For TE-polarized light the absorption mainly originates from excitation of heavy- and light-hole excitons, but for TM polarized light only the light-hole exciton exists [37]. Here the polarization dependency of the EAM originates, since the heavy- and light-hole excitons have different wavelength characteristics [18]. The polarization dependency can be reduced by optimizing the design of the waveguide structure [5], [36]. Due to the electric field the probability functions of the electrons and the holes are tilted in opposite directions as can be seen in Figure 2.5. Therefore, when a bias voltage is applied the overlap of electrons and holes is reduced, which decreases the absorption strength of the EAM. This effect is visible when we look at the absorption coefficient as a function of the wavelength (Figure 2.6); a bias voltage (curve b) decreases the absorption strength.

![Absorption Coefficient vs Wavelength](image.png)

Figure 2.6: The absorption coefficient as a function of the wavelength

Similar to the bulk EAM an effective MQW EAM is realized by choosing the wavelength of the optical signal coupled into the waveguide slightly lower than the band-gap wavelength (with no external voltage applied). The insertion loss of the EAM (the loss in optical power between the input and output when no external voltage is applied) mainly originates out of the coupling loss [17].
2.2 Basic characterization

The EAM used in the experiment is a MQW EAM fabricated by Oki. Oki has two types of EAM generators; one low chirp version and one with a low polarization dependent loss (PDL). Since low chirp is crucial for a pulse source, the low chirp version (type: OM5554W-400B) is used in the research. This EAM is not a commercially available product; therefore the datasheet cannot be given in this report. This EAM is designed to work at a frequency of 40 GHz and has a characteristic insertion loss of 8.7 dB at 1550 nm. The black box diagram of the EAM is given in Figure 2.7.

![Figure 2.7: The black box diagram of the EAM](image)

The absorption the EAM gives as a function of the electrical input ($V_{in_{ee}}$) can be described by the function $EAM$, which is the extinction of the optical output ($P_{out_{opt}}$) signal with respect to the optical input ($P_{in_{opt}}$) signal:

$$Ext[dB] = P_{out_{opt}}[dBm] - P_{in_{opt}}[dBm] = EAM(V_{in_{ee}})$$  \hspace{1cm} (2.1)

This function $EAM$ can be characterized by measuring at all allowed voltages the extinction the EAM gives. By using a wavelength tunable laser also the dependency of optical extinction on wavelength can be investigated. Results of these measurements using the Oki EAM are given in Figure 2.8. This type of measurement represents a static characterization method of the EAM.
This dependency on wavelength is remarkable: Shorter wavelengths (around 1530 nm) have a much steeper edge than longer wavelengths (around 1570 nm). All simulations and results given in this report are performed using a 1530 nm laser.
3 The EAM as a pulse source

3.1 The principle of pulse generation

In Figure 3.1 a basic configuration is given for generating pulses using an EAM.

\[ P_{\text{in, opt}}(t) \rightarrow \text{EAM} \rightarrow P_{\text{out, opt}}(t) \]

In this setup a continuous wave (CW) optical output is generated by the distributed feedback (DFB) laser. This signal is fed into the optical input of the EAM. By now applying a negatively biased sine wave at the electrical input the CW power introduced to the EAM is converted into short pulses. The effect a RF signal has on the extinction characteristics is visualized in Figure 3.2.

\[ \text{Extinction ratio characteristics} \]

\[ \text{Applied voltage} \]

\[ \text{Time} \]

\[ -V_{\text{Bias}} \]

\[ V_{\text{in, el}}(t) \]

\[ V_{\text{syn}}(t) \]

Figure 3.1: The single EAM pulse generator

From equation (2.1) it can be seen that the optical output signal \( P_{\text{out, opt}}(t) \) equals,
Chapter 3. The EAM as a pulse source

\[ P_{\text{out, opt}}(t) = P_{\text{in, opt}}(t) + \text{Ext}(V_{\text{in, el}}(t)) = P_{\text{in, opt}}(t) + EAM(V_{\text{in, el}}(t)). \] (3.1)

The radio frequency (RF) signal is produced by a function generator. The shape of it can be described by the following relation:

\[ V_{\text{synth}}(t) = V_{MD} \cos(\omega t) \] (3.2)

in which \( V_{MD} \) equals the amplitude of the modulation depth and \( \omega \) is the modulation frequency. The sinus wave from the synthesizer \( V_{\text{synth}}(t) \) is negatively biased by a bias tee. This results in the following electrical signal:

\[ V_{\text{in, el}}(t) = V_{\text{synth}}(t) - V_{\text{Bias}} = V_{MD} \cos(\omega t) - V_{\text{Bias}} \] (3.3)

where \(-V_{\text{Bias}}\) is the negative Bias voltage. A sketch of this electrical signal \( V_{\text{in, el}}(t) \) is shown in the Figure 3.2. By introducing the biased output of the synthesizer to the electrical input of the EAM the following optical signal will be detected at the output of the EAM,

\[ P_{\text{out, opt}}(t) = P_{\text{in, opt}} + \text{Ext}(V_{\text{in, el}}(t)) = P_{\text{in, opt}} + EAM(V_{MD} \cos(\omega t) - V_{\text{Bias}}). \] (3.4)

In order to create even smaller pulse widths and higher extinction ratios a second EAM can be added to the first one (Figure 3.3).

Figure 3.3: The configuration with two cascaded EAMs

In this setup the signal is manipulated by two cascaded EAMs. The output \( P_{\text{out, opt}} \) can be conceived as the initial optical input to the first EAM that is subsequently altered by the extinction from the first and the second EAM:

\[ P_{\text{out, opt}}(t) = P_{\text{in, opt}}(t) + EAM(V_{\text{in, el}}(t)) = P_{\text{in, opt}}(t) + EAM(V_{\text{in, el}}(t)) + EAM(V_{\text{in, el}}(t)) \]

(3.5)
Chapter 3. The EAM as a pulse source

The electrical signal $V_{in_{-}el1}$ is the same as the electrical signal $V_{in_{-}el}$ applied in the single EAM configuration:

$$V_{in_{-}el1}(t) = V_{synch}(t) - V_{bias} = V_{MD} \cos(\omega t) - V_{bias}$$

(3.3)

The optical extinction ($Ext_1$) that the first EAM applies on the light signal is therefore the same as in equation (3.3),

$$Ext_1(t) = EAM_1[V_{in_{-}el1}(t)] = EAM_1[V_{MD} \cos(\omega t) - V_{bias}].$$

(3.6)

The electrical signal $V_{in_{-}el2}$ that is applied to the second EAM is phase-shifted by $\tau$,

$$V_{in_{-}el2}(t) = V_{synch}(t - \tau) - V_{bias} = V_{MD} \cos(\omega(t - \tau)) - V_{bias}.$$  

(3.7)

The optical extinction ($Ext_2$) that the second EAM applies on the light can thus be written as,

$$Ext_2(t) = EAM_2[V_{in_{-}el2}(t)] = EAM_2[V_{MD} \cos(\omega(t - \tau)) - V_{bias}].$$

(3.8)

Using a DFB as a constant laser source of $P_{in_{-}opt} = 0 \text{ dBm}$, the optical output power ($P_{out_{-}opt}$) reduces to:

$$P_{out_{-}opt}(t) = Ext_1(t) + Ext_2(t)$$

(3.9)

### 3.2 Characterization of a pulsed signal

There are two main factors that determine the quality of the pulsed signal at the output of the EAM: the extinction ratio and the pulse width

- **The extinction ratio**
  The extinction ratio is defined as the ratio of the peak intensity to the background intensity. The rule of thumb for a good functioning data channel is that an extinction ratio of 30 dB is required. With lower extinction ratios the use of orthogonally polarized waves for the different channels [22] may be a solution, but since the use of both states of polarization waves requires more equipment and is less stable, this type of an experimental setup will be avoided if possible.

- **The pulse width**
  The pulse width is characterized by the full width at half maximum (FWHM) which can be determined from the autocorrelation of the signal (explained in chapter 3.2.1). The goal is to obtain pulses with a pulse width as small as possible. By making use of special lasers with integrated EAMs pulse durations as low as 0.87 ps at 43.5 GHz have already been reported [28].
Chapter 3. The EAM as a pulse source

The following techniques can be used to obtain certain characteristics of the pulses generated. These characteristics give an indication of the quality of the EAM as a pulse generator.

- The autocorrelation to infer the width of the pulses generated
- The optical spectrum to infer the spectral width
- The display of the pulse train
- The electrical spectrum to detect phase noise

The time-bandwidth product can be used as an indication on how short the duration of a pulse could be if dispersion compensation would be applied. From the autocorrelation and the optical spectrum the time-bandwidth product can be computed.

### 3.2.1 Autocorrelation

The (time-) autocorrelation of a signal is the cross correlation of the signal with itself. The autocorrelation is defined as:

\[
R_v(\tau) = \frac{1}{T_0} \int_{-T_0/2}^{T_0/2} v(t)v(t-\tau)dt
\]  

(3.10)

where \(v(t)\) is a periodic signal of period \(T_0\). The autocorrelation can easily be measured with a setup shown in Figure 3.4.

![Figure 3.4: The principle of an autocorrelator](image)

The incoming pulse is split by a beam splitter. The pulse going up to mirror 1 is reflected and represents \(v(t)\). The pulse going to mirror 2 is delayed by \(\tau\), reflected and represents \(v(t-\tau)\). Subsequently the pulses are combined in the beam splitter and send to a second harmonic generator. The generated second harmonic light is detected by a photodiode. By varying \(\tau\) (optical delay) from \(-T_0/2\) to \(T_0/2\) the
autocorrelation function can be recorded. Since the intensity of the second harmonic light is a measure of the temporal pulse overlap of $v(t)$ and $v(t - \tau)$ the full-width half-maximum (FWHM) can be determined. For Gaussian shaped pulses, the width of the pulse can be inferred by dividing the FWHM of the autocorrelation by $\sqrt{2}$. Note that since $v(t)$ is real, the autocorrelation is always symmetric with respect to $\tau$. Therefore the autocorrelation does not give information about the shape of the pulse.

3.2.2 Optical spectrum
From the optical spectrum the spectral bandwidth of the pulse can be determined. The spectral bandwidth is the width at 3 dB beneath the maximum value of the optical spectrum. Also the optical signal-to-noise ratio (OSNR) can be determined. This OSNR is defined as the difference between the maximum of the pulse and the noise power at the same wavelength. The OSNR is given by:

$$OSNR = \frac{P_{Signal}}{P_N}$$

where $P_{Signal}$ is the optical signal power and $P_N$ is the noise power at the signal wavelength at the output of the nonlinear device.

3.2.3 Electrical spectrum
The electrical spectrum is the spectrum of the signal that is received after detection by a photodiode. Or in other words the signal without the carrier wavelength (the wavelength of the laser used). With the electrical spectrum we can investigate the phase noise properties of the pulse train. The phase noise is a good indication for the amount of time-jitter that is present in the signal.

3.2.4 Direct detection with a sampling oscilloscope
The high frequency oscilloscope available cannot receive a trigger with a frequency higher than 18 GHz. In order to be able to visualize the optical 40-GHz output of the EAM on the oscilloscope, a trigger signal with a frequency of 18 GHz or less is needed. This trigger signal can be realized by synchronizing a second frequency generator working at 10 GHz with the 40-GHz frequency generator that feeds the EAM. The 10 GHz frequency generator is fed directly into the oscilloscope as a trigger signal. Since the resolution of the oscilloscope is 50 GHz, the 40-GHz pulse train will be low pass filtered and therefore distorted.

3.2.5 Time-bandwidth product
The time-bandwidth product is the relation between a pulse’s FWHM and the bandwidth of the frequencies necessary to construct the pulse (its bandwidth). For ideal
pulses, the product of the pulse width times its bandwidth has a minimum constant value, which depends on the pulse shape (e.g. Gaussian, Lorentian, etc). This principle tells us that shorter pulses possess a larger bandwidth because the product of the pulse width times its bandwidth remains constant. The time-bandwidth product \( C_p \) is defined as

\[
C_p = \Delta t \Delta \omega
\]  

in which \( \Delta \omega \) is the spectral width of the pulse and \( \Delta t \) equals the pulse width. The spectral width of the pulse can be determined using the optical spectrum (described in 3.2.2). The pulse width can be determined using the autocorrelation (described in 3.2.1). For a certain pulse shape the minimum time-bandwidth product is reached when the pulse is free of chirp. Since an EAM pulse source introduces chirp the time-bandwidth product gives an indication on how much dispersion compensation is needed. Assuming only contribution from linear dispersion, the pulse can be easily compressed using 2R (Re-amplification and Re-shaping) regeneration [24], [27]. Figure 3.5 shows the most common way to perform 2R regeneration.

![EAM Pulse Source](image)

**Figure 3.5: A common 2R regeneration**

The chirp introduced by the EAM can be compensated for using a Dispersion Compensating Fiber (DCF). The DCF shortens the pulses, but due to nonlinear effects also introduces peaks at unwanted frequencies. These frequencies are filtered out by the bandpass filter (BPF) placed right after the DCF. Other 2R regeneration schemes have been proposed [10]. The setups of these schemes are more complicated (the equipment for it is more expensive) and the performance is not significantly better.

### 3.3 The single EAM configuration

In this chapter the single EAM as pulse source will be studied and characterized at 40 GHz. At a wavelength of 1530 nm the measured EAM(\( in_e \)) function (as described in section 3.1) of the OKI EAM will be used. Using this curve the optical wave that will be output can be simulated for a certain input electrical signal. In Figure 3.6 an example is given of such a simulation.
Chapter 3. The EAM as a pulse source

Figure 3.6: Simulation of the single EAM with $V_{\text{Bias}} = -2\text{V}$ and $V_{\text{MD}} = 1\text{V}$ at 40 GHz

The first plot of Figure 3.6 shows an electrical signal with 2 Volts peak-to-peak ($V_{\text{pp}}$) amplitude and a bias of -2V. The measured optical extinction as a function of the applied electrical voltage $\text{Ext}(V_{\text{in}} - e_l)$ is depicted in the second plot. Using the software Matlab the optical extinction as a function of time ($\text{Ext}(t)$) is given in the third plot. The Matlab code used can be found in Appendix II - A. The optical pulse that would be obtained with these settings would have an extinction ratio of 18.6 dB and a pulse width of 6.3 ps.

3.3.1 Determining the optimal parameter values

The single EAM configuration has two parameters that affect its output signal; the modulation depth and the bias voltage of the 40-GHz electrical input signal. As shown in Figure 3.2 the EAM needs to be negatively biased in order to work properly. The optimal bias voltage will also depend on the modulation depth.
Chapter 3. The EAM as a pulse source

Since the EAM can only be operated between its maximum allowed input voltages ($V_{EAM_{\text{max}}}$ and $V_{EAM_{\text{min}}}$), the bias voltage and modulation are constrained by the following relations:

$$V_{EAM_{\text{max}}} \geq \max(V_{MD \cos(\omega t)} - V_{Bias}) = V_{MD} - V_{Bias}$$

and

$$V_{EAM_{\text{min}}} \leq \min(V_{MD \cos(\omega t)} - V_{Bias}) = -V_{MD} - V_{Bias} \quad (3.13)$$

For all the combinations of the bias voltage and the modulation depth we can now compute the pulse width and extinction ratio (as shown in the example in Figure 3.6 for $V_{Bias} = -2$ V and $V_{MD} = 1$ V). The result is plotted in Figure 3.7. The Matlab code for this plot can be found in Appendix II-B. We can see that the bias voltage mainly affects the pulse width and the modulation depth mainly affects the extinction ratio.

![Figure 3.7: The pulse width – extinction ratio relation for different $V_{bias}$ and $V_{MD}$ at 40 GHz](image)

Figure 3.7 also shows that extinction ratios up to 23 dB can be obtained and pulses as short as 4 ps. Hence we can conclude that in the single EAM configuration we cannot comply with the requirements for a pulse source to be used in the FASHION project. In
this project an extinction ratio larger than 30 dB is needed with pulses as short as 2 ps. From Figure 3.7 we see that a minimal pulse width will be obtained for large negative values of $V_{\text{Bias}}$ ($V_{\text{Bias}} = -2.8 \text{ V} \text{ to } -3.2 \text{ V}$), while high extinction ratios will be obtained using modulation depths as high as possible. Since it is not allowed to apply lower voltages than $V_{\text{EAM min}}$ we cannot make both the bias voltage very negative and the modulation depth high. In other words we find ourselves in a tradeoff position between extinction and pulse width. A satisfying working point is obtained using a bias voltage of $V_{\text{bias}} = -3 \text{ V}$ and a modulation voltage of $V_{\text{mod}} = 2 \text{ V}$. With these values for bias voltage and modulation voltage the pulse width equals 4.4 ps at an extinction ratio of 20 dB. From Figure 3.7 we may also notice that for a certain bias voltage the optimal values for both extinction ratio and pulse width are obtained at maximum modulation voltage.

3.3.2 Experimental results
The frequency generator available did not have a higher output power than 1 dBm ($V_{\text{MD}} = 0.35 \text{ V}$) at 40 GHz. Therefore a 40-GHz electrical driver needed to be ordered. Due to delivery problems the drivers arrived two weeks before the end of the thesis project. Brief testing showed that in the single EAM setup the EAM was capable of producing pulses with a pulse width of 6.7 ps. Compared to the simulated pulse width of 4.4 ps the performance is not as good as expected. Two causes explain the difference between the simulated and the measured performance: The inspection sheet of the EAM (at the request of Oki not included in this report) states that the electrical reflection coefficient ($S_{11}$) of the EAM at 40 GHz is -4 dB. This implies that almost half of the input electrical power is reflected and only 60 % can enter the EAM. Secondly at 40 GHz nonlinear effects inside of the EAM take part. The spectral width of the modulated pulse was very small (~0.5 nm), hence using 2R regeneration a smaller pulse width is not to be expected. In the short period of time the drivers were available, the OSNR of the signal could not be measured. Oki recently presented a new line of EAMs which have a significantly lower reflection coefficient (-14 dB). These EAMs are small band EAMs, which means that they are designed to work at a specific repetition rate. From these EAMs better performance is to be expected.

3.4 The configuration with two cascaded EAMs
As described in section 3.1 the pulse width and extinction ratio can significantly be improved by placing two EAMs in cascade [2]. Apart from the parameters bias voltage and modulation depth (as in the single EAM configuration), now also the phase-shift ($\tau$) will affect the pulse train at the output (Figure 3.3). In Figure 3.8 an example is given
Chapter 3. The EAM as a pulse source

analogous to the explanation of a single EAM in Figure 3.6. The source code can be found in Appendix II - C.

Figure 3.8: Cascaded EAMs with $\tau = 0.2 \pi$, $V_{\text{Bias}} = -2V$ and $V_{\text{MD}} = 1V$

With a phase-shift of $\tau = 0.2 \pi$ a bias voltage of $V_{\text{Bias}} = -2V$ and a modulation depth of $V_{\text{MD}} = 1V$ as used in Figure 3.8 we find an extinction ratio of 36 dB and a pulse width of 4.4 ps.

3.4.1 Determining the optimal parameter values

In Figure 3.9 the effect of the phase-shift ($\tau$) on the optical output is given (Matlab code in Appendix II - D). The phase-shift is plotted from $\tau = 0$ to $\tau = \pi$. Please note that the phase-shift can range from 0 to $2\pi$, but since the two signals are sinus shaped the phase-shift trajectory from $\pi$ to $2\pi$ is the same as the shift from 0 to $\pi$ (in reverse).
Figure 3.9: The extinction as a function of $\pi$, with $V_{\text{Bias}} = -2$ V and $V_{\text{MD}} = 1$ V at 40 GHz

From Figure 3.9 we observe that the phase-shift ($\tau$) has a large influence on the shape of the plot, so also on the extinction ratio and the pulse width. Clearly we see that for high phase-shifts ($\tau > 0.4 \pi$) the applied extinction drops to zero. In this figure the phase-shift dependency is only given at a certain bias voltage ($V_{\text{Bias}} = -2$ V) with a certain modulation depth ($V_{\text{MD}} = 1$ V). In section 3.3.1 we noticed that at a certain bias voltage the extinction ratio and pulse width can be optimized by maximizing the modulation depth. Therefore in Figure 3.10 the modulation depth is maximized for each bias voltage. In order to see the effect of the phase-shift ($\tau$), the phase-shift is changed from 0 to 0.4 $\pi$. The Matlab source code is given in Appendix II – E.
Chapter 3. The EAM as a pulse source

Figure 3.10: The pulse width – extinction ratio relation for different $V_{\text{bias}}$ and $\tau$

Figure 3.10 shows that using the cascaded EAM setup extinction rates up to 48 dB and pulses as short as 2.1 ps can be obtained. Point A is a remarkable point in the figure; if $V_{\text{bias}} < -3.1$ V (below point A) and the phase-shift is increased, the widths of the generated pulses tend to be longer while for $V_{\text{bias}} > -3.1$ V (above point A) the widths of the pulses become shorter when the phase-shift is increased. For $V_{\text{bias}} = -2.4$ V ($V_{\text{MD}} = 2.6$ V) and $\tau = 0.4 \pi$ (point B) the pulses are very short (3.2 ps) and the extinction ratio is very high (45 dB). In Figure 3.11 the extinction is given as a function of time.
Figure 3.11: Cascaded EAMs with $\tau = 0.4 \pi$, $V_{\text{Bias}} = -2.4\text{V}$ and $V_{\text{MD}} = 2.6\text{V}$ at 40 GHz

In Figure 3.11 we see that because of the large phase-shift between the EAMs the net applied extinction as a function of time is distorted (with respect to a Gaussian pulse shape). As described in the research objectives (section 1.2) for the FASION project an extinction ratio higher than 30 dB is needed and a pulse width as short as 2 ps. If we allow a moderate deformation on the produced pulse an optimal set of parameters could be $\tau = 0.20 \pi$, $V_{\text{MD}} = 2.9\text{V}$ and $V_{\text{Bias}} = -2.1\text{V}$. With this set the extinction ratio is 41.6 dB and the pulse width is 3 ps. This means that in the cascaded EAM setup the extinction ratio produced by the EAMs is high enough, but that the pulses generated by the EAMs are still too broad. The width of the pulses may be shortened using 2R regeneration (section 3.2.5), but since the time-bandwidth product cannot be computed without the optical spectrum the effect of the 2R regeneration cannot be predicted with the theory used in this chapter.

3.4.2 Experimental results

In order to carry out an experiment using a cascaded EAM setup two EAMs are needed. During the research period only one EAM was available. Hence no testing in the cascaded setup could be done. In the single EAM setup the EAM produced, due
the high electrical reflection coefficient, a broader pulse width than simulated using the static characterization method. In the cascaded EAM setup, the same problem will arise. The new type of Oki EAMs have a smaller reflection coefficient and hence perform better, but in order to minimize the coupling loss of the setup a integrated cascaded EAM (on a single chip) may be preferable [16].
4 Conclusion

In the FASHION project stable pulse sources are needed which produce pulses as short as 2 ps with an extinction ratio of more than 30 dB. In the single EAM configuration, according to the static characterization method, the EAM can produce pulses with an extinction ratio up to 27 dB and pulse widths as low as 4 ps. The extinction ratio as well as the pulse width does not meet the requirements needed for a pulse source to be used in the FASHION project.

Experiments with the EAM in the single EAM configuration showed that it was not possible to produce pulses with a pulse width smaller than 6.7 ps. The 2.7 ps difference compared to the static characterization method is mainly due to high electrical reflection and nonlinear effects that occur when the carrier band band-edge of the EAM is modulated at 40 GHz. Recently EAMs with a lower reflection coefficient have been reported. The performance of these EAMs could be significantly better.

Using the cascaded setup the static characterization method shows that the extinction of the generated optical signal is high enough (41 to 48 dB) to be used in the FASHION project. The achievable pulse width however will (without deforming the pulse) not be shorter than 3 ps. This does not meet the requirements for the FASHION project. Using 2R regeneration the produced pulses might be shortened. However, since the time-bandwidth product cannot be computed without the optical spectrum (which cannot be computed by the means of the static characterization method) the effect of the 2R regeneration cannot be predicted.

Since an EAM is a compact, cost effective and stable device it would be very suitable for system applications, but up to now it will be difficult to use an EAM as a pulse source in a 160-Gbit/s OTDM system. Only when the performance of the EAM improves it will be able to compete with other RZ pulse sources like the MLFL.

The cascaded EAM offers an extinction ratio up to 48 dB with a pulse width of 4 ps. In a demultiplexing situation this means that a 4 ps switching window can be realized, hence it is worth while to investigate the possibilities of employing an EAM as demultiplexing device.
Section 2: Optical time-division channel demultiplexing using four-wave mixing (FWM) in semiconductor optical amplifiers (SOAs)

5 Optical time-division multiplexing (OTDM)

In today’s telecommunication net electrical time-division multiplexing (ETDM) is frequently used. In ETDM systems, several digital signals are routed through the same electrical channel by separating the bits as a function of time. Due to speed limitations of the electrical circuit ETDM systems with a data rate higher than 80 Gbit/s are difficult to realize. For these data rates that exceed the speed limitations of the electrical circuit optical time-division multiplexing (OTDM) can be used.

In OTDM systems several digital signals are routed through the same optical channel. Creating an OTDM signal is relatively easy (described in section 5.2). The main problem in OTDM systems is the demultiplexing. Because the bit rate of the OTDM signal is high (>100 Gbit/s) the signal cannot be detected using a photodiode, hence the OTDM signal needs to be demultiplexed in the optical domain (or at least partially optical). Several demultiplexing techniques are given in section 5.3. In this thesis report the emphasis will lay on the demultiplexing technique employing four-wave mixing (FWM), hence a detailed analysis of FWM in a semiconductor optical amplifier (SOA) is given in chapter 6.

5.1 Concept

In Figure 5.1 an OTDM signal is shown where four independent channels are interleaved as a function of time. The timeslots where an optical pulse is present (with a ‘1’ written in them) represent a logical ‘1’, the timeslots where no pulse is present (with a ‘0’ written in them) represent a logical ‘0’.

![Figure 5.1: An OTDM signal](image)
Chapter 5. Optical time-division multiplexing (OTDM)

For OTDM systems a RZ format is mandatory otherwise pulses of different channels would overlap as a function of time. This contrasts with ETDM systems in which NRZ signals are mostly used because NRZ pulses are easier and cheaper to generate for an ETDM system. Also, since NRZ pulses have a broader pulse width, they use less optical bandwidth (section 3.2.5).

5.2 Transmitter

Figure 5.2 shows how we obtain an OTDM signal. The radio frequency (RF) synthesizer delivers a RZ pulse source at ‘B’ GHz, the base rate of the system (the channel frequency).

The RZ pulse source produces very short pulses, shorter than the timeslot of the OTDM signal (< 6.25 ps for 160-Gbit/s systems). The pulse stream is split n times and fed to the modulators (1 to n). The modulated data channels are now interleaved by giving each channel a bit more delay. As a result a n x B Gbit/s OTDM signal is created. Since in the laboratory only one modulator is available this setup is simulated. Figure 5.3 shows a setup in which with one modulator an OTDM signal is created.
Figure 5.3: An OTDM transmitter using only one modulator

In this setup, the produced optical RZ pulse is directly modulated using a MLFL. The pulse stream is modulated with a pseudo random bit sequence (PRBS). This bit sequence makes it possible to check at the receiver side whether an error occurred during the transmission. After modulation the signal is interleaved by passive multiplexers. Each multiplexer doubles the number of channels it receives (the output of the first multiplexer, Mux 1, is 2 x B GHz, the second multiplexer, Mux 2, outputs 4 x B GHz, etc.). The multiplexer splits the received signal. Subsequently one of the branches is delayed by $\Delta t$ and the signals are merged together again. In order to maintain the PRBS of the OTDM signal, the signals are delayed more than the length of the PRBS sequence used. Would the signals be delayed shorter, extra bit dependencies could arise.

5.3 Demultiplexing techniques

On the receiver side of an OTDM system the optical signal needs to be demultiplexed. The challenge is to develop a compact and stable demultiplexing module. Several demultiplexing techniques that have been proposed [6], [23], [30] are discussed in the next subchapters. In the last subchapter a comparison is given between active and passive demultiplexers.
Chapter 5. Optical time-division multiplexing (OTDM)

5.3.1 Electroabsorption modulator

The EAM is a device that absorbs the input optical signal as a function of the electrical input. By applying an electrical RF signal at the base rate of the OTDM signal to the electrical input a switching window in time is created. Using this feature it is possible to demultiplex an OTDM signal.

![Diagram of Electroabsorption Modulator (EAM) as a Demultiplexer]

Figure 5.4: An electroabsorption modulator (EAM) as a demultiplexer

Figure 5.4 shows a basic demultiplexer using an EAM. By adjusting the delay (τ) so that the clock at the electrical input of the EAM coincides with one of the optical channels of the OTDM signal at the optical input of the EAM, this channel is filtered out at the optical output. The great advantage of this technology is that EAMs are very compact and therefore very easy to implement. Since an EAM has an electrical input, demultiplexing using EAMs is not an all-optical solution. It is generally difficult to achieve ultrafast switching, because the electrical interconnections limit the bandwidth of the switch. Recently Kodama et al overcame this problem by employing an optical gate on an EAM and error-free demultiplexing of a 160-Gbit/s data stream to a base rate of 10 Gbit/s was demonstrated [20]. The extinction the EAM offers is not very high (20 dB), which results in a switching window with a low contrast ratio. Better extinction ratios can be obtained by using two EAMs in cascade (35 dB) [22], [24], [27], but the extinction ratio is still relatively low.

5.3.2 Interferometric structures

Several interferometers exist that can be used for demultiplexing an OTDM signal. The three best known interferometers are the Sagnac interferometer, the Mach-Zehnder Interferometer and the ultrafast-nonlinear-interferometer (UNI). Each of them will be discussed.

Sagnac interferometer
There exist several types of Sagnac interferometers. The configurations for the Sagnac interferometers can be divided into passive and active (SOA based) configurations. The most frequently used passive configuration is the nonlinear optical loop mirror (NOLM) (Figure 5.5).

**Figure 5.5: The Nonlinear Optical Loop Mirror (NOLM) as demultiplexer**

For the SOA based configuration the semiconductor laser amplifier in a loop mirror [9] (SLALOM) (Figure 5.6 a) and the terahertz optical asymmetrical demultiplexer [31] (TOAD) (Figure 5.6 b) are most frequently used.

**Figure 5.6: Active Sagnac interferometers**

Since all Sagnac interferometers work according to the same principle, only the NOLM will be described. Figure 5.5 shows how a NOLM can be used to demultiplex an OTDM signal [8]. A 50/50 coupler splits the data clockwise and counterclockwise into the ring structure. Due to the 50/50 coupler the counterclockwise traveling signal has a 90
degrees phase-shift with respect to the other one. If no control signal is present the signals are not changed in the ring and arrive at the same time at the 50/50 coupler. Again the coupler gives a 90 degrees phase-shift to the signal that traveled counterclockwise with respect to the signal that traveled clockwise. The signals now have a 180 degrees phase-shift with respect to each other. Due to this phase-shift they completely cancel each other at the demultiplexed output of the coupler and thus are fully reflected into the data input. When a strong control signal is present cross phase modulation (XPM) occurs between the control and the part of the data signal that travels clockwise. This imposes a 180 degrees phase-shift on that (clockwise traveling) data pulse. The second time the two parts of the data signal arrive at the coupler the clockwise and the counterclockwise signals will interfere constructively and will therefore exit the demultiplexer at the demultiplexed output. For high data rates, the walk-off between the signal and control pulses causes a serious problem. Recently, with the use of a highly nonlinear dispersion shifted fiber (HNL-DSF) this problem has been overcome and a 640- to 10-Gbit/s demultiplexer has been reported [32].

Mach-Zehnder interferometer (SOA-MZI)

The Mach-Zehnder interferometer (Figure 5.7) relies on the same principle as the Sagnac interferometer described above. The data signal enters the interferometer through a 50/50 coupler. The split data signals travel independently through the arms of the interferometer and recombine at the coupler output. The difference to the Sagnac interferometer is that the output is a second coupler which is not identical with the input coupler.

![Figure 5.7: The Mach-Zehnder interferometer as demultiplexer](image)

When only a data signal is fed to the SOA-MZI the data will be output through the "Transmitted data" channel. The switching gate is realized by launching two control pulses (with a slight delay with respect to each other) into the control inputs. Control 1
introduces a phase-shift in the upper SOA by which the data signal will be routed through the demultiplexed data output. The second control pulse closes the switching window by applying a phase-shift to the lower SOA. Recently error-free demultiplexing of a 160-Gbit/s data stream to a base rate of 10 Gbit/s and almost error-free demultiplexing to a base rate of 40 Gbit/s has been demonstrated by Heid et al [12], [13].

Ultrafast-nonlinear-interferometer (UNI)
A simple setup of a gain transparent ultrafast-nonlinear-interferometer (UNI) [6] is depicted in Figure 5.8.

![Figure 5.8: Basic setup of a gain transparent UNI](image)

In the UNI, the polarization of the data signal is aligned by PC 1 in the way that it is output through port 3 of the polarization beam splitter (PBS). The polarization-maintaining fiber (PMF) is highly birefringent, which means that the two propagation modes of the fiber have a different breaking index. By the means of PC 2 the data channel is aligned 45 degrees to the axes of the PMF. Inside the PMF the data pulse is split into two pieces (E₁ and E₂) since E₁ experiences a different breaking index than E₂. In the situation that no control pulse is present, the data pulse passes passing through the polarization insensitive 1300-nm SOA the pulse pair and is launched back into the PMF at -45 degrees where the two components are recombined again. After
Chapter 5. Optical time-division multiplexing (OTDM)

recombination the pulse exits the UNI through the Transmitted data port. The data pulse can be switched through the demultiplexed data port by inserting a control pulse in between the pulse pair $E_1$ and $E_2$. Now the slower pulse ($E_2$) is subject to a nonlinear phase-shift in the SOA. Due to the phase-shift, after recombination the polarization of the switched data pulse is orthogonal to the polarization of the data pulse when no control pulse is present. Hence the switched data pulse exits the PBS through port 4 and the pulse exits the UNI through the demultiplexed channel.

5.3.3 Four-wave mixing

Four-wave mixing (FWM) is a nonlinear process that occurs when two or more strong signals propagate through an optical nonlinear medium. In this medium new signals are generated extracting optical power from the original signals. A detailed analysis of FWM is given in chapter 6.

![Figure 5.9: Optical demultiplexing using FWM in a nonlinear device.](image)

Figure 5.9 shows how FWM can be used for demultiplexing an OTDM signal. A control signal is temporally overlapped with the OTDM signal at the exact times of a single channel (channel 1 in the example). At the output of the nonlinear medium a new frequency component appears that corresponds to the selected channel of the OTDM signal (channel 1). We now can obtain the demultiplexed signal by using a bandpass filter.

5.3.4 Advantages and disadvantages of active optical switching

In the demultiplexing techniques described in this chapter we saw several active (SOA based) demultiplexers (FWM in a SOA, SOA-MZI, UNI, etc.) and several passive devices (FWM in a passive fiber, NOLM, etc.). An active demultiplexer has several advantages over a passive demultiplexer:

- In an active device the energy needed for the control pulse is significantly lower than in a passive device.
• Since active devices are much shorter in length than passive devices phase matching is less critical.

• Active devices are more compact than passive devices. Hence active devices are much more suitable for integration [29]. By integrating a device on a small print the working conditions are easier to control. Therefore the device will be more stable and robust.

• The active device has an active component which enhances the gain of the demultiplexed signal. This gain benefits the OSNR of the demultiplexed signal at the output.

The disadvantages compared to a passive device however are:

• The active component (SOA) in an active device produces amplified spontaneous emission (ASE). The ASE decreases the OSNR of demultiplexed signal at the output.

• The nonlinearity in active devices originates from the saturation of the gain. Thereby it is not instantaneous in its response. The gain relaxation time reduces the switching speed. In passive devices the response is instantaneous, so the switching speed is (almost) limitless.

In a laboratory setup both active and passive demultiplexers are suitable for optical demultiplexing at high date rates. But in system applications compact devices are mandatory; the active demultiplexer is the only option in that case.
6 Four-wave mixing

FWM is a nonlinear process that can be classified as a parametric process. The parametric processes can be divided into second- or third-order processes depending on whether the second-order susceptibility or third-order susceptibility is responsible for them. The second-order susceptibility only occurs in media that lack inversion symmetry. In isotropic media such as silica glass fibers, SOAs, etc the second-order susceptibility is not present, hence in practice the contribution of the second-order susceptibility can be neglected. A thorough derivation of the origin of FWM can be found in [1].

6.1 The principle

When two signals, a control and a data signal enter a nonlinear medium, two FWM components \( f_{\text{FWM}} = 2f_{\text{control}} - f_{\text{data}} \) and \( f_{\text{FWM}} = 2f_{\text{data}} - f_{\text{control}} \) are generated. Higher order mixing products \( n f_{\text{control}} \pm m f_{\text{data}} \), with \( n, m > 2 \) are also generated, but these highly nondegenerate wave mixing signals are very weak and will be ignored. The two types of FWM are described in Figure 6.1.

![Diagram of FWM](image)

**Figure 6.1: The four-wave mixing process with positive detuning**

In this figure the control photons \( E_{\text{control}} \) possess more energy per photon than the data photons \( E_{\text{data}} \). This is called positive detuning. In a reversed configuration \( E_{\text{control}} < E_{\text{data}} \) a negative detuning is also possible. Since negative and positive detuning are identical for brevity only the derivation of positive detuning is given here. In the FWM process the energy law is conserved.

\[
\sum E = 0 \quad (6.1)
\]
Chapter 6. Four-wave mixing

As depicted in Figure 6.1a, when two control photons are absorbed and a data photon is stimulated, due to the energy conservation law, a FWM photon with high photon energy is stimulated.

\[ E_{\text{FWM}_a} = 2E_{\text{control}} - E_{\text{data}} \]  

(6.2)

Figure 6.1b shows how the other FWM component is generated. Because two data photons are absorbed and one control photon is stimulated, a FWM photon with low photon energy is stimulated.

\[ E_{\text{FWM}_b} = 2E_{\text{data}} - E_{\text{control}} \]  

(6.3)

The frequency of a photon and its energy are related through Planck's constant \((h = 6.625 \times 10^{-34} \text{ Js})\).

\[ E = hf \]  

(6.4)

Equation (6.4) states that the photon's frequency is proportional to its energy per photon. Hence the FWM frequencies can be written as:

\[ f_{\text{FWM}_a} = 2f_{\text{control}} - f_{\text{data}} \]  

(6.5)

and

\[ f_{\text{FWM}_b} = 2f_{\text{data}} - f_{\text{control}} \]  

(6.6)

Similar to the positive and negative detuning the two FWM processes are in principle identical; thus for brevity only FWM using two control and one data signal (Figure 6.1a) will be discussed here. From equation (6.2) we saw that two control photons and one data photon are needed to produce one FWM photon. Hence the FWM intensity is proportional to \(I_{\text{control}}^2I_{\text{data}}\). Here \(I_{\text{control}}\) is the control pulse intensity and \(I_{\text{data}}\) is the data pulse intensity. Apart from the energy conservation law also the momentum conservation law needs to be fulfilled. This requirement leads to the phase-matching condition [1].

\[ \Delta k = 2k_{\text{c}} - k_{\text{d}} - k_{\text{FWM}} \]  

(6.7)

where \(k\) is the propagation constant \(k = n_\text{i} \omega / c\), \(n_\text{i}\) is the refractive index and \(c\) the speed of light in vacuum. A strong FWM signal is produced only when the phase-mismatch factor equals zero; \(\Delta k = 0\). In this case the phase of the FWM signal reproduces the phase of the input signals, hence it can be said that FWM is a coherent process. Two important measures define the quality of the FWM signal generated; the optical signal-to-noise ratio (OSNR) and the conversion efficiency. The OSNR is described in section 3.2.2 of this report. The conversion efficiency is defined as the output FWM power divided by the input power of the data;
Chapter 6. Four-wave mixing

\[ C_{\text{eff}} = \frac{P_{\text{FWM}}}{P_{\text{Data_in}}} \]  
\hspace{1cm} (6.8)

Where \( P_{\text{Data_in}} \) is the power of the input data signal and \( P_{\text{FWM}} \) is the power of the output FWM signal. This conversion efficiency describes the efficiency by which an optical (data) signal is converted from the input optical signal \( \omega_s \) to the output FWM signal \( \omega_c \).

6.2 Nonlinear media

Several devices can be used as nonlinear medium for generating FWM. In waveguides intense light is confined in a small area along a length. In order to have a clear and strong FWM signal a waveguide structure is therefore preferable. For this reason, optical fibers and SOAs are mostly used as nonlinear medium [15]. In the next two subchapters the origins of the nonlinearities of those two media is discussed.

6.2.1 FWM using fiber nonlinearity

The nonlinear character of fibers originates from a non-harmonic motion of bound electrons in a glass medium. The process is nonresonant resulting in a short response time (<50 fs). The nonlinear coefficient is small. This means that to generate FWM efficiently several kilometers of fiber are needed. This requirement can be fulfilled as fiber show very small attenuation. A drawback however is that FWM is very dependant on phase-matching as defined in equation (6.7); FWM is only generated when the propagation constant of FWM light matches with the sum of the propagation constants of the control and the data signal. Due to chromatic dispersion it is difficult to obtain perfect phase matching. In theory phase matching can be realized by setting the pump wavelength at the zero-dispersion wavelength of the fiber. In practice the zero-dispersion wavelength varies along the fiber, which makes good phase matching very difficult [18].

6.2.2 FWM using SOA nonlinearity

In a SOA three mechanisms contribute to the nonlinear gain dynamics that are responsible for the FWM (spectral-hole burning (SHB), carrier heating (CH) and carrier density pulsation (CDP)) [7]. In Figure 6.2 the process that follow the injection of an ultrashort optical pulse (>10 ps) into the gain medium of a SOA. For simplicity only the carrier distribution in the conduction band is shown.
Chapter 6. Four-wave mixing

Figure 6.2: The temporal process of the carrier distribution in the conduction band that follow the injection of an ultrashort optical pulse into the gain medium of a SOA.

The spectral-hole burning (SHB) and the carrier heating (CH) are intraband effects. SHB occurs when a stimulated emission due to incoming light burns a hole in the carrier distribution in the conduction band causing a perturbation from the Fermi distribution. For SHB the characteristic time is the time in which the Fermi distribution is restored again, which is on the order of several tens of femtoseconds. Subsequently CH takes place; free carriers at low energy levels are removed by stimulated emission or transferred to higher levels due to free carrier absorption. The characteristic time for CH is on the order of several hundred femtoseconds. The original Fermi distribution is now restored, but with a lower carrier density. The interband effect carrier density pulsation (CDP) leads to an increase of the carrier density due to electrical pumping. CDP is in some literature also referred to as carrier density modulation (CDM). The characteristic time is the effective carrier lifetime which is in the order of several hundred picoseconds. Since all three mechanisms (CDP, SHB and CH) have varying efficiencies and different characteristic times, the nonlinearity in a SOA is strongly dependent on the frequency separation between input signals. It has been found that FWM is mainly mediated by CDP, SHB and CH as long as the detuning does not exceed 4 THz [21]. However, the intraband dynamics (SHB and CH) are dominant over interband dynamics (CDP) for repetition rates exceeding 10 GHz [35].

6.3 Four-wave mixing in a SOA

In sections 6.1 and 6.2 it is shown where FWM originates. This chapter addresses the optimization of the FWM signal in a SOA. It has been shown by Diez et al. [7] that the performance of a SOA used in a pulsed FWM application cannot be described by experiments with static transmittance. In picosecond pulsed FWM applications the fast
gain dynamics of the SOA substantially influence the temporal and spectral shape of
the input signals; hence the FWM system can only be optimized using pulsed sources.

6.3.1 Optical input power and injection current

Both optical input power and injection current launched into the SOA influence the
FWM process. A weaker input power as well as a smaller injection current decreases
the interaction because the SOA is less saturated. Also, a stronger optical input power
causes not enough interaction due to gain saturation in the SOA. Unlike in continuous
wave FWM applications where the maximum injection current results in the best
OSNR, in FWM applying picosecond pulses, the OSNR of the FWM signal decreases
at high injection currents. This degradation at high currents results from two
phenomena [7]:

1. The input pulses are spectrally broadened due to SPM and XPM.
2. For an increasing current, the ASE gain (and noise) increases faster than the
gain the SOA gives to the FWM signal.

Small deviations in the input power can be compensated by adjusting the injection
current and visa versa (For example a weaker input power can be compensated by a
higher injection current). Conclusion: The input power and injection current are related.
There exists a combination of input power and injection current at which maximum
interaction takes place.

Since a SOA is not instantaneous in its response the SOA introduces pattern
dependencies. A pattern dependency is a dependency of the switching gate extinction
ratio on the bit sequence. In order to minimize the pattern dependency, the data signal
should have a low optical power. It has been shown in [33] that the optimum ratio of
$P_{\text{control}}/P_{\text{data}}$ varies between 8 and 12 dB depending on several factors, such as bit rate,
modulation format, frequency detuning, etc. At a certain wavelength configuration
(shown in section 6.1) two FWM components are generated; one FWM component that
(per produced FWM photon) needs two control and one data photon and one FWM
component that needs one control and two data photons. Since the data signal will
have a low optical power, the FWM signal using two control photons and one data
photon, described by equation (6.2), will be significantly larger than the other FWM
signal described by equation (6.3). Hence for demultiplexing the FWM signal of
equation (6.2) should be taken.
6.3.2 Frequency spacing

As shown in section 6.1 FWM can be generated with positive detuning \((f_{\text{control}} > f_{\text{data}})\) and with negative detuning \((f_{\text{control}} < f_{\text{data}})\). Das et al showed in [3] that the FWM conversion efficiency is higher for the positive detuning than for the negative detuning when the detuning \((|f_{\text{control}} - f_{\text{data}}|)\) is smaller than the gain region of the SOA \(\sim 2.5\) THz \((20\ \text{nm})\). If the detuning is larger than the gain region of the SOA, the FWM conversion efficiency sharply decreases, because the data and FWM signal are outside the gain region.

Each SOA has a gain peak, which is determined by the composition of the material and the structure of the active layer. In this gain peak the SOA has a maximum ASE, but the input signal at that wavelength also experiences the maximum gain. In order to realize a strong FWM signal with a high OSNR after demultiplexing two effects are important:

- A maximum nonlinear effect is realized when the control signal is placed on the gain maximum of the SOA (as depicted in Figure 6.3a). This is the result from the fact that two photons out of the control signal and only one photon out of the data- and FWM signal take part in the nonlinear process.
- A maximum amplification of the FWM signal is obtained by placing the FWM signal at the gain maximum of the SOA (as depicted in Figure 6.3b).

![Figure 6.3: Extremes of wavelength configurations for efficient FWM](image)

The wavelength configuration for a high OSNR at the receiver will be a tradeoff between the two configurations (Figure 6.4).
Figure 6.4: Ideal wavelength configuration for efficient FWM

In order to minimize pattern dependencies a wavelength configuration as depicted in Figure 6.4 is the best configuration; the data channel is the main contribution to the bit pattern dependency. Hence we want the data channel (spectrally) far away from the gain peak. The FWM signal however also introduces a small pattern dependency and should thus spectrally not be placed at the center of the gain peak. Therefore the configuration depicted in Figure 6.4 where neither the data nor the FWM channel is placed at the gain peak and the data channel is far away from the gain peak is the optimal configuration. Each SOA has its gain peak at a different wavelength. For the 160-Gbit/s demultiplexing two types of SOAs could be used; the Samsung OA40B3A-0G3C2 and the Opto Speed X1500. The Samsung SOA is a SOA with a ‘standard’ length of 500 μm. The Opto Speed SOA is a long SOA with a length of 2 mm. Since both the Samsung and the Opto Speed are not commercially available products, the datasheets could not be included in this report. In Figure 6.5 the ASE characteristics of the two SOAs, the Samsung and the Opto Speed, are depicted. From this figure we see that the gain maximum of the Samsung SOA for $I_{SOA} = 90$ mA (normal working point) is at 1544 nm and the gain maximum of the Opto Speed for $I_{SOA} = 500$ mA is at 1557 nm.
In order to obtain the wavelength configuration depicted in Figure 6.4, the control signal should be placed a bit higher than the gain peak. The data signal is placed at a higher wavelength than the control signal so that the signals spectrally do not overlap (6 to 8 nanometers higher than the control signal). For the Samsung SOA this means that the control and the data signal should be placed at 1547 nm and 1554 nm respectively, for the Opto Speed this would mean that the control and data signal should be placed at 1558 nm and 1565 nm respectively. These wavelengths (1558 nm and 1565 nm) are beyond the reach of any RZ pulse source available. Therefore only measurements carried out with the Samsung SOA are reported.
7 Demultiplexing 160-Gbit/s using FWM in a SOA

In the first two sections of this chapter two demultiplexing setups are discussed. In section 7.1 a 160-Gbit/s OTDM signal is demultiplexed to a base rate of 10 Gbit/s and in section 7.2 the 160-Gbit/s signal is demultiplexed to a base rate of 40 Gbit/s. In the third section of this chapter a setup for a polarization independent demultiplexer is given.

7.1 160- to 10-Gbit/s demultiplexing

7.1.1 Experimental setup

In Figure 7.1 the setup is given for the 16x10-Gbit/s demultiplexer. A 9.95328-GHz\(^1\) clock was fed into two MLFL lasers; the laser for the data (MLFL 1) and the laser for the control (MLFL 2). The pulses the laser for the data and the control produce were

\(^1\) Based on OTU 2 frame definition out of the ITU-T G.709 recommendations and the STM 64 frame definition out of the ITU-T G.707 standard
respectively 1.4 ps and 2.5 ps. The data signal was modulated using a $2^7 - 1$ PRBS bit sequence. After modulation the 10-Gbit/s signal was interleaved to 160 Gbit/s (159.25248 Gbit/s) in a passive fiber delay line multiplexer. After multiplexing via appropriate optical delays the PRBS was maintained from the OTDM signal. The pulsewidths of the data- and the control signal at the input of the SOA were respectively 1.9 ps and 2.8 ps. The reason the pulses had broadened from the laser to the input of the SOA was due to dispersion in the amplifiers and patch cords. The total power launched into the SOA was 12.8 dBm. The data comprised 13.7 % (4.2 dBm) of the SOA input. The SOA current ($I_{SOA}$) was set to 90 mA. At the output of the SOA an isolator was placed to prevent backreflection from going back into the SOA. The FWM signal was now filtered out using an optical bandpass filter (FWHM = 11 nm). Finally the FWM signal is detected using a 10-Gbit/s bit error rate (BER) detector.

### 7.1.2 Experimental results

As already discussed in section 6.3.2, the control signal's optimal wavelength using the Samsung SOA is about 1547 nm. In Figure 7.2 the optical output spectrum of the SOA is given for several different control wavelengths. In all configurations error-free ($<10^{-10}$) demultiplexing was obtained.

![Figure 7.2: Frequency dependency of the FWM](image-url)
The best wavelength for the control was determined by decreasing the power of the input data signal to the receiver until the BER was $1 \times 10^{-9}$. The input data power at which the BER is $1 \times 10^{-9}$ is defined as the ‘sensitivity’ of that channel. The best sensitivity was measured for a control wavelength of $\lambda_{\text{control}} = 1547$ nm. This confirms the optimal wavelength configuration discussed in section 6.3.2.

![Figure 7.3: Optical spectrum of the SOA input and output for $I_{\text{SOA}} = 90$ mA](image)

Figure 7.3 shows the optical input and output spectrum of the SOA with the control signal at 1547 nm and a spectral resolution of 0.1 nm. While the data signal experienced some amplification, the control signal had significantly less power at the output compared to the input and was shifted to longer wavelengths. This was mainly due to self-phase modulation caused by gain saturation produced by the control pulse [4]. Clearly a FWM signal was present at about 1542 nm. The FWM efficiency, as defined in equation (6.8), was 0.6 % in this setup.
Figure 7.4: Bit error rate measurements for 160- to 10-Gbit/s demultiplexing

In Figure 7.4 the BER performance is depicted for all 16 demultiplexed base rate channels. Error-free operation (BER < $10^{-10}$) was obtained for all channels. The sensitivities (the input power for a BER of $1 \times 10^{-9}$) of the best and the worst demultiplexed channel were $-24$ dBm and $-20.3$ dBm respectively. The 3.7-dB power penalty for the worst channel was mainly caused by an imperfect adjustment of amplitude and delay in the multiplexers.
Figure 7.5: Eye of the demultiplexed 10 Gbit/s out of the 160-Gbit/s signal

Figure 7.5 depicts the clear and open demultiplexed eye diagram that was obtained. The eye diagram clearly shows that more amplitude variation is present on the "1"-bit than on the "0"-bit. This is due to a residual bit pattern dependency. The small bump on the right hand side of the eye is caused by ringing of the photodiode inside the oscilloscope. Ringing is a side effect of a diode that occurs when the detected pulses have very steep flanks.

7.2 160- to 40-Gbit/s demultiplexing

7.2.1 Experimental setup

The 4x40-Gbit/s setup is quite similar to the 16x10 Gbit/s (section 7.1.1). From the setup given in Figure 7.6 it is obvious that the way the 160-Gbit/s OTDM data signal is demultiplexed has almost remained the same.
In this setup the two MLFL were fed with a 10.616-GHz RF signal. Please note that this clock was slightly higher than the clock used in the 16x10-Gbit/s setup. The reason the clock had to be increased was that the BER transmitter and receiver only worked at the forward error correction (FEC) frequency of 42.464 GHz (which is 4x10.616 GHz). Because of the higher clock the lasers could not be locked at the same wavelengths as used in the 16x10-Gbit/s setup. The highest wavelength at which the control laser could be stabilized was 1538 nm. Now the data laser was locked at 1547 nm. Although the system worked at a FEC frequency during the measurements no FEC algorithms were applied. The data laser (MLFL 1), which produced a 1.5-ps pulsewidth pulsetrain, was first multiplexed to 42.464 GHz in a passive fiber delay line multiplexer and then modulated. The modulation signal was generated using ETOM (16 x 2.654-Gbit/s channels). Each channel was generated using a $2^7 - 1$ pseudo random bit sequence (PRBS). The delay applied between the interleaved channels was equal to seven bits. Eight bits would have been required for maintaining the PRBS since a $2^7 - 1$ PRBS sequence was used. It can be said though that the PRBS was almost maintained. After modulation the 169.856-Gbit/s OTDM signal was obtained by delaying and multiplexing.
42.464-Gbit/s signal four times. Appropriate optical delays were used in the multiplexer to maintain the PRBS from the OTDM signal. The control laser (MLFL 2), which produced a 1.7-ps pulsewidth pulsetrain at 1538.3 nm, was multiplexed to the base rate of 42.464 GHz. The total power launched into the SOA was 13.2 dBm. The data signal comprised 3.2 % (-1.7 dBm) of the SOA input. Since MLFLs could not be aligned on the wavelengths used in the 16x10-Gbit/s setup, but could only be locked on lower wavelengths, the gain peak of the SOA needed to be lowered as well. This was done by increasing the injection current of the SOA to the maximum (200 mA). At that current, the gain peak of the SOA lowered to 1535 nm. The FWM signal was filtered by an optical bandpass filter (FWHM = 11 nm). Finally the FWM signal was detected using a 42.464- to 2.654-Gbit/s ETDM demultiplexer followed by a 2.654-Gbit/s BER detector (Rx).

7.2.2 Experimental results

Figure 7.7 shows the optical input and output spectrum of the SOA with a spectral resolution of 0.1 nm.

![Figure 7.7: Optical spectrum at SOA input and output for ISOA = 200 mA](image_url)
Chapter 7. Demultiplexing 160-Gbit/s using FWM in a SOA

Analogous to the optical spectrum we saw in the 16x10 setup (Figure 7.3), in the 4x40 setup we also see that the data signal experienced some amplification and that the control signal had significantly less power at the output compared to the input and was shifted to longer wavelengths. This was again mainly due to self-phase modulation caused by gain saturation produced by the control pulse [4]. The FWM signal was present at about 1530 nm. The FWM efficiency (defined in equation (6.8)) was 2.4 % in this setup.

![Graph showing BER measurements for demultiplexing](image)

**Figure 7.8: Bit error rate measurements of 160- to 40-Gbit/s demultiplexing**

In Figure 7.8 the BER performance is depicted for the four demultiplexed base rate channels. Error-free operation (BER < $10^{-10}$) was obtained for all channels. The sensitivities (the input power for a BER of $1 \times 10^{-9}$) of the best and the worst demultiplexed channel were -20.8 dBm and -20.3 dBm respectively. The power penalty of only 0.5 dB for the worst channel is much less than the penalty measured in the 16x10-Gbit/s setup (3.7 dB). The main reason the penalty is so much smaller is that in the 4x40-Gbit/s setup only four channels needed to be aligned instead of sixteen in the 16x10-Gbit/s setup.
Figure 7.9: Eye of the demultiplexed 40 Gbit/s out of the 160-Gbit/s signal

Figure 7.9 depicts the clear and open demultiplexed eye diagram that was obtained. The eye diagram clearly shows that more amplitude variation is present on the "1"-bit than on the "0"-bit. This is due to a residual bit pattern dependency. The bit pattern dependency is more visible than in the 16x10 Gbit/s setup. This is mainly due to the fact that the SOA works at its maximum current. A modest current would have been preferable, but was not possible in this setup (section 7). Similar to the 16x10 Gbit/s setup ringing of the photodiode is present. The ringing of a bit appears as a small bump in its neighboring bit.

7.3 Polarization independent demultiplexing

Many demultiplexing techniques, including FWM in a SOA, require the received data signal to possess a certain state of polarization. Since the optical polarization of a data signal at a certain position in a real transmission system cannot be predicted, polarization independent schemes will have to be applied. A concept for such a polarization independent demultiplexer is proposed in [11].
Figure 7.10: A polarization independent demultiplexer with a beam splitter using FWM in a SOA

On the receiver side the received data signal is split in a polarization beam splitter (PBS). When the data signal possesses a wrong state of polarization, a part of the data signal is detected by the feedback system. The feedback system minimizes the received data power by adjusting the polarization of the received data by the means of the polarization controller (PC). Thereby the received power ($P_{\text{rec}}$) at the demultiplexer's input is maximized. Because of the beam splitter the demultiplexer will always receive the right state of polarization. The received power of the data signal at the input of the demultiplexer will vary depending on the speed of the feedback loop.
8 Conclusion

In OTDM systems with a data rate of 100 Gbit/s and higher, it is no longer possible to perform electrical demultiplexing due to the speed limitations of the electrical circuit. Therefore demultiplexing must be performed optically. For system applications, the demultiplexer must fit on a small print in order to be integratable into the system. Because passive demultiplexers are too large, an active demultiplexer such as FWM in a SOA is required.

In order to obtain a clear FWM signal several factors must be considered:

- The input power and injection current are related. At a certain line rate, there exists an optimum combination of input power and injection current at which maximum interaction takes place.
- In order to reduce pattern dependencies the control signal should be significantly stronger than the data signal since only the FWM term that scales with $I_{\text{control}}^2I_{\text{data}}$ is detected.
- Positive detuning gives a stronger FWM signal than negative detuning.
- The gain maximum of the SOA should be spectrally placed between the control and the FWM signal. This represents a compromise between maximum nonlinear effect when the control is placed at the gain peak and highest FWM amplification when the FWM signal coincides with the SOA gain peak.

Error-free demultiplexing of a 160-Gbit/s OTDM signal to a base rate of 10 Gbit/s was demonstrated. In this configuration a high sensitivity of -24 dBm was obtained for the best channel. The power penalty of 3.7 dB for the worst channel was mainly caused by an imperfect alignment of amplitude and delay in the multiplexers.

In the 4x40-Gbit/s configuration the MLFLs could not be aligned at the preferred wavelengths (with respect to the gain peak of the SOA), hence the gain peak of the SOA needed to be shifted towards a shorter wavelength. This was achieved by increasing the injection current of the SOA to the maximum value. Even though increasing the injection current degraded the OSNR of the output FWM signal, error-free demultiplexing was obtained for the four demultiplexed base rate channels. The eye trace in the 4x40 Gbit/s configuration showed a stronger bit pattern dependency than in the 16x10-Gbit/s configuration. The sensitivity of the best channel
was -20.8 dBm, about 3 dB higher than in the 16x10-Gbit/s setup. However, the measured power penalty for the worst channel was only 0.5 dB. The much lower power penalty compared to the 16x10-Gbit/s configuration was due to the fact that four channels are easier to align than sixteen.

Since demultiplexers such as FWM in a SOA are polarization sensitive, in real transmission systems the received polarization of the data signal needs to be stabilized. In this paper a simple scheme to realize such a polarization independent system was presented.

In conclusion, applying FWM in a SOA as a demultiplexer is a very stable and reliable technique for demultiplexing an OTDM signal. Compared to the Mach-Zehnder interferometer the performance at high base rates is significantly better and therefore a viable alternative. However, applying FWM in a SOA, the demultiplexed data channel will still be present in the transmitted channel; hence, unlike with the Mach-Zehnder interferometer, add-drop multiplexing is not possible.
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Appendix I – List of abbreviations

ASE – Amplified Spontaneous Emission
BER – Bit Error Rate
BPF – BandPass Filter
CDM – Carrier Density Modulation
CDP – Carrier Density Pulsation
CH – Carrier Heating
CW – Continuous Wave
DFB – Distributed FeedBack
EDFA – Erbium Doped Fiber Amplifier
ESA – Electrical Spectrum Analyzer
ETDM – Electrical Time-Division Multiplexing
FASHION – ultraFast All-optical Switching for High speed OTDM Networking
FEC – Forward Error Correction
FWHM – Full-Width Half-Maximum
FWM – Four-wave Mixing
IST – Information Society Technology
MD – Modulation Depth
MLFL – Mode Locked Fiber Laser
MQW – MultiQuantum Well
MZI – Mach-Zehnder Interferometer
NALM – Nonlinear Amplified Loop Mirror
NOLM – Nonlinear Optical Loop Mirror
NRZ – Non-Return to Zero
OSA – Optical Spectrum Analyzer
OSNR – Optical Signal-to-Noise Ratio
OTDM – Optical Time-Division Multiplexing
OTU – Optical channel Transport Unit
PC – Polarization Controller
PDL – Polarization Dependent Loss
PI – Polarization Independent
PMF – Polarization Maintaining Fiber
PP – Peak-to-Peak
PRBS – Pseudo-Random Bit-Sequence
Appendix I – List of abbreviations

QCSE – Quantum Confined Stark Effect
Rx – Receiver
RF – Radio Frequency
RZ – Return to Zero
SHB – Spectral-Hole Burning
SLALOM – Semiconductor Laser Amplifier in a LOop Mirror
SNR – Signal-to-Noise Ratio
SOA – Semiconductor Optical Amplifier
SPM – Self Phase Modulation
STM – Synchronous Transport Module
TOAD – Terahertz Optical Asymmetrical Demultiplexer
Tx – Transmitter
UNI – Ultrafast Nonlinear Interferometer
WDM – Wavelength-Division Multiplexing
XPM – Cross Phase Modulation
Appendix II – Matlab files

A – Single EAM static characterization method

% note: This function is called by a Macro in Excel which has all the calibration data and
% takes care of the user interface.
function [PulseWidth, ExtRatio] = eam(Vbias_calibration, Ext_calibration, ModulationDepth,
Vbias_setpoint, ModulationFrequency, Resolution, NrOfPeriods, GenerateGraph)

%plot bias voltage - extinction ratio characteristics
if GenerateGraph == 1
    figure;
    subplot(2, 2, 2);
    plot(-Vbias_calibration, Ext_calibration);
    title('Ext(V_{i,n,eJ})');
    xlabel('Applied voltage on electric input: V_{i,n,eJ} (-V)');
    ylabel('Optical extinction: out_o_p_t - in_o_p_t (dB)');
end

%create timescale in nano seconds
T = linspace(0, NrOfPeriods, Resolution);
T = T/ModulationFrequency;
%create electrical input for EAM
%S = ModulationDepth * cos(2*pi*ModulationFrequency*T) + Vbias_setpoint;

%adjust the timescale to picoseconds (mod_freq is in GHz= 1/GHz = ns=1000 ps = 1 ns)
T = 1000 * T;

%plot electric input
if GenerateGraph == 1
    subplot(2, 2, 1);
    plot(T, S);
    title('V_{i,n,eJ}(t)');
    xlabel('Time(ps)');
    ylabel('Applied voltage(V)');
end

%compute extinction ratio at the output
Ext_ratio = interp1(Vbias_calibration, Ext_calibration, S);

%plot extinction ratio
if GenerateGraph == 1
    subplot(2, 2, 3);
    plot(T, Ext_ratio);
    title('Ext(t)');
    xlabel('Time(ps)');
    ylabel('Optical extinction(dB)');
end

ExtRatio = max(Ext_ratio) - min(Ext_ratio);

%Compute pulsewidth
max_Ext_ratio = 0.001 * 10^ (max(Ext_ratio) / 10);
min_Ext_ratio = 0.001 * 10^ (min(Ext_ratio) / 10);
widthlineLin = min_Ext_ratio + (max_Ext_ratio - min_Ext_ratio) / 2;
Appendix II – Matlab files

widthline = 10 * log10(widthlineLin/0.001);
halfPeriod = floor(Resolution/NrOfPeriods/2);
% since there is no phase shift and the source is a cosine the Pulsewidth
% is twice the distance to the first crosspoint of the wave
PulseWidth = 2*interp1(Ext_ratio(2:halfPeriod), t(2:halfPeriod), widthline);

if GenerateGraph == 1
    subplot(2, 2, 3);
    hold on;
    plot(t, widthline);
    Axis = axis;
    y = linspace(Axis(4), Axis(3), Resolution);
    plot(Resolution / NrOfPeriods - PulseWidth/2, y);
    plot(Resolution / NrOfPeriods + PulseWidth/2, y);
    hold off;
end

B – Single EAM pulse width - extinction ratio relation

% note: This function uses the calibration data imported by excel, named: Vbias_calibration and Ext_calibration

close all;
figure(1);
Vbias_step = 0.1
ModulationFrequency = 40
Resolution = 200
NrOfPeriods = 4
GenerateGraph = 0
Color = ['k', 'b', 'g', 'r', 'c', 'm', 'k', 'b', 'g', 'r', 'c', 'm', 'k', 'b', 'g', 'r', 'c'];

ModDepth_start = 0.6
ModDepth_step = 0.2
ModDepth_end = 2.4

for p=0:floor((ModDepth_end-ModDepth_start)/ModDepth_step)
    ModulationDepth = ModDepth_start + p*ModDepth_step;
    Vbias_low = -5 + ModulationDepth;
    Vbias_high = 0 - ModulationDepth;
    NrOfMeasurements = floor((Vbias_high - Vbias_low)/Vbias_step);
    PW = zeros(NrOfMeasurements, 1);
    ER = zeros(NrOfMeasurements, 1);
    VB = zeros(NrOfMeasurements, 1);
    for i = 0: NrOfMeasurements,
        Vbias_setpoint = Vbias_low + i*Vbias_step;
        VB(i+1) = Vbias_setpoint;
        [PW(i+1), ER(i+1)] = eam(Vbias_calibration, Ext_calibration, ModulationDepth, Vbias_setpoint, ModulationFrequency, Resolution, NrOfPeriods, GenerateGraph);
    end
    hold on;
    plot(PW, ER, 'r');
    hold off;
end
Appendix II – Matlab files

```
ModDepth_step = 0.01
minModDepth = 0.6

Vbias_start = -4
Vbias_end = -0.4
Vbias_step = 0.4

for p=0:f1oor(abs((Vbias_start-Vbias_end)/Vbias_step))
    Vbias_setpoint = Vbias_start + p*Vbias_step;
    maxModDepth = min(-Vbias_setpoint, 5 + Vbias_setpoint);
    NrOfMeasurements = f1oor((maxModDepth - minModDepth)/ModDepth_step);
    PW = zeros(NrOfMeasurements,1);
    ER = zeros(NrOfMeasurements,1);
    MD = zeros(NrOfMeasurements,1);
    for i = 0: NrOfMeasurements,
        ModulationDepth = minModDepth + i * ModDepth_step;
        MD(i+1) = ModulationDepth;
        [PW(i+1), ER(i+1)] = eam(Vbias_calibration, Ext_calibration, ModulationDepth, Vbias_setpoint, ModulationFrequency, Resolution, NrOfPeriods, GenerateGraph);
    end
    hold on;
    plot(PW, ER, 'b');
    hold off;
end
xlabel('Pulse width (ps)');
ylabel('Extinction ratio (dB)');

C – Cascaded EAM static characterization method

% note: This function is called by a Macro in Excel which has all the calibration data and
% takes care of the user interface.

function [PulseWidth, ExtRatio] = eam(Vbias_calibration1, Ext_calibration1,
Vbias_calibration2, Ext_calibration2, ModulationDepth, Vbias_setpoint, ModulationFrequency,
tau, Resolution, NrOfPeriods, GenerateGraph)

widthlinePercentage = 0.5;

if GenerateGraph == 1
    figure;
    subplot(2, 2, 2);
    hold on;
    plot(-Vbias_calibration1, Ext_calibration1);
    plot(-Vbias_calibration2, Ext_calibration2);
    title('EAM(V_{i\,n\,e\,j})');
    xlabel('Applied voltage on electric input(-V)');
    ylabel('Optical extinction(dB)');
end

t = linspace(0, NrOfPeriods, Resolution);
t = t/ModulationFrequency;
x = ModulationDepth * cos(2*pi/ModulationFrequency*t) + Vbias_setpoint;
```
%adjust the timescale to picoseconds (mod_freq is in GHz-> 1/GHz = ns->1000 ps = 1 ns)
t_in_ps = 1000 * t;

y = ModulationDepth * cos(2*pi*ModulationFrequency*t - pi*tau) + Vbias_setpoint;

if GenerateGraph == 1
    subplot(2, 2, 1);
    hold on;
    plot(t_in_ps, x, 'k--', t_in_ps, y, 'm:');
    title('Electric inputs');
    xlabel('Time(ps)');
    ylabel('Applied voltage');
    legend('S_1(t)'), 'S_2(t)');
    hold off;
end

Ext_ratio1 = interp1(Vbias_calibration1, Ext_calibration1, x);
Ext_ratio2 = interp1(Vbias_calibration2, Ext_calibration2, y);

if GenerateGraph == 1
    subplot(2, 2, 3);
    hold on;
    plot(t_in_ps, Ext_ratio1, 'k--', t_in_ps, Ext_ratio2, 'm:');
    title('Seperate Extinctions');
    xlabel('Time(ps)');
    ylabel('Applied voltage');
    legend('Ext_1(t)'), 'Ext_2(t)');
    hold off;
end

Ext_ratio = Ext_ratio1 + Ext_ratio2;

if GenerateGraph == 1
    subplot(2, 2, 4);
    hold on;
    plot(t_in_ps, Ext_ratio);
    title('Extinction of EAM 1 and EAM 2 in succession');
    xlabel('Time(ps)');
    ylabel('Optical extinction (dB)');
    hold off;
end

ExtRatio = max(Ext_ratio) - min(Ext_ratio);

%Compute pulsewidth
max_Ext_ratio = 0.001 * 10^(max(Ext_ratio) / 10);  
min_Ext_ratio = 0.001 * 10^(min(Ext_ratio) / 10);  
widthlineLin = min_Ext_ratio + (max_Ext_ratio - min_Ext_ratio) / 2;

widthline = 10 * log10(widthlineLin/0.001);

%split up pulse
Period = floor(Resolution/NrOfPeriods);  
halfPeriod = floor(Resolution/NrOfPeriods/2);

if tau<0.99 | tau>1.01
    begin = floor(Period*tau/4);  %Piek exists on half of second moved applied wave
    Point1 = interp1(Ext_ratio(begin+2:begin + halfPeriod), t_in_ps(begin+2:begin + halfPeriod), widthline);
end
Appendix II - Matlab files

Point2 = interp1(Ext_ratio(begin+2 + halfPeriod:begin + Period), t_in_ps(begin+2 + halfPeriod:begin + Period), widthline);

if (widthline - interp1(t_in_ps, Ext_ratio, Point1+1) > 0
    tmpPoint = Point1;
    Point1 = Point2;
    Point2 = interp1(Ext_ratio(begin + Period:begin + Period + halfPeriod), t_in_ps(begin + Period:begin + Period + halfPeriod), widthline);
end

PulseWidth = Point2 - Point1;

if GenerateGraph == 1
    subplot(2, 2, 4);
    hold on;
    plot(t_in_ps, widthline);
    Axis = axis;
    y = linspace(Axis(4), Axis(3), Resolution);
    plot(Point1, y);
    plot(Point2, y);
    hold off;
else
    PulseWidth = t_in_ps(Period);
end

D – Cascaded EAM simple τ shift algorithm

close all;

ModulationDepth = 1;
Vbias = -2;
ModulationFrequency = 10
Resolution = 200
NrOfPeriods = 4

tau_start = 1;
tau_step = 0.1;
tau_end = 2;

for p=0:floor((tau_end - tau_start)/tau_step)
    tau = tau_start + p*tau_step;
    eameam2(Vbias_calibration, Ext_calibration, Vbias_calibration, Ext_calibration, ModulationDepth, Vbias, ModulationFrequency, tau, Resolution, NrOfPeriods, 1);
end

E – Cascaded EAM pulse width - extinction ratio relation

close all;
figure(1);

ModulationFrequency = 40;
Resolution = 200;
NrOfPeriods = 4;
GenerateGraph = 0;
Color = ['k', 'b', 'g', 'r', 'c', 'm', 'k', 'b', 'g', 'r', 'c', 'm', 'k', 'b', 'g', 'r', 'c'];

Vbias_start = -4;
Vbias_end = -0.4;
Appendix II – Matlab files

Vbias_step = 0.4;

tau_start = 0;
tau_end = 0.4;
tau_step = 0.01;

for p=0:floor(abs((Vbias_start-Vbias_end)/Vbias_step))
    Vbias_setpoint = Vbias_start + p*Vbias_step;
    ModDepth = min(-Vbias_setpoint, 5 + Vbias_setpoint);
    PW = zeros(floor(abs((tau_start-tau_end)/tau_step)),1);
    ER = zeros(floor(abs((tau_start-tau_end)/tau_step)),1);
    MD = zeros(floor(abs((tau_start-tau_end)/tau_step)),1);

    for i = 0:floor(abs((tau_start-tau_end)/tau_step))
        tau = tau_start + i*tau_step;
        MD(i+1) = ModDepth;
        [PW(i+1), ER(i+1)] = eameam(Vbias_calibration, Ext_calibration, Vbias_calibration,
        Ext_calibration, ModDepth, Vbias_setpoint, ModulationFrequency, tau, Resolution,
        NrOfPeriods, GenerateGraph);
    end

    hold on;
    plot(PW, ER, 'b');
    hold off;
end

Vbias_step = 0.02;
tau_step = 0.1;

for i = 0:floor(abs((tau_start-tau_end)/tau_step))
    tau = tau_start + i*tau_step;
    PW = zeros(floor(abs((Vbias_start-Vbias_end)/Vbias_step)),1);
    ER = zeros(floor(abs((Vbias_start-Vbias_end)/Vbias_step)),1);
    MD = zeros(floor(abs((Vbias_start-Vbias_end)/Vbias_step)),1);

    for p=0:floor(abs((Vbias_start-Vbias_end)/Vbias_step))
        Vbias_setpoint = Vbias_start + p*Vbias_step;
        ModDepth = min(-Vbias_setpoint, 5 + Vbias_setpoint);
        [PW(p+1), ER(p+1)] = eameam(Vbias_calibration, Ext_calibration, Vbias_calibration,
        Ext_calibration, ModDepth, Vbias_setpoint, ModulationFrequency, tau, Resolution,
        NrOfPeriods, GenerateGraph);
    end

    hold on;
    plot(PW, ER, 'r');
    hold off;
end

xlabel('Pulse width (ps)');
ylabel('Extinction ratio (dB)');
axis([1, 14, 0, 50]);