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Fabrication of polarization-maintaining and polarization-splitting optical fiber couplers using the fused-biconical taper technology

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Fabrication of polarization-maintaining and polarization-splitting optical fiber couplers using the fused-biconical taper technology.

by M. Groten.


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SUMMARY.

This graduation report describes the fabrication of polarization-maintaining and polarization-splitting fiber optic 2X2 couplers. The graduation work has been carried out at the Eindhoven University of Technology in co-operation with the Philips Research Laboratory.

The technique used for fabricating the fiber couplers, was the fused-biconical taper method. The fibers used in the experiments were so-called PANDA high birefringent polarization-maintaining fibers.

Nowadays, polarization-splitting fiber couplers made of PANDA fibers are commercially available. These couplers are fabricated using a polishing and etching technique. It has been a challenge to realize a polarization-splitting fiber coupler using the fused-biconical taper method. Polarization-splitting coupler fabrication using PANDA fibers and applying the fused-biconical taper method, has not been reported so far.

In this report, the optical properties of the PANDA fiber, the coupling mechanism between two optical fibers, the measurement set-up as well as the fabrication technique are described.

Coupler fabrication using PANDA fibers has shown to be rather difficult due to the geometrical structure of this fiber. Only one 'low loss' polarization-maintaining 3-dB coupler has been realized. The polarization characteristics of this coupler are reported.
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APPENDIX A

APPENDIX B
1. Introduction to the applicability of polarization-splitting optical fiber couplers.

Optical fiber communication has gained interest because of the technical specifications. Low attenuation and high transmission bandwidth are the major advantages over conventional communication systems. Modern single mode optical fibers are designed to operate at a wavelength of 1550 nm because of the very low loss which can be achieved, typically about 0.2 dB/km [1]. A bandwidth-distance product of about 100 GHz·km is possible, with an appropriate choice of laser diode, optical fiber and coherent receiver.

Conventional receiver systems use IM/DD, intensity-modulation / direct-detection schemes. The IM/DD schemes have a great advantage in system simplicity and low cost [2]. However, IM/DD receivers are not applicable in long haul optical communications due to attenuation of the information carrying signal power. The output current of the photo detector of a ASK modulated signal can be written as

\[ i(t) = R p(t) \]  
(1.1)

where \( R \) is the detector responsivity and \( p(t) = \sum_k s_p(t-kT) \), where \( s_p(t) \) is the ASK modulated optical power.

For long haul optical communications coherent techniques are used. Coherent receivers, whether homodyne or heterodyne, offer a higher receiver sensitivity (10-25 dB) at the 1.5-1.6 µm wavelength region [2]. The more sophisticated coherent receivers are the so-called phase diversity receivers and polarization diversity receivers used in coherent optical communications. The key feature of these receivers is that the attenuated optical information carrying signal is multiplied with the (linearly polarized) signal of a local oscillator. Properly designed coherent receivers are less sensitive to phase noise terms and the relative intensity noise of the local oscillator can be eliminated. Amplification of the in-
formation carrying signal by the local oscillator signal and sup­pression of the relative intensity noise of the local oscillator offer the coherent optical communication system a much higher sig­nal to noise ratio than the IM/DD system.

Fig. 1.1 shows a coherent phase diversity receiver [3]. In this figure, the state of polarization (SOP) of the information carry­ing signal and the local oscillator signal are supposed to be mat­ched.

![Diagram of coherent phase diversity receiver](image)

Suppose ASK modulation and linear state of polarization of the local oscillator and the information carrying signal as well. The output power at the photodiode can be written as [3], [4]

\[
i(t) = 2dR \sqrt{P_s P_{lo}} \cos \theta \cos (\omega_{IF} t + (\phi_{lo} - \phi_s))
\]  

(1.2)

where \(d\) is the binary signal, \(R\) the detector responsivity, \(P_{lo}\), \(\omega_{lo}\) and \(\phi_{lo}\) the power, the angular frequency, and the phase of the local oscillator, respectively and \(P_s\), \(\omega_s\) and \(\phi_s\) the power, the angular frequency and phase of the information carrying signal, \(\theta\) the angle between the states of polarization of the signal and local oscillator and \(\omega_{IF}\) the intermediate frequency \(\omega_{lo} - \omega_s\).
For homodyne coherent receivers $\omega_{10} = \omega_s$ and $\phi_{10} = \phi_s$, for heterodyne coherent receivers, $\omega_{10} \neq \omega_s$. Homodyne receivers give better BER specifications, but require phase locking. Homodyne receivers may degenerate if $\phi_{10} - \phi_s = \frac{\pi}{2}$, i.e. the receiver is useless. Moreover, phase locking is very difficult to realize.

To achieve a maximum signal to noise ratio, the state of polarization of the optical signal and the local oscillator have to be matched, i.e. $\theta = 0$.

Nowadays, conventional single mode fiber is used for long haul optical communications. In these fibers, the state of polarization of the information carrying signal is not maintained along the fiber.

This implies that control of polarization is necessary. Control of polarization can be achieved in many ways [5]:

1: Rotatable fiber coil,
2: Fiber squeezer,
3: Faraday rotator,
4: Rotatable fiber crank.

The major disadvantages of these control systems is that they operate either slowly or inaccurately or that active control is required. A more elegant solution to solve this polarization control problem is the polarization diversity scheme, in which a polarization splitting fiber coupler is applied. The behaviour of this kind of coupler is shown in Fig. 1.2 schematically.

Arbitrarily polarized light which is incident upon input port 1 of the polarization splitting coupler is decomposed into two mutual orthogonal components, i.e. the x-polarized component of the input light is coupled to output port 3, whilst the y-polarized component is coupled to output port 4.
A polarization splitting coupler can be fabricated by several techniques. Commercially available polarization splitting couplers are made using etching techniques. The goal of this graduation work is the realization of a polarization-maintaining and polarization-splitting couplers using the fused-biconical taper technique. The fibers used in the experiments were polarization maintaining so-called PANDA fibers.

The couplers discussed in this graduation report consist of two fused and tapered fibers. The fibers are labeled as the main fiber and tap fiber respectively, the input ports of the coupler are numbered 1 (main fiber) and 2 (tap fiber), whilst the output ports of the coupler are numbered 3 (main fiber) and 4 (tap fiber), see Fig. 1.2.
2. Analysis of fundamental comprehensions.

The production of polarization-maintaining and polarization-splitting optical fiber couplers made of polarization-maintaining PANDA fibers requires an experimental set-up which is capable of fabricating these couplers under nearly reproducible circumstances. There is the input angle of the polarized light which is incident upon the main fiber. The light source available was a semiconductor laser diode (λ = 1.519 μm) which emitted linearly polarized light. To provide comparable measurements, the input light should be launched along one of the principal axes of the PANDA fiber. The basic terms of the coupler fabrication are discussed in this chapter.

2.1. Polarized light.

Transversely polarized light can be described by the motion of the end point of the electric field vector \( E(x,y,z,t) \). The transverse electric field can be described by [6]

\[
\hat{E}(x,y,z,t) = E_x(z,t) \hat{e}_x + E_y(z,t) \hat{e}_y + E_z(z,t) \hat{e}_z
\]

\[
E_x(z,t) = A_x \cos(\omega t - k z + \delta_x) \quad \text{(2.2a)}
\]

\[
E_y(z,t) = A_y \cos(\omega t - k z + \delta_y) \quad \text{(2.2b)}
\]

\[
E_z(z,t) = 0 \quad \text{(2.2c)}
\]

\[
k = 2\pi/\lambda
\]

where \( \omega \) denotes the optical angular frequency, \( k \) the wave number, \( \lambda \) the wavelength, \( \delta_x \) and \( \delta_y \) the initial phase of \( E_x \) and \( E_y \) respectively, and \( \hat{e}_x, \hat{e}_y \) and \( \hat{e}_z \) the unit vectors in the directions \( x, y \) and \( z \) respectively.
Fig. 2.1 shows a possible wave pattern

Fig. 2.1: Transversal wave pattern of linearly polarized light.

Generally, polarized light is elliptically polarized (EP), which can be shown as follows:

\[ E_x(z,t) = A_x \cos(\omega t - k z) \]  \hspace{1cm} (2.4a)

\[ E_y(z,t) = A_y \cos(\omega t - k z + \delta) \]  \hspace{1cm} (2.4b)

where \( \delta = \delta_y - \delta_x \).

\[ \frac{E_x}{A_x} = \cos(\omega t - k z) \]  \hspace{1cm} (2.5a)

\[ \frac{E_y}{A_y} = \cos(\omega t - k z) \cos \delta - \sin(\omega t - k z) \sin \delta \]  \hspace{1cm} (2.5b)

\[ \sin(\omega t - k z) = \sqrt{1 - \frac{E_x^2}{A_x^2}} \]  \hspace{1cm} (2.5c)

After elimination of the time dependent terms it follows

\[ E_y = A_y \left( \frac{E_x}{A_x} \cos \delta - \sqrt{1 - \frac{E_x^2}{A_x^2}} \sin \delta \right) \]  \hspace{1cm} (2.5d)

which can be rewritten as
\[
\frac{E_x^2}{A_x^2} + \frac{E_y^2}{A_y^2} - 2 \frac{E_x E_y}{A_x A_y} \cos \delta = \sin^2 \delta
\]  

(2.6)

which is the equation of an ellipse.

One can easily see that if \( \delta = 0 \) or \( \delta = \pi \) the end of the electric field vector describes a line. If the relative phase difference \( \delta \) between the two orthogonally components \( E_x \) and \( E_y \) equals a multiple of \( \pi \), the light is called \textit{linearly polarized} (LP).

If \( A_x \) equals \( A_y \) and \( \delta = \pi/2 \) or \( \delta = -\pi/2 \) the tip of the electric field vector describes a circle clockwise or counterclockwise respectively. Under mentioned conditions the light is called \textit{right circular polarized} and \textit{left circular polarized} (RCP and LCP) [6],[7].

Fig. 2.2 illustrates the possible \textit{states-of-polarization (SOP)} of monochromatic coherent light [7].

\[\begin{array}{c}
\delta = 0 \\
\delta = \pi/4 \\
\delta = \pi/2 \\
\delta = 3\pi/4 \\
\delta = \pi
\end{array}\]

Fig. 2.2: States of polarization.
2.2. Birefringence.

The phenomenon of birefringence occurs in optically anisotropic media [7]. Anisotropic media have optical properties depending on the direction. A ray incident upon a birefringent medium can propagate in two different directions, depending on the direction of polarization of the incident ray. The two rays travelling along these directions are referred to as the ordinary and extraordinary rays. The ordinary ray propagates with velocity \( v_o = c/n_o \), and the extraordinary ray with velocity \( v_e = c/n_e \), where \( n_o \) and \( n_e \) are the refractive indices in the two optical directions.

Because of the two different velocities in the anisotropic medium, the two rays become out of phase. The phase difference between the outgoing rays is used in many applications.

One of these applications is the half wave plate. The half wave plate is an anisotropic optical device, a parallel slab of birefringent material with thickness \( d \) (e.g. quartz, calcite), which introduces a phase difference of \( \pi \) radians between the ordinary and extraordinary rays [7].

The retardation of the o-ray and e-ray is expressed by \( \Delta \phi_o \) and \( \Delta \phi_e \), respectively:

\[
\Delta \phi_o = \frac{-2\pi}{\lambda} n_o \ d \quad (2.7a)
\]

\[
\Delta \phi_e = \frac{-2\pi}{\lambda} n_e \ d \quad (2.7b)
\]

For the half wave plate the thickness \( d \) is such that the phase difference \( \Delta \phi \) equals \( \pi \):

\[
\Delta \phi = \Delta \phi_o - \Delta \phi_e = \frac{-2\pi}{\lambda} (n_o - n_e) \ d = \pi \quad (2.8a)
\]

\[
(n_e - n_o) \ d = \frac{\lambda}{2} \quad (2.8b)
\]
The half wave plate is characterized by a so called *optical axis*. When linearly polarized light with azimuthal angle $\theta$ with respect to the optical axis is incident upon the half wave plate, the outgoing light is also linearly polarized, but the plane of polarization has been rotated over $2\theta$:

The electric field is described by:

\[
E_x(0) = A \cos \theta \cos(\omega t) \quad (2.9a)
\]
\[
E_y(0) = A \sin \theta \cos(\omega t) \quad (2.9b)
\]

where $E_x(0)$ and $E_y(0)$ are the components of the electric field vector at the input plane, i.e. $z=0$, of the half wave plate. At the output plane of the half wave plate, i.e. $z=d$, the retardations of $E_x$ and $E_y$ are $\phi$ and $\phi+\pi$, respectively:

\[
E_x(d) = A \cos \theta \cos(\omega t-kd+\phi) \quad (2.10a)
\]
\[
E_y(d) = A \sin \theta \cos(\omega t-kd+\phi+\pi) = -A \sin \theta \cos(\omega t-kd+\phi) \quad (2.10b)
\]

which implies a rotation the plane of polarization about $2\theta$, see Fig. 2.3 [8].

![Fig. 2.3: The half wave plate.](image)
2.3 Polarization-maintaining fibers.

Conventional single mode fibers are used in long distance optical communications. Theoretically, these fibers can maintain a state of polarization (SOP) under the following conditions [9]:

1: perfectly circular fiber core,
2: no bend of the fiber,
3: no transverse pressure,
4: constant temperature,
5: no randomly varying intrinsic stress in the fiber.

Practically, none of these conditions will be met. The SOP of the incident light can't be preserved due to random mode coupling. In this context, random mode coupling means the influence of two orthogonal modes HE₁₁ₓ and HE₁₁ᵧ, propagating along the fiber with different velocities, on the state of polarization of the propagating light. Random mode coupling can arise from a slightly elliptical core, squeezing or bending of the fiber. All these unwanted effects make that the optical fiber is very little birefringent in an unpredictable way. To overcome the polarization fluctuations along the length of the conventional single mode fiber, polarization-maintaining fiber has been developed.

Polarization-maintaining (PM) fibers can be classified on the ground of their characteristics and geometrical structure as shown in Fig. 2.4 [2].
Fig. 2.4: Classification of PM-fibers.

PM fibers are characterized by the following parameters [9]:

1: modal birefringence $B$ or beat length $L_p$,  
2: cross talk $CT_x,y$,  
3: transmission loss.

Modal birefringence $B$ is the difference of the effective refractive index between orthogonal linear-polarization modes and is related to the beat length $L_p$ as:

$$L_p = \frac{\lambda}{B} = \frac{2\pi}{\Delta\beta} \quad (2.11)$$

where $\lambda$ is the wavelength.
Only the HE\(_{11}\) mode is guided by a single mode (polarization-maintaining) fiber. This mode can be decomposed into two mutual orthogonal directions \(x\) and \(y\). In the following of this report, these components, i.e. \(\text{HE}_{11x}\) and \(\text{HE}_{11y}\), are considered to be two independent modes [2].

When the beat length \(L_p\) is much shorter than the curvatures along the fiber, then the \(\text{HE}_{11x}\) and \(\text{HE}_{11y}\) are nearly 100% decoupled.

Cross-talk \(CT_{x,y}\) characterizes the polarization-maintaining ability of a PM fiber based on random mode coupling and is expressed as:

\[
CT_x = 10 \log \frac{P_{y2}}{P_{x1}} \quad (2.12a)
\]
\[
CT_y = 10 \log \frac{P_{x2}}{P_{y1}} \quad (2.12b)
\]

where \(P_{x1}\) and \(P_{y1}\) are the powers of \(\text{HE}_{11x}\) and \(\text{HE}_{11y}\) components of the excited \(\text{HE}_{11}\) mode, respectively.

Cross-talk \(CT_x\) is measured when the \(\text{HE}_{11x}\) mode is launched into the fiber, and at the end of the fiber the coupled output power \(P_{y2}\) is measured. \(CT_y\) is measured similarly. Generally, \(CT_x\) and \(CT_y\) are unequal, because of the non-circular symmetry of PM fibers.

PM fibers are designed so that the two orthogonal modes are decoupled, i.e. there is almost no coupling between the orthogonal modes. The decoupling of the orthogonal modes is realized by making the fiber highly birefringent. The PANDA fiber is a so called linear polarization fiber. The propagation constants of \(\text{HE}_x\) and \(\text{HE}_y\) modes are different. For brevity, the indices \(11\) are omitted.

The birefringence of a PM fiber can have three causes [9]:

1: geometrical effect
2: self-stress component
3: stress-applying parts.
The fiber used in the experiments is a so-called PANDA fiber. The cross section of the fiber is showed in Fig. 2.5.

![Diagram of PANDA fiber cross section](image)

**Fig. 2.5: Cross section of a PANDA fiber.**

The birefringence of the PANDA fiber is a result of the thermal expansion of the stress-applying parts in the cladding of the fiber. The stress-applying parts take account for an asymmetric stress distribution in the fiber core and cladding. The stress-applying parts are positioned on opposite sides of the fiber core. The result of this placement is a different refractive index in the x-direction, i.e., $n_x$, compared to the refractive index in the y-direction, i.e., $n_y$.

There is another cause of the birefringence of the fiber. The cladding glass of the fiber is made of pure silica $\text{SiO}_2$, whereas the stress-applying parts are made of $\text{SiO}_2$, doped with $\text{B}_2\text{O}_3$ and $\text{GeO}_2$. Because of this different chemical composition, the refractive index of the stress-applying parts isn't perfectly matched to the fiber cladding. This effect also accounts for a difference of refractive indices in the orthogonal directions.

In a proper designed PM-fiber, both effects (stress and refractive index mismatch), contribute to the final refractive index difference, see Fig. 2.6 [2]:

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Because of the different refractive index profiles in the orthogonal directions, the propagation velocities of the orthogonal modes are different. Therefore the PANDA fiber is characterized by two optical axes, a fast axis, i.e. the $y$-axis, and a slow axis, i.e. the $x$-axis, see Fig. 2.5.

The different refractive index profiles imply also different cut-off frequencies for the $HE_{11x}$ and $HE_{11y}$ modes, which can be explained by the normalized frequency $V_i$ [10], [11]:

$$V_i = \frac{2\pi a}{\lambda} \sqrt{n_{1i}^2 - n_{2i}^2} \quad i = x, y$$  \hspace{1cm} (2.13)

where $a$ is the core radius, $n_{1i}$ and $n_{2i}$ the refractive indices of the core and cladding, respectively.

The polarization-maintaining ability of the PANDA fiber depends on input angle $\theta$ of the incident linearly polarized light. If the pla-
ne of polarization of the incident light coincides with one of the optic axes, the incident state-of-polarization is maintained [12]. On the contrary, when there is an input angle mismatch of $\pi/4$ with respect to the optic axes, both HE$_{11x}$ and HE$_{11y}$ modes are excited.

Because of the short beat length in the highly birefringent fiber, maximum interference of the orthogonal modes arises. This means a maximum variation of the state of polarization of the propagating light along the fiber. In the latter case, the output state-of-polarization is not predictable. Generally, the outgoing light is elliptically polarized.

PM fibers exhibit generally a higher loss than conventional monomode fibers because of the large refractive-index difference and imperfection of the core shape.
3. Fiber optic 2x2 couplers.

3.1. Introduction.

Two methods for making fiber optic couplers are known: 1) the polishing and etching method and 2) the fused-biconical taper method \[13,14,15,16,17,18,19\]. The fuse-taper method is a relatively quick method which can be partly automated. A disadvantage of the fused-taper method is that the coupling region dimensions are small compared to those of the coupling region of a polished coupler. The fused-taper coupler is less sensitive to temperature fluctuations than a polished coupler. The glue used in polished couplers is very sensitive to temperature fluctuations.

Nowadays, conventional single mode fiber as well as polarization maintaining fiber is available. Couplers made of conventional single mode fibers may have the same properties as couplers made of polarization-maintaining fibers, e.g. polarization-splitting, but are not capable of preserving a state of polarization. Compared to conventional fiber couplers, couplers made of polarization-maintaining fibers require a much shorter coupling length to achieve the desired polarization characteristics. A disadvantage of using polarization-maintaining fibers is the higher insertion loss.

The coupling mechanism which explains the power transfer between the fiber cores is the same for the conventional coupler as for the coupler made of polarization-maintaining fibers, but differs of the coupling mechanism which takes place in polished couplers.

For polished couplers the fiber core dimensions do not change during the polishing process. Moreover, polished couplers do have a nearly parallel coupling region. The mechanism of power coupling which occurs in the parallel coupling region where the core separation distance is of the same order of magnitude as the core diameter, is called the coupled mode theory.
3.2. Coupling between two parallel fibers.

The coupling mechanism between two identical parallel non-birefringent optical fibers can be described by the coupled mode equations [20]:

\[
\begin{align*}
\frac{d}{dz} e_1 + j \beta e_1 + j c_{21} e_2 &= 0 \quad \text{(3.1a)} \\
\frac{d}{dz} e_2 + j \beta e_2 + j c_{12} e_1 &= 0 \quad \text{(3.1b)}
\end{align*}
\]

where \( e_1, e_2 \) is the electromagnetic field in the fiber 1 and 2, respectively, \( \beta \) the propagation constant in each fiber without coupling and \( c_{ij} \) the coupling coefficient of fiber i to fiber j.

To solve the aforementioned equations \( e_1 \) and \( e_2 \) are substituted:

\[
\begin{align*}
e_1 &= a_1 \exp(-j \beta z) \quad \text{(3.2a)} \\
e_2 &= a_2 \exp(-j \beta z) \quad \text{(3.2b)}
\end{align*}
\]

Equations (3.1) can be rewritten as:

\[
\begin{align*}
\frac{d}{dz} a_1 + j c a_2 &= 0 \quad \text{(3.3a)} \\
\frac{d}{dz} a_2 + j c a_1 &= 0 \quad \text{(3.3b)}
\end{align*}
\]

where \( c = c_{12} = c_{21} \) for identical fibers.

The coupling coefficient c is defined as in Fig. 3.1.

![Diagram](image)

Fig. 3.1: Coupling coefficient \( c_{12}, c_{21} \) and c.
The solution for $a_1$ and $a_2$ can be written as:

$$a_1 = b_{11} \exp(j m_1 z) - b_{21} \exp(j m_2 z) \quad (3.4a)$$

$$a_2 = b_{12} \exp(j m_1 z) - b_{22} \exp(j m_2 z) \quad (3.4b)$$

Substitution in Eqs. (3.3) gives:

$$j b_{11} m_1 - j b_{12} c = 0 \quad (3.5a)$$

$$j b_{21} m_2 - j b_{22} c = 0 \quad (3.5b)$$

$$j b_{12} m_1 - j b_{11} c = 0 \quad (3.5c)$$

$$j b_{22} m_2 - j b_{21} c = 0 \quad (3.5d)$$

$$m_1 = -c \quad (3.6a)$$

$$m_2 = c \quad (3.6b)$$

With these results Eqs. (3.4) can be rewritten:

$$a_1 = b_1 \exp(j c z) + b_2 \exp(-j c z) \quad (3.7a)$$

$$a_2 = -b_1 \exp(j c z) + b_2 \exp(-j c z) \quad (3.7b)$$

where $b_1 = b_{11} = -b_{12}$, and $b_2 = b_{21} = b_{22}$.

Assuming that optical power $P_0$ is inserted into only one fiber, at $z = 0$ yields $a_1 = A_0$, and $a_2 = 0$, i.e. $b_1 = b_2 = A_0/2$. 

18
\[ a_1 = \frac{\lambda_0}{2} (\exp(jcz) - \exp(-jcz)) \]
\[ = \lambda_0 \cos(cz) \] (3.8a)

\[ a_2 = -\frac{\lambda_0}{2} (\exp(jcz) + \exp(-jcz)) \]
\[ = -j\lambda_0 \sin(cz) \] (3.8b)

For the optical powers \( P_1 \) and \( P_2 \) yields, with \( P_0 = |\lambda_0|^2 \):

\[ P_1 = a_1 a_1^* = \lambda_0^2 \cos^2(cz) \] (3.9a)

\[ P_2 = a_2 a_2^* = \lambda_0^2 \sin^2(cz) \] (3.9b)

where \( ^* \) denotes complex conjugation.

The coupling coefficient \( c \) is defined for a parallel coupling region. Generally, the coupling region is not parallel. Then the coupling coefficient is \( z \)-dependent, i.e. \( c = C(z) \).

\[ C(z) = \frac{1}{z} \int_0^z C(r) \, dr \] (3.10)

The constant coupling coefficient \( c \) is given as [5]

\[ c = \frac{\sqrt{2} \Delta}{a \nu^3} \frac{u^2 K_0(\nu d/a)}{K_1^2(\nu)} \] (3.11)

where \( a \) is the core radius, \( d \) the fiber center separation, \( \Delta = (n_1 - n_2)/n_1 \), \( n_1 \) and \( n_2 \) are the refractive indices of the core and cladding respectively, \( u = a \sqrt{k^2 n_1^2 - \beta^2} \), \( w = a \sqrt{\beta^2 - k^2 n_2^2} \), \( \nu^2 = u^2 + w^2 \), \( k = 2\pi/\lambda \), \( \beta \) the propagation constant and \( K_n(x) \) is the modified Bessel function.
The coupled mode theory briefly discussed here, is applicable in case of coupler fabrication using the polishing technique. The cladding of the fibers is polished away to some extend and the flattened surfaces are glued together. In this case the core radius and the core center separation is kept constant and the coupling mechanism of two parallel fiber is valid.
3.3. Fused-biconical taper couplers.

Fused-biconical taper fiber couplers are fabricated by fusing two aligned fibers together using a heat source and elongation of the fused interaction region until the desired power ratio and/or polarization characteristics are obtained. Because of the elongation of the coupling region, they can not be modeled like a coupler with parallel fiber cores. During the tapering process the coupling region gets a biconical structure, the core center separation distance varies along the coupling region and is large compared to the core radii.

A single mode optical fiber is characterized by its V number

\[ V = \frac{2 \pi a}{\lambda} \text{NA} \]  \hspace{1cm} (3.12)

where \( a \) is the core radius, \( \lambda \) the wavelength and NA the numerical aperture, i.e. \( \sqrt{n_1^2 - n_2^2} \), where \( n_1 \) and \( n_2 \) are the refractive indices of the fiber core and cladding, respectively.

The solutions to Maxwell's electromagnetic wave equations are denoted as \( HE_{nm} \), \( EH_{nm} \) modes and \( E_{0m} \) and \( H_{0m} \) modes [10,11]. These are the exact solutions to the Maxwell equations applied to circular step-index profile fibers. Fig. 3.2 shows the normalized specific phase shift of the lowest order solutions.

Fig. 3.2: Lowest order solutions to the Maxwell equations.
For the weakly guiding approximation, i.e. \( \frac{n_1}{n_2} \approx 1 \), the exact solutions can be rewritten as nearly linearly polarized \( \text{LP}_{nm} \) modes, where the \( \text{LP}_{nm} \) modes are the superposition of \( \text{HE}_{nm} \) and \( \text{EH}_{nm} \) modes [10,11]

\[
\text{LP}_{0m} = \text{HE}_{1m} \\
\text{LP}_{1m} = \text{HE}_{2m} + E_{0m} + H_{0m} \\
\text{LP}_{nm} = \text{HE}_{n-1,m} - \text{EH}_{n-1,m}
\]

For single mode fibers, \( V < 2.405 \), i.e. only the \( \text{HE}_{11} \) mode will exist as a guided mode.

In the non-tapered optical fiber far below cut-off the electromagnetic field is bounded strongly to the core region. To explain the coupling mechanism in a fused-taper coupler a model of such a coupler is given in Fig. 3.3

![Model of a fused-taper coupler](image)

**Fig. 3.3: Model of a fused-taper coupler.**
Because of the tapering process the coupler gets a biconical structure. The core radius becomes smaller in the coupler. This implies that the electromagnetic field is spread out further and further along the coupler into the cladding. At some place, the electromagnetic field is no longer confined to the core region but is spread out completely into the cladding and bound by the cladding-air interface. The composite cladding structure forms a new guiding medium with refractive index $n_2$ and external medium, e.g. the surrounding air, with refractive index $n_3$.

The $V$ number changes correspondingly

$$V_{\text{comp}} = \frac{2 \pi a_{\text{comp}}}{\lambda} \text{NA}_{\text{comp}}$$

where $a_{\text{comp}}$ is the width of the coupling region at the waist and $\text{NA}_{\text{comp}}$ the numerical aperture $\sqrt{n_2^2 - n_3^2}$ of the composite structure.

Around the waist of the coupling region, the composite structure is multimode. The power transfer between the two fiber cores can be explained by the interference or beating of the two lowest order linearly polarized modes, i.e. $\text{LP}_{01}$ and $\text{LP}_{11}$. The linearly polarized $\text{LP}_{01}$ modes is a symmetric or even mode with propagation constant $\beta_e$, and the $\text{LP}_{11}$ mode is an anti-symmetric or odd mode with propagation constant $\beta_o$.

A cross-section of a conventional non-birefringent fiber coupler is given in Fig. 3.4.

Fig. 3.4: Cross-section of the conventional fiber coupler.
The cross-section of the coupler has a symmetrical structure with two privileged directions \( x \) and \( y \). It is convenient to dissolve the two linearly polarized modes \( \text{LP}_{01} \) and \( \text{LP}_{11} \) into four modes, each polarized along whether the \( x \)-axis or the \( y \)-axis.

The propagation of the four modes are given by

\[
\beta^x_e, \beta^y_e, \beta^x_o \text{ and } \beta^y_o.
\]

The polarized input light may be decomposed into two mutual orthogonal components with propagation constant \( \beta^x_e - \beta^x_o \) for the \( x \)-polarized mode, and \( \beta^y_e - \beta^y_o \) for the \( y \)-polarized mode.

Fig. 3.5 shows the relation among the propagation constants.

![Diagram of propagation constants](image)

Fig. 3.5: Propagation constants.
Polarization splitting is based on the difference between the propagation constants of the orthogonal modes of the composite structure, i.e. \( \Delta \beta = (\beta_e^y - \beta_o^y) - (\beta_e^x - \beta_o^x) \neq 0 \).

For the coupling ratio \( c_x \) and \( c_y \) can be written \([21]\):

\[
\begin{align*}
  c_x &= \cos^2 \left( \frac{1}{2} \int_0^L \Delta \beta^x \, dz \right) \\
  c_y &= \cos^2 \left( \frac{1}{2} \int_0^L \Delta \beta^y \, dz \right)
\end{align*}
\]  

(3.15a) (3.15b)

Polarization splitting is achieved when the relative phase between the \( x \)-polarized and \( y \)-polarized mode equals \( \pi \) (see Fig. 3.7), i.e. when

\[
\begin{align*}
  \int_0^L (\beta_e^y - \beta_o^y) \, dz &= 2m \pi \\
  \int_0^L (\beta_e^x - \beta_o^x) \, dz &= (2n + 1) \pi
\end{align*}
\]  

(3.16a) (3.16b)

or

\[
\begin{align*}
  \int_0^L (\beta_e^y - \beta_o^y) \, dz &= (2m+1) \pi \\
  \int_0^L (\beta_e^x - \beta_o^x) \, dz &= 2n \pi
\end{align*}
\]  

(3.16c) (3.16d)

where \( L \) is the interaction length of the coupling region.

For the PANDA fiber the different propagation constants arise from both the birefringence and the refractive index of the stress-applying parts.

If unpolarized light is incident upon input port 1, i.e. both orthogonal modes are equally excited, then the power at output port 3 is described by \([22]\)
\[ P = \frac{1}{2} \left(1 + \cos (c_x - c_y) L \cos (c_x - c_y) L\right) \]
\[ = \frac{1}{2} + \frac{1}{4} \left(\cos 2c_x L + \cos 2c_y L\right) \quad (3.17) \]

where for the strongly fused coupler
\[ c_x - c_y = \frac{3 \pi \lambda}{32 n_2 a^2} \left(\frac{1}{1 + \frac{1}{V} f^2} + \frac{1}{1 + (n_3/n_2)^2} \frac{1}{V f^2}\right) \quad (3.18a) \]
\[ c_x - c_y = \frac{3 \pi \lambda}{16 n_2 a^2} \frac{1}{V} \left(1 - (n_3/n_2)^2\right) \quad (3.18b) \]

where \(V = \frac{2 \pi a}{\lambda} \sqrt{n_2^2 - n_3^2}\), \(n_2\) and \(n_3\) are the refractive indices of the fiber cladding and external medium, e.g. air, respectively, and \(a\) is the width of the coupling region.

Eq. (3.17) can also be deduced from the coupled mode equations of paragraph 3.2. In the coupling region, two orthogonal modes are excited. Suppose the x-polarized electromagnetic wave \(e_1\) and the y-polarized electromagnetic wave \(e_3\) in the main fiber, i.e. the electromagnetic waves \(e_1\) and \(e_3\) are incident upon input port 1. The x-polarized wave \(e_1\) couples to the x-polarized wave \(e_2\) in the tap fiber and the y-polarized wave \(e_3\) couples to the y-polarized wave \(e_4\) in the tap fiber.

The coupled mode equations can be written as:
\[ \frac{d e_1}{dz} + j \beta e_1 + j c_x e_2 = 0 \quad (3.19a) \]
\[ \frac{d e_2}{dz} + j \beta e_2 + j c_x e_1 = 0 \quad (3.19b) \]
\[ \frac{d e_3}{dz} + j \beta e_3 + j c_y e_4 = 0 \quad (3.19c) \]
\[ \frac{d e_4}{dz} + j \beta e_4 + j c_y e_3 = 0 \quad (3.19d) \]
The electromagnetic waves $e_i$ can be written as:

$$e_i = a_i \exp(-j \beta z) \quad i = 1, 2, 3, 4$$  \hspace{1cm} (3.20)

The coupled mode equations can be solved for the x-polarized and y-polarized mode, separately:

$$\frac{da_1}{dz} + j c_x a_2 = 0$$  \hspace{1cm} (3.21a)

$$\frac{da_2}{dz} + j c_x a_1 = 0$$  \hspace{1cm} (3.21b)

$$\frac{da_3}{dz} + j c_y a_4 = 0$$  \hspace{1cm} (3.21c)

$$\frac{da_4}{dz} + j c_y a_3 = 0$$  \hspace{1cm} (3.21d)

For the x-polarized mode the former two equations are solved, for the y-polarized mode the latter two equations are solved.

$$a_1 = b_1 \exp(j c_x z) + b_2 \exp(-j c_x z)$$  \hspace{1cm} (3.22a)

$$a_2 = -b_1 \exp(j c_x z) + b_2 \exp(-j c_x z)$$  \hspace{1cm} (3.22b)

$$a_3 = b_3 \exp(j c_y z) + b_4 \exp(-j c_y z)$$  \hspace{1cm} (3.23a)

$$a_4 = -b_3 \exp(j c_y z) + b_4 \exp(-j c_y z)$$  \hspace{1cm} (3.23b)

The orthogonal modes are excited in the main fiber, equally powered, i.e. at $z=0$ (see Fig. 3.6)

$$a_1(0) = a_3(0) = \frac{A_0}{\sqrt{2}}$$  \hspace{1cm} (3.24a)

$$a_2(0) = a_4(0) = 0$$  \hspace{1cm} (3.24b)
Fig. 3.6: Both x-polarized and y-polarized mode are excited, equally powered.

\[ b_1 = b_2 = b_3 = b_4 = \frac{\lambda_0}{2 \sqrt{2}} \]  
(3.25)

\[ a_1 = \frac{\lambda_0}{\sqrt{2}} \cos (c_x z) \]  
(3.26a)

\[ a_2 = -j \frac{\lambda_0}{\sqrt{2}} \sin (c_x z) \]  
(3.26b)

\[ a_3 = \frac{\lambda_0}{\sqrt{2}} \cos (c_y z) \]  
(3.26c)

\[ a_4 = -j \frac{\lambda_0}{\sqrt{2}} \sin (c_y z) \]  
(3.26d)
For the power in the main fiber can be written:

\[ P_{\text{main}} = P_1 + P_3 = a_1 a_1^* + a_3 a_3^* \]
\[ = \frac{A_0}{2} \left( \cos^2(cx z) + \cos^2(cy z) \right) \]
\[ = \frac{A_0}{4} \left( 2 + \cos(2cx z) + \cos(2cy z) \right) \]  

(3.27a)

Suppose \( A_0 = 1 \):

\[ P_{\text{main}} = \frac{1}{2} + \frac{1}{4} \left( \cos(2cx z) + \cos(2cy z) \right) \]  

(3.27b)

For the power in the tap fiber can be written:

\[ P_{\text{tap}} = P_2 + P_4 = a_2 a_2^* + a_4 a_4^* \]
\[ = \frac{1}{2} \left( \sin(2cx z) + \sin(2cy z) \right) \]
\[ = \frac{1}{4} \left( 2 - \cos(2cx z) - \cos(2cy z) \right) \]
\[ = \frac{1}{2} - \frac{1}{4} \left( \cos(2cx z) + \cos(2cy z) \right) \]  

(3.27c)

The powers of the \( x \)-polarized and \( y \)-polarized modes are plotted in Fig. 3.7 for \( \lambda = 1.55 \mu m \), \( n_2 = 1.45 \), \( n_3 = 1 \) and \( a = 10 \mu m \).

Fig. 3.7: \( P_x \) and \( P_y \) at output port 3.
One can see that along the coupler length the two powers $P_x$ and $P_y$ become out of phase, due to the different couplings $C_x$ and $C_y$. The relative phase difference is $\pi$ at a coupling length of about 20 mm. At this point, polarization splitting is achieved. Fig. 3.8 shows the output power at output port 3, i.e. $P_x + P_y = P_{\text{main}}$.

**Fig. 3.8:** Output power $P_{\text{main}} = P_x + P_y$ at output port 3.

In the experiments a linearly polarized light source will be used. The angle of the incident polarized light is called $\theta$ and is defined as shown in Fig. 3.9.

**Fig. 3.9:** Input polarization angle $\theta$. 
From [23] the output powers of the birefringent coupler are known

\[
P_3(z) = P_0 \left[ \cos^2 cxz - \sin(cx-cy)z \sin(cx-cy)z \sin^2 \theta \right]
\]

\[
P_4(z) = P_0 \left[ \sin^2 cxz - \sin(cx-cy)z \sin(cx-cy)z \sin^2 \theta \right]
\]

where \( \theta \) is the input angle of the linearly polarized incident light.

For \( \theta = \pi/4 \), Eqs. 3.28 can be written as Eqs. 3.27. Suppose \( \theta = \pi/4 \), which means that the \( x \)-polarized and \( y \)-polarized wave are excited equally powered, then the aforementioned equations become more suitably:

\[
P_3(z) = P_0 \left[ \cos^2 cxz - \sin(cx-cy)z \sin(cx-cy)z \sin^2 \theta \right]
\]

\[
= P_0 \left[ \cos^2 cxz - 0.5 \left( \sin^2 cxz \cos^2 cyz - \cos^2 cxz \sin^2 cyz \right) \right]
\]

\[
= P_0 \left[ \cos^2 cxz + 0.5 \left( \cos^2 cyz - \cos^2 cxz \right) \right]
\]

\[
= 0.5 P_0 \left[ \cos^2 cxz - \cos^2 cyz \right]
\]

(3.29a)

and equivalently:

\[
P_4(z) = 0.5 P_0 \left[ \sin^2 cxz - \sin^2 cyz \right]
\]

(3.29b)

To eliminate the input power fluctuations, the ratio \( R \) of \( P_3 - P_4 \) and \( P_3 + P_4 \) is measured:

\[
R = \frac{P_3 - P_4}{P_3 + P_4} = \cos 2cxz + \cos 2cyz
\]

(3.30)

This ratio shows no dependence of \( P_0 \).

Ratio \( R \) can be evaluated as follows:

\[
R = \cos 2cxz - \cos 2cyz
\]

\[
= 2 \cos(cx-cy)z \cos(cx+cy)z
\]

(3.31)
Ratio $R$ can be considered to be an amplitude modulated carrier. The amplitude modulation arises from $2 \cos(c_x-c_y)z$. The carrier wave is characterized by frequency $(c_x+c_y)$.

Actually, both $c_x$ and $c_y$ are functions of $z$. In many practical situations $c_x-c_y \ll c_x+c_y$, which means that the amplitude varies slowly. For the values calculated in Fig. 3.6 yields $c_x \approx 3100$ and $c_y \approx 3020$, i.e. $\frac{c_x-c_y}{c_x+c_y} \approx 0.013 < 1$.

Under the assumption of constant coupling coefficients $c_x$ and $c_y$, the ratio function $R$ is plotted for $\theta=\pi/4$, i.e. both orthogonal modes are excited equally powered, in Fig. 3.10.

![Power ratio $R$](image)

**Fig. 3.10:** Coupling ratio $R$.

Complete dephasing between the output ports, i.e. polarization splitting, is achieved when the amplitude modulation equals 0, which can be shown as follows:

\[ \cos(c_x-c_y)z = 0 \]  \hspace{1cm} (3.32a)

\[ (c_x-c_y)z = \frac{\pi}{2} \]  \hspace{1cm} (3.32b)

\[ 2(c_x-c_y)z = \pi \]  \hspace{1cm} (3.32c)
If $\theta = 0$, then only one of the orthogonal modes is excited, and the coupler should be polarization-maintaining for $\theta = 0$ at the first cross-over point [25].

The analyses shown is applicable to conventional single mode fiber couplers as well as to fiber couplers made of polarization-maintaining fibers. The difference between these two couplers is, that for couplers made of highly birefringent fibers, the relative phase difference between the orthogonal modes of the composite structure is larger than the phase difference of the conventional fiber coupler. This means that for PANDA couplers a much shorter coupling length is required to achieve polarization-splitting. The second difference is the ability of the PANDA coupler to preserve the state of polarization at the output ports.

The major disadvantage of using PANDA fibers is the high loss, caused by the non-matched refractive index of the stress-applying parts. Theoretically, the loss can be kept very low. Hereto the taper shape has to be controlled very accurately [16,19]. This can be visualized with Fig. 3.11.

Fig. 3.11: Influence of the refractive index of the stress-applying parts on the coupling coefficient.
Fig. 3.11 shows that for a descending \( V \) number the coupling coefficient reaches a maximum at \( V_{\text{max}} \) which is just before cut-off. At this point, the coupler geometry should be kept unchanged, which is very hard to achieve. During the tapering process, the transversal dimensions of the coupling region will become smaller. In this figure one can clearly see the importance of stress-applying parts with a refractive index matched to the surrounding fiber cladding, i.e. parameter \( R = 0 \).
4. Experiments.

4.1. Preparations of the fused-taper process.

The fabrication of low loss polarization maintaining or polarization splitting fused-tapered couplers is more complicated than the fabrication of conventional fused-tapered fiber couplers. To achieve a low polarization cross-talk at the output ports of the coupler, highly birefringent polarization maintaining PANDA fibers are used. A second advantage of using polarization maintaining fibers is that a shorter coupling length is required to achieve polarization splitting. The disadvantage of using polarization maintaining fibers is the need to control the orientation of the birefringent fibers in the coupling region.

To achieve a low loss fiber coupler, the following conditions have to be met:

1: a careful removal of the primary fiber coating,
2: a perfectly cleaned coupling region,
3: stress-free, i.e. without torsion, mounting in the rotatable experimental set-up,
4: an accurate control of the orientation of the individual fibers,
5: fixing the orientated fibers,
6: alignment of the orientated fibers in the fused-taper set-up,
7: determination of the orientation of the stress applying parts at the input and output port of the main fiber,
8: connecting the optical devices, i.e. half wave platelet, microscope objectives and analyzer to the main fiber.
4.1.1.: Careful removal of the primary coating.

The type of PANDA fiber used in the experiments is produced by Fujikura, Japan. The specifications of this fiber are given in appendix A. Of practical interest was the composition of the protecting primary coating. No chemical solution was found to dissolve this coating without attacking, i.e. etching, the PANDA fiber cladding glass. The removal of the primary coating was achieved by carefully cutting into the coating along the coupling region, followed by the chemical weakening of the coating by \( \text{Cl}_2\text{CH}_2 \), without attacking the fiber cladding. Then the primary coating could be stripped off easily.

4.1.2.: Cleaning of the coupling region.

After the removal of the primary coating, the cladding glass is still contaminated by dust particles and coating particles. The cladding glass is cleaned by a volatile alcoholic fluid which doesn't attack the cladding glass nor leaves behind any remainders. Essential in the process of making fiber couplers using PANDA fibers are perfectly cleaned fibers in order to be able rotate the fibers freely as well as to fuse the fibers together without losses.

4.1.3. Mounting in an experimental set-up.

The fibers have to be orientated as is shown in Fig. 4.1. A photograph taken from the experimental set-up is shown in Fig. 4.2.

Fig.4.1.: Orientation of the fibers.
Fig. 4.2.: Photograph of experimental set-up.

1: rotatable fiber clamp,
2: clamp holder,
3: clamps connecting brace,
4: glass with alcoholic solution,
5: microscope,
6: external light source.
7: clamps of fused-taper set-up,

The fibers are observed in the coupling region by a microscope. The fibers are illuminated by an external light source. In order to make visible the stress-applying parts of the fibers, they are embedded in a matching volatile fluid which doesn't attack the cladding glass nor leaves behind any remainders. The refractive index of the fluid is nearly matched to the refractive index of the fiber cladding. This is done to eliminate unwanted reflections at the air-cladding interface. Fig. 4.3. shows a detail of the set-up.
Each fiber is mounted such that it can be rotated individually, without affecting the orientation of the other fiber. The top view of the aligned fibers is shown in Fig. 4.4. The microscope is focussed to the stress-applying parts. The fibers are supposed to be well orientated if the overlap of the two stress-applying parts is maximum.

Fig. 4.4: Top view of the fibers.
Fig. 4.5a shows the cross section of two fused fibers whose stress-applying parts are orientated correctly, whereas Fig. 4.5b shows the cross section of two fused fibers whose stress-applying parts are orientated incorrectly.

a) correctly orientated.  

b) incorrectly orientated.

Fig. 4.5: Photographs of fused fibers.

4.1.4. Fixing the well-orientated PANDA fibers.

Once the correct orientation is achieved, the fibers have to be positioned in the fused-taper set-up, without loosing their mutual orientation. This is done as follows. The bench designed to orientate the optic axes of the individual fibers is positioned only a few millimeters above the actual fused-taper set-up. The bench is moved downwards by a z-manipulator until the stripped fibers fall into the fiber clamps of the fused-taper set-up. Then the fibers are clamped with the right clamp and the primary coatings of the fibers are glued together at the right hand side of this clamp. The coatings of the fibers are glued together as close as possible to the coupling region. The fibers are glued together at only one side, to prevent any tension or torsion in the coupling region.
4.1.5. Alignment of the orientated fibers.

After gluing the fibers together the four clamps of the bench are loosened and the bench is removed. At this stage the fibers are clamped into the fused-taper set-up at one side only. In this way relaxation of the fibers is possible, whilst the mutual orientation is maintained.

The fibers are clamped at the left side of the coupling region. The fiber clamps of the fused-taper set-up are mounted onto two slides. The slides are pushed apart by a spring. Consequently, very little tension is given to the fibers which is needed to achieve a good alignment of the fibers. Finally, the bench is replaced by the burner.

4.1.6.: Determination of the orientation of the optic axes at the input and output port of the main fiber.

Fig. 4.6 shows the set-up used for finding the orientation of the optic axes at the input port 1 and output port 3 of the main fiber.

![Fig. 4.6: Set-up for finding the orientation of the optic axes.](image)

The orientation of the optic axes at input port 1 is determined as follows. Linearly polarized light, emitted by the semiconductor
laser (SCL), is collimated by a microscope objective $M_1$, is rotated about an arbitrary angle by the half wave platelet $\lambda/2$, and launched into the fiber by another microscope objective $M_2$. At the output port 3 of the fiber the light is elliptically polarized, generally. The elliptically polarized light is characterized by its major and minor axes. At the output port, the diverging light bundle is collimated by a third microscope objective $M_3$ and passes a polarizing beamsplitter (PBS), which operates as an analyzer at 1.55 $\mu$m. If the optic axis of the analyzer coincides with either the major or minor axis of the ellipse, the lock-in amplifier 1, LIA1, detects a local maximum or minimum intensity, respectively. Generally, the intensity of a local maximum isn't an absolute maximum. The analyzer is rotated until a local maximum is detected. At this stage, the optic axes of the PANDA fiber at output port 3 are found. To find the optic axes at input port 1, the half wave platelet is rotated until the absolute maximum is detected.

One has to take into account the different rotation angles of the half wave platelet and the analyzer. The analyzer has to be rotated twice as much as the half wave platelet. If the absolute maximum has been found, the optic axes of the main fiber have been found. The optic axes of the optical devices and the PANDA fiber have been aligned, i.e. the laser light is launched into the fiber along one of the principle axes. The SOP of the propagating light is maintained along the fiber.

For a polarization-maintaining 3 dB coupler, the incident angle of the polarized light $\theta$, see Fig. 3.9, should be 0°. In this case, only one mode, whether $HE_{11x}$ or $HE_{11y}$, is excited. For a polarization-splitting 3 dB coupler, the incident angle of the polarized light should be 45° for exciting the two orthogonal modes equally powered. Moreover, the amplitude modulation of ratio $R$ (Eq. 3.31) vanishes if the input polarization angle equals 0° or 90°, i.e. the polarization behaviour of the coupler can't be examined. With respect to the latter, the half wave platelet is rotated about 22.5° to achieve an input polarization angle of 45° with respect to the optic axes of the PANDA fiber.
Once the optic axes at the input and output ports are found, the microscope objective and analyzer are removed and the fiber ports 3 and 4 are placed just in front of the photo detectors. The lock-in amplifiers will detect equally attenuated output powers.

4.1.7.: Connecting the optical devices to the fibers.

The experiments have been carried out with a semiconductor laser. The laser operates at a wavelength of 1.519 µm. It emits linearly polarized light. The semiconductor laser is connected to a pigtail of conventional single mode optical fiber. Generally, these fibers can't maintain an incident state of polarization along relative long fiber lengths. The length of the pigtail connected to the semiconductor laser was about 1m. The output state of polarization of the fiber end was nearly linearly. This has been verified at an intermediate experimental set-up. This laser can also be used in the following experiments.

The linearly polarized laser light is collimated by the first microscope objective. Then the light passes through a half wave platelet. The half wave platelet operates at a wavelength of 1.523 µm which is the wavelength of a HeNe-laser. The plane of polarization of the laser light can be rotated by this device. The plane of polarization rotates twice as much as the rotation angle of the half wave platelet. The retardation achieved with the half wave platelet may not be π exactly, because of the slight mismatch between the half wave platelet wavelength (1.523 µm) and the semiconductor laser wavelength (1.519 µm).

At the transmission port 3 of the coupler, the light is collimated by a third microscope objective and passes through an analyzer. The analyzer used is a narrow band, i.e. 1.55 µm ± 2%, polarization splitting beamsplitter which can also be used at a wavelength of 1.529 µm.

A lock-in amplifier is connected to a memory oscilloscope to follow the coupling process continuously.
1.2. The fused-taper process.

Fig. 4.7 shows the fuse-taper set-up.

Fig. 4.7: Fuse-taper set-up.

SCL : semiconductor laser ($\lambda = 1.519 \ \mu m$),
M1,2,3: microscope objective,
$\lambda/2$ : half wave platelet ($\lambda = 1.523 \ \mu m$),
E : electrodes,
P S : power supply for the electrodes,
LIA1 : lock-in amplifier 1,
LIA2 : lock-in amplifier 2,
A/D : analog/digital converter,
R E : recording equipment.

The fused-taper process is automated partially. The taper session is automated, whereas the fuse session is not. Except for the relative position of the electric arc-flame to the aligned fibers, all parameters needed for the process are controlled by a personal computer. There are the arc-intensity, taper strategy and start-stop signals.
4.2.1. The fusion session.

First step in the process is the fusion session. The fibers are fused together. Once the electric arc-flame has been ignited by the personal computer, the flame is moved towards the fibers. The fusion session is terminated by the operator. The electric arc-flame used is a very wide flame, i.e. the distance between the electrodes is 12 mm approximately, resulting in a long fused region, i.e. about 4 mm. While the fusion session goes on, the output power of the main fiber is monitored constantly. Experiments have shown that during the fusion session no power loss occurs, i.e. the losses are less than 2%, . To achieve a relatively high coupling efficiency, a completely fused structure, i.e. a circular cross section at the coupler waist, is necessary, as well as nearly perfectly aligned and orientated fibers. Low loss during the fusion session has shown to be possible only if the perfectly clean fibers are clamped without torsion.

4.2.2. The taper session.

The second step in the process is the taper session. There are four taper strategies available:

1: control of the main route (main fiber),
2: control by interruption,
3: control of the secondary route (tap fiber),
4: control of the coupling ratio $\frac{P_4}{P_3 + P_4}$.

For conventional 3 dB fiber couplers, strategy 4 is used. For these couplers a coupling ratio of 0.5 is established. Because of the different power distribution between the output ports during the tapering process and after cooling respectively, the electric arc-flame is switched off before the coupling ratio has reached the value of 0.5. The input value of the coupling ratio is fiber dependent. This strategy can be used for polarization-maintaining couplers.
Strategy 3 is used for polarization-splitting couplers. To achieve polarization-splitting, the coupler is overcoupled, i.e. there is more than one power exchange between the two output ports.

The tapering process is carried out with the same electric arc-flame as is used during the fusion session, though the temperature is diminished. The tapering process has to be controlled very accurately. In the beginning of the process, the coupling region is relatively thick and the electric arc-flame has to be moved close enough to weaken the fused region. However, because of the tapering of the coupling region, the coupling region becomes thinner and as a consequence less heat is needed to provide further tapering. So, the operator has to observe the tapering process closely.

To fabricate a low loss coupler, the shape of the taper is important [16,19]. A short electric arc-flame should be used to modify the taper shape, i.e. the heat can be applied to the fibers more locally. Experiments have shown that a very slow tapering process, i.e. up to 15 minutes, gives the best results.
4.3. Results.

The first experiments have been carried out under the following conditions:

1: orientated fibers,
2: the linearly polarized input light is launched into the fiber under an arbitrary angle.

The only 'low loss' 3 dB coupler fabricated is coupler no. 180. The specifications of this coupler have been collected in Appendix B. The total transmission of this coupler is 63 % at a coupling ratio of 0.5. The polarization characteristics of this coupler have not been monitored during the fabrication, but have been measured afterwards. The polarization characteristics of this coupler are displayed in Figs. 4.8 where input port 1 is excited and in Figs. 4.9 where input port 2 is excited. The input angle \( \theta \) reflects on the rotation angle of the half wave platelet. During fabrication the input angle \( \theta \) must have been 10° or 80°.

Fig. 4.8a: Polarization behaviour of coupler 180, input port 1.
Fig. 4.8a shows that the power distribution is polarization-dependent. For $\theta = 10^\circ, 80^\circ$ the coupler is a $3 \text{ dB}$ coupler. The yield of the coupler measured after cooling at this angle was 63%. At $\theta = 45^\circ$ the yield is even higher, i.e. about 78%.

Fig. 4.8b shows the degree of polarization-maintaining ability of output port 3. It shows that for output port 3 the output light is not linearly polarized. The $+$-marked graph shows the polarization characteristics of the fast axis, whereas the $\Delta$-marked graph shows the polarization characteristics of the slow axis. It shows that the fast axis is more sensitive to fluctuations of the input polarization angle than the slow axis. At $\theta = 80^\circ$ the cross-talk $CT_x$ achieved is about 8 dB, whilst at $\theta = 40^\circ$ the cross-talk $CT_y$ achieved is about 4.7 dB.

![Polarization behaviour of transmission output port 3.](image)

Fig. 4.8b: Polarization behaviour of transmission output port 3.

Fig. 4.8c shows the polarization behaviour of output port 4. It shows that the output light is nearly linearly polarized and at $\theta = 45^\circ$, the cross-talk $CT_x$ equals 14.4 dB. However, at $\theta = 80^\circ$, cross-talk $CT_y$ equals 2.8 dB.
Fig. 4.8c: Polarization behaviour of cross-coupled output port 4.

Figs. 4.9 show the polarization behaviour of the same coupler, in the case of initiating input port 2.

Fig. 4.9a: Polarization behaviour of coupler 180, input port 2.

Fig. 4.9a shows that for none input polarization angle the coupler can be a 3 dB coupler. In analogy with Fig. 4.8a the variation of
the power of the cross-coupled output port 3, i.e. P3, exceeds the variation of the power of the transmission output port 4, i.e. P4.

Fig. 4.9b shows nearly the same polarization behaviour of the transmission output port as Fig. 4.8b. For the transmission output port 4, the outcoming light is not linearly polarized, whereas the outcoming light of the cross-coupled output port 3 is nearly linearly polarized, see Fig. 4.9c.

Fig. 4.9b: Polarization behaviour of transmission output port 4.

Fig. 4.9c: Polarization behaviour of cross-coupled output port 3.
5. Conclusions and remarks.

The fabrication of low loss polarization-maintaining and polarization-splitting couplers has proven to be rather difficult. The PANDA fiber used in the experiments does have good properties with respect to the propagation of linearly polarized light, but the geometrical structure of the fiber causes problems in making optical fiber couplers using the fused-taper technology. The stress-applying parts on opposite sides of the fiber core account for the polarization-maintaining ability of the fiber. The birefringence in the fiber core is caused by the thermal expansion coefficient of the stress-applying parts. The heat necessary for fusing the fiber claddings deforms the stress-applying parts. An example of a deformation is given in Fig. 4.5. The photographs shown are taken from the fused cross-section, before tapering.

However, fabrication of polarization-dependent fiber couplers with PANDA fibers is possible, using another fabrication technique, e.g. a polishing technique. With this technique, a major part of the fiber cladding is polished away, and these flattened sides of the fiber claddings are glued together. Now the distance between the fiber cores is reduced sharply. Optimization of the coupler fabrication by change of fabrication technique is not very convenient. A better solution is the purchase of other polarization maintaining optical fibers, that can be used in the fused-taper experimental set-up. At the moment, so called C- and D-shaped fibers are developed. These fibers have an elliptical core. This core shape accounts for the birefringence of the fiber, stress-applying parts are not necessary. Secondly, the core is positioned out of the center of the fiber, close to the cladding-air boundary. C- and D-shaped fibers are shown in Fig. 5.1. Fabrication of polarization-splitting couplers is expected to be quite easily using C-shaped fiber.
Fig. 5.1: Polarization-maintaining fibers.

Not only the type of fiber is to blame for the poor results. The heat source used in the experiments is an electric arc-flame. The length of the flame is 12 mm, approximately. The flame is positioned along the fiber which results in a fused area length of about 4 mm. The advantage of this relatively long fused area is the shorter coupling length needed to achieve polarization splitting. The major disadvantage of the use of a very wide electric arc-flame is that the smoothness of the taper is hard to control. Experiments have shown that the losses can be reduced by smoothing the shape of the tapered structure at the output ports. To realize the little corrections of the taper shape, positioning of the electric arc-flame perpendicular to the fibers should be considered.

The rotatable set-up used for orientating the PANDA fibers has shown to function satisfactorily. The method of orientating the fibers at the same place as the fuse-taper process shows to be convenient. Transport of the orientated fiber from the one set-up to another is not necessary, and, as a consequence, the orientation of the fibers is maintained quite easily.

The major problems encountered in fabricating optical couplers, are the environmental conditions. There are the stability of the mounting of the optical devices, and the preparation of the fi-
bers, i.e. the stripping of the primary coating, the cleaning of the coupling region, and the positioning in the set-ups. To achieve a stable set-up, all optical devices should be mounted on an optical table. Measurement equipment that causes vibrations should be placed on a separate table. More important are the environmental conditions at the coupling region. The fused-taper set-up should be placed in a dust-free environment.

The minimum loss achieved for a polarization-preserving 3 dB coupler was 37%, i.e. -2 dB. This value has been measured with nearly linearly polarized light launched into the main fiber at an input angle $\theta$ (Fig. 3.9) of 0°.

To fabricate polarization-dependent fiber couplers using the set-up of Fig. 4.7, the input angle of the linearly polarized light should be defined accurately. For polarization-maintaining couplers, this angle is 0°. As has been pointed out in paragraph 4.1.6, this is easy to realize. However, without monitoring the surface of the main fiber at the input port, the input angle can be 0° or 90°, i.e. the polarized light is launched into the fiber either along the fast axis or along the slow axis. To overcome this uncertainty, the input plane of the main fiber (input port 1) is examined using a conventional beamsplitter.

The problem in making couplers using PANDA fibers, is the moment of ending the tapering process. Experiments have shown that the monitored power distribution between the output ports during the taper session, can deviate significantly from the power distribution after cooling. Moreover, it is hard to predict in which way the power distribution will change during cooling. Suppose a conventional 3 dB coupler. Initially, no power is coupled from branch 3 to branch 4. During the taper session power is coupled from branch 3 to branch 4. When the coupling ratio $P_4/(P_3+P_4)$ reaches the value of 0.5, the tapering process is terminated. After cooling the coupler may show to be overcoupled, i.e. the coupling ratio exceeds 0.5, or the coupling ratio drops below 0.5. Both can happen with equal probability.
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6.1. Reference index.


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6.2. Author index.

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Polarization Maintaining Optical Fiber

SM-P Series

Features

- PANDA: (Polarization maintaining AND Absorption reducing)
- Preservation of polarization of propagated light as it is transmitted.
- Suitable in applications where differences in the phase of polarized light is exploited. High precision measurements can be achieved.
- Utilization in coherent telecommunications permits high-capacity transmission.

FUJIKURA'S POLARIZATION MAINTAINING OPTICAL FIBER has a beautiful, bilateral symmetrical structure which consists of a core and two round stress applying parts on opposite sides of the core. It is called PANDA fiber developed by NTT IECL. High birefringence in the fiber results from the structure and maximum value is more than $1 \times 10^{-3}$. So the fiber holds high polarization stability under adverse conditions of bending and temperature change. Typical mode coupling parameter is less than $10^{-6}/m$. 
APPENDIX A-II

Applications

Polarization maintaining optical fiber

- Optical fiber gyroscope
- Flow meter
- Vibrograph
- Magnetic field intensity sensor
- Other kinds of sensor

Optical fiber gyroscope

Specification

Fiber specification for general applications

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<th>SM-85-P</th>
<th>SM-13-P</th>
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<td>Cladding diameter (µm)</td>
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<td>Silicone coating Diameter (mm)</td>
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<td>Polyamide jacketing diameter (mm)</td>
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<td>Loss (dB/km)</td>
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<td>3</td>
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<td>Coupling length (mm)</td>
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<td>3</td>
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<tr>
<td>Extinction ratio</td>
<td>30 dB/100m</td>
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Cords are also available. Fibers can be manufactured to user specificlbutions.

Fiber specification for compact optical components

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Designation

SM-63-P

Optical fiber Polarization maintaining optical fiber

Extinction Ratio

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Fiber length (m)

59
Date: 04-26-1989
Experiment number: 180
Taper Strategy No.: 4
Halt Value: 10
Coupling Ratio: 0.45
Weld Intensity (WS): 124
Weld Intensity (TS): 127
Wavelength: 1519 nm

Final Percentage Main Route: 32
Final Percentage Sec. Route: 32

Final Total Transmission: 63 %
Final Excess Loss: -2 dB
Final Coupling Ratio \( \frac{P_4}{P_3 + P_4} \): 0.5

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<td>#sample-pairs Cool after taper</td>
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Y-axis: 10 % initial power per division
X-axis: 66 samples per division