Integrated-optics-based optical coherence tomography
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Chapter 4

Integrated-optics directional couplers for optical coherence tomography

We simulated, fabricated, and characterized symmetric 2x2 directional couplers in silicon oxynitride for swept-source optical coherence tomography (SS-OCT). The output spectra of directional couplers are measured and the wavelength dependence of the splitting ratio is determined. We discuss the design of wavelength-independent directional couplers based on asymmetric directional couplers. Finally we show the design, fabrication, and characterization of an integrated optics 3x3 directional coupler, which can be used to remove the depth degeneracy in Fourier-domain optical coherence tomography.
4.1 Introduction

A fiber optical coupler is a device with one or more input fibers to distribute or combine light into one or many outputs. The most common use of optical fiber couplers is power splitting, however fiber optical couplers also can be used to split different wavelengths into different output channels in wavelength division multiplexing systems [1]. Commercial optical fiber couplers typically are made using a fiber fusion technique and can be designed for a single wavelength or for a broad wavelength range [2-4].

An important optical component in bulk optics OCT systems are fiber optic couplers that are used to split light into the sample/reference arm of the interferometer and/or are used in a balanced detection scheme [5]. As discussed in chapter 1, in bulk optics SD-OCT and SS-OCT, light from a swept source typically is split by a 2x2 optical fiber coupler, guiding 90% of the light to the sample arm and 10% of the light to the reference arm. In SS-OCT a second 50:50 fiber coupler is used to split the interference signal into two signals with 180 degrees phase difference that is subtracted in a balanced detector to suppress relative intensity noise. In SS-OCT, 3x3 fiber optical couplers are used for depth degeneracy removal, which enhances the OCT imaging depth [6-8].

In integrated optics, directional couplers (DCs) perform an equivalent function as fiber optical couplers and are used in many complex integrated optical circuits. They are the basic building blocks for integrated optics devices such as Mach-Zehnder modulators, power dividers, optical switches, optical filters, and biosensors [9-12]. The DC operation is based on the field overlap in waveguides that are close together. Light in one waveguide can transfer to the other waveguide by the overlap of the evanescent field between the waveguides. In the coupled mode theory description [9-11] the field in the two waveguides is described by odd and even super field modes propagating independently with respect to each other. Since the odd and even supermodes have different propagation constants, power couples back and forth from one waveguide to the other depending on the distance propagated in the coupling region (spatial beat phenomena).

In this chapter, we discuss the design, simulation, and characterization of integrated optics DCs for application in OCT. The chapter is divided in two main parts:

1- Symmetric 2x2 DCs: we discuss the theory, design, simulation, fabrication, and characterization of symmetric 2x2 DCs in integrated optics. Furthermore, we discuss their application to OCT.
Chapter 4

2- Integrated optics 3x3 DCs: we discuss the design, simulation, fabrication, characterization, and phase shift measurements of integrated optics 3x3 directional couplers. We also discuss their application to depth degeneracy removal in SS-OCT.

4.2 Symmetric 2x2 directional couplers

4.2.1 Theory of directional couplers

2x2 DC structure

A 2x2 DC consists of two input waveguides, two input S-bends (transition region), a coupling region (straight waveguide), two output S-bends, and two output waveguides as illustrated in Fig. 4.1. In general, 2x2 DCs are characterized by the set of parameters \( w, w', L, R \) and \( d \) where \( w, w' \) are the waveguide widths of the bottom and top waveguide respectively, which are assumed to be constant over the whole coupling region of the DC. The parameter \( L \) is the length of the straight waveguides in the coupling region, \( R \) is the bending radius of the S-bend, \( d \) is the gap between the two waveguides in the coupling region. For a 2x2 DC, the term “symmetric” implies that the widths of two waveguides in the coupling region are identical (\( w = w' \)), while “asymmetric” implies that widths of the two waveguides are different (\( w \neq w' \)).

![Figure 4.1: Schematic of a 2x2 waveguide directional coupler. In wg = input waveguide, out wg = output waveguide.](image)

2x2 DC splitting ratio

In 2x2 DCs, power exchange between the waveguides not only takes place in the coupling region, but also in parts of the S-bend regions. Hence, a DC with coupling length \( L \) and S-bend radius \( R \) is considered to be equivalent to an ideal DC with two parallel optical waveguides of an effective coupling length \( L_{\text{eff}} \). Ignoring power losses, the output electric fields \( E_{1\text{out}}, E_{2\text{out}} \) at the two output waveguides of the DC are calculated by the use of the transfer matrix \( M \) as:

\[
\begin{bmatrix}
E_{1\text{out}} \\
E_{2\text{out}}
\end{bmatrix} = M \begin{bmatrix}
E_{1\text{in}} \\
E_{2\text{in}}
\end{bmatrix}
\]  (4.1)
Where $E_{1in} = E_{10}e^{i\omega t}$ and $E_{2in} = E_{20}e^{i(\omega t + \phi)}$ are the two input electric fields with a single polarization (TE or TM), $\omega$ is angular frequency, $\phi$ is the phase difference between the two input fields, $E_{10}$ and $E_{20}$ are the field amplitudes. For a general (a) symmetric DC with an arbitrary effective coupling length, the transfer matrix $M$ is defined as [13]:

$$M = \begin{bmatrix} \cos(\delta L_{\text{eff}}) - jQ \sin(\delta L_{\text{eff}}) & -jS \sin(\delta L_{\text{eff}}) \\ -jS \sin(\delta L_{\text{eff}}) & \cos(\delta L_{\text{eff}}) + jQ \sin(\delta L_{\text{eff}}) \end{bmatrix} \quad (4.2)$$

where $\delta = \sqrt{((\beta_1 - \beta_2)/2)^2 + \kappa^2}$ and $Q = (\beta_1 - \beta_2)/2\delta, S = \kappa/\delta$

The parameter $\kappa$ is the coupling constant, which can be calculated from the overlap integral between the fields in the uncoupled waveguides, $\beta_{1,2}$ are propagation constants in the top and bottom uncoupled waveguides. If light is only coupled into one input waveguide, i.e. $E_{20} = 0$, in a symmetric 2x2 DC ($Q=0$) the light intensities $I_1, I_2$ at the two output waveguides are derived from Eq. (4.1) and Eq. (4.2)

$$I_1 = |E_{1out}^*E_{1out}| = \cos^2(\kappa L_{\text{eff}})E_{10}^2 \quad (4.3)$$
$$I_2 = |E_{2out}^*E_{2out}| = \sin^2(\kappa L_{\text{eff}})E_{10}^2 \quad (4.4)$$

**Figure 4.2**: Calculated output intensities at the two output waveguides of a symmetric 2x2 directional coupler with the field launched into one input.

To illustrate the power transfer in DCs, Fig. 4.2 shows the calculated light intensity at the output waveguides of a symmetric 2x2 DC for a single wavelength as function of the coupling strength. As can be seen in Fig. 4.2, for a single wavelength, the maximum power transfer from one waveguide to the other can reach 100% and either the effective coupling length $L_{\text{eff}}$ or the coupling constant $\kappa$ can be adjusted to achieve an arbitrary splitting ratio. This is equivalent to changing the coupling length and the gap width, respectively.
To evaluate the 2x2 DC performances, we define a bar and a cross transmission according to the way the input and output intensities are measured. Bar is defined as the intensity transmitted from the top/bottom input waveguide to the top/bottom output waveguide. Vice versa, cross is defined as the intensity transmitted from top/bottom input waveguide to the bottom/top output waveguide. The splitting ratio of a 2x2 DC is then defined by the ratio $I_1/I_2$.

**2x2 DCs for balanced detection**

In SS-OCT, the backscattered light from the sample and the light from the reference arm are coupled and then split by a 50:50 DC for balanced detection. Using the transfer matrix description, the light intensities at two output waveguides of a symmetric 2x2 DC are derived based on Eq. (4.1) and Eq. (4.2) as:

\[
I_1 = E_R^2 \cos^2(\kappa L_{\text{eff}}) + E_S^2 \sin^2(\kappa L_{\text{eff}}) + E_R E_S \sin(2\kappa L_{\text{eff}}) \sin(\varphi) \tag{4.5}
\]

\[
I_2 = E_R^2 \sin^2(\kappa L_{\text{eff}}) + E_S^2 \cos^2(\kappa L_{\text{eff}}) - E_R E_S \sin(2\kappa L_{\text{eff}}) \sin(\varphi) \tag{4.6}
\]

The parameters $E_R$, $E_S$ are the field amplitudes of the sample and reference arm field, and $\varphi$ is the phase difference between the sample and the reference arm caused by delays in the reflection from the sample arm. In case of a 50:50 splitting ration DC, $\kappa L_{\text{eff}} = \pi/4$ and Eq. (4.5) and Eq. (4.6) become:

\[
I_1 = \frac{1}{2} E_R^2 + \frac{1}{2} E_S^2 + E_R E_S \sin(\varphi) \tag{4.7}
\]

\[
I_2 = \frac{1}{2} E_R^2 + \frac{1}{2} E_S^2 - E_R E_S \sin(\varphi) \tag{4.8}
\]

Equations (4.7) and (4.8) show that the phase difference between the intensities at the two output ports of a DC is always $180^\circ$. The signal after balanced detection is:

\[
I_{\text{balanced}} = I_1 - I_2 = 2 E_R E_S \sin(\varphi) \tag{4.9}
\]

Equations (4.5), Eq. (4.6), and Eq. (4.9) show that for a 50:50 splitting ratio, the largest signal is obtained and that for any other splitting ratio, the detected balanced signal is reduced. Furthermore, if the DC is exactly 50:50 the direct current part of the detected balanced signal, $\frac{1}{2} E_R^2 + \frac{1}{2} E_S^2$, which is related to the source power, is removed. As a result any slow fluctuations in the DC output power of the source are removed from the signal.

**4.2.2 Materials and experimental methods**

**Waveguide design and simulation**

Single mode waveguides are designed and fabricated in silicon oxynitride (SiON) technology. We perform mode field calculations (Field Designer, PhoeniXbv, Enschede, the Netherlands) to simulate the electric field (quasi-TE polarization) in the waveguide.
Based on the effective indices obtained from the mode field calculations, two-dimensional BPM simulations (OptoDesigner, PhoeniXbv, Enschede, the Netherlands) are performed to study the propagation of light in the DCs. More details about the simulations and the waveguide design, fabrication can be read in Section 1.2.2 & 2.3.1. The DC splitting ratio is calculated in the BPM simulations by taking the ratio of the simulated field intensities at the two output waveguides.

**Experimental methods**

DCs are characterized using single polarization light (TE polarization) from a swept laser source (Axsun Technologies, Inc., $\lambda_c = 1300$ nm, $\Delta\lambda = 92$ nm), which is coupled into the input waveguide of the DC. Light from the output waveguides is collected by a 25x microscope objective lens (Newport) and focused onto the two detectors of a balanced detector (Thorlabs, PDB-450C). Bar and cross spectra from two output waveguides are digitized and the splitting ratio is calculated by taking the ratio between the bar and cross spectrum at every wavelength. A schematic of the experimental setup is shown in Fig. 4.3.

![Schematic of the experimental setup](image)

**Figure 4.3:** Schematic of the experimental setup for spectrum and splitting ratio measurements of directional couplers. L=Objective lens, PD=Photo diode, SS=Swept source. The dashed rectangular box indicates the boundary of the optical chip.

For symmetric 2x2 DCs, we investigated three DC structures with a fixed set of parameters $(w, d, R) = (2.0, 1.0, 1040) \mu$m and varying coupling lengths, $L= 35, 50$ and 65 $\mu$m.

**4.2.3 Results**

Figure 4.4 shows a BPM simulation results of the electric field amplitude (TE polarization) in the horizontal plane for a 50:50 DC with $L = 50$ $\mu$m at 1300 nm wavelength. The white dashed line indicates the boundary between the end-facet of the directional coupler (left) and the air region (right). As can be seen from Fig. 4.4, light from the input waveguide is split equally into the two output waveguides. The simulated splitting ratio is 50:50.
Chapter 4

Figure 4.5 (a) show the measured input (source) spectrum that is coupled into the input waveguide of the DC. Figure 4.5 (b) shows the measured bar and cross spectra at the two output waveguides of the symmetric 2x2 DC with \( L = 50 \, \mu m \). The measured spectra at the two DC output waveguides are different from the input spectrum due to the wavelength dependence of the splitting ratio, as shown in Fig. 4.5 (c). The measured splitting ratio at the center wavelength of 1300 nm is 0.72. Over the swept-source wavelength band, the splitting ratio approximately varies by a factor of 4, from 0.41 (at \( \lambda_{\text{min}}=1266 \, \text{nm} \)) to 1.81 (at \( \lambda_{\text{max}} = 1358 \, \text{nm} \)). An ideal 50:50 DC has a 50:50 splitting ratio independent of wavelength, as indicated by the dashed line in Fig. 4.5 (c).

![Figure 4.4: BPM optical field amplitude simulation of a 2x2 symmetric directional coupler with \((w, d, R, L) = (2.0, 1.0, 1040, 50) \, \mu m\). The simulated splitting ratio at 1300 nm wavelength is 50:50.](image)

Figure 4.6 shows a comparison between the simulated and measured splitting ratios for three directional couplers \((L = 35, 50, 65 \, \mu m)\) at 1300 nm wavelength. The difference between the simulated and measured splitting ratio is attributed to a deviation of the fabricated SiON effective refractive index and the effective refractive index used for the 2D BPM simulations and in fabrication errors of the DCs.
Figure 4.5: Measurements of the symmetric 2x2 directional coupler with the set of parameters \((w, d, R, L) = (2.0, 1.0, 1040, 50) \mu m\). (a) Input (source) spectrum. (b) Cross output spectrum, (solid line) and Bar output spectrum (dashed line). (c) Splitting ratio measurement (solid line). The dashed line indicates an ideal DC with 50:50 splitting ratio independent of wavelength.

Figure 4.6: A comparison of the measured and simulated splitting ratios versus coupling length at 1300 nm wavelength. The dots and squares indicate the measurement and the simulation results, respectively. The lines are a guide to the eye.
4.2.4 Discussion

In SS-OCT system, balanced detection is used to suppress the relative intensity noise (RIN) of the light source. Our results, presented in section 4.2.3, show a strong dependence of the splitting ratio on wavelength. As a result, in direct balanced detection, RIN will not be optimally cancelled at all wavelengths in the sweep thus leading to a reduction in the OCT sensitivity [14]. To achieve optimal noise suppression, the DC has to be designed with a flattened wavelength response. This can be achieved through the introduction of an asymmetry in the waveguide width at opposite sides of the gap [13, 15]. For asymmetric 2x2 DCs, the output intensities are calculated [15] as:

\[ I_1 = \left[ 1 - \left( \frac{\kappa^2}{\ell^2} \right) \sin^2(\delta L_{eff}) \right] E_{10}^2 \]  \hspace{1cm} (4.10)

\[ I_2 = \left( \frac{\kappa^2}{\ell^2} \right) \sin^2(\delta L_{eff}) E_{10}^2 \]  \hspace{1cm} (4.11)

It can be seen from Eq. (4.10) and Eq. (4.11) that for asymmetric DCs, complete power (100%) transfer from one waveguide to the other cannot be achieved. The coupling power depends on both the phase term \( \delta L_{eff} \) and the amplitude term \( \frac{\kappa^2}{\ell^2} \). The wavelength-dependent response of the phase term can be suppressed by the amplitude term. Similar to symmetric DCs, the phase difference between the intensities at two output ports of the asymmetric DCs is always 180° (calculation not shown here) and thus fulfills the requirement for balanced detection in OCT.

Figure 4.7 shows the result of a BPM simulation of the splitting ratio versus wavelength for a wavelength-flattened DC designed with a set of parameters \((w, w', d, R, L) = (2.0, 1.8, 1.0, 1040, 50) \ \mu m\). It can be observed that the maximum splitting ratio variation is only 25%, from 1.34 (at \( \lambda_c = 1300 \ \text{nm} \)) to 0.89 (at \( \lambda_{max} = 1358 \ \text{nm} \)), which is considerably smaller than that of the conventional symmetric DCs shown in section 4.2.3.

**Figure 4.7:** Simulated splitting ratio of a 2x2 wavelength-flattened directional coupler with the set of parameters \((w, w', d, R, L) = (2.0, 1.8, 1.0, 1040, 50) \ \mu m\). The dashed line indicates an ideal DC with 50:50 splitting ratio independent of wavelength.
4.3 Integrated optics 3x3 directional coupler

4.3.1 Introduction

Quadrature FD-OCT with 3x3 fiber based couplers

In conventional FD OCT systems it is impossible to distinguish between positive and negative delays, an effect known as the complex conjugate artifact. This leads to the superposition, or folding, of the positive-delay image upon the negative-delay image. As a result the depth range of FD-OCT is limited since the zero delay always has to be well in front of the tissue and hence, the roll-off of the signal in tissue is stronger. To avoid this limitation, the full complex interferometric signal has to be measured, with the phase difference between the real and imaginary part 90° (quadrature components). This can be accomplished by shifting the phase of the reference and sample reflections and has been implemented in SS-OCT using high-speed electronic-optical phase modulators [16], high-speed acoustic-optical frequency shifters [17], linearly polarized beams [18], and 3x3 fused optical fiber couplers [6-8], the latter also in SD-OCT. Of all the phase shifting methods, quadrature detection with 3x3 fiber based couplers in SS-OCT has the advantage of simple implementation and no image corruption resulting from small phase shifts or birefringence variations.

The most basic setup for quadrature detection in FD-OCT is by using a 3x3 fused fiber coupler as shown in Fig. 4.8. Light from a swept source (or broadband source) is coupled into port 1 of the 3x3 fiber coupler and split up into a sample and reference arm. Back-reflected light from the sample arm and reference arm mirror goes back through the same 3x3 fiber coupler and is collected by two photo diodes (or two spectrometers). The optical intensity incident on the n\textsuperscript{th} detector (n = 1, 2, 3) due to a single reflection in the sample is [19]:

\[
I_n = I_0 \left[ \alpha_{11}\alpha_{1n} + \alpha_{13}\alpha_{3n} + 2E(\Delta x)(\alpha_{11}\alpha_{1n}\alpha_{13}\alpha_{3n})^1 \cos(2k\Delta x + \phi_n) \right] (4.12)
\]

where \(\alpha_{ab}\) is the power transfer coefficient from fiber \(a\) to fiber \(b\), \(k\) is the wave number, \(\Delta x\) is the path-length difference between reference and sample arms, \(E(\Delta x)\) is the interferometric envelope (i.e., magnitude of the complex signal), and \(\phi_n\) is the phase shift between the optically heterodyned fields when \(\Delta x = 0\). For a 3x3 fused fiber couplers, \(\alpha_{ab} = 1/3\) for all \(a\) and \(b\).
Figure 4.8: A schematic of FD-OCT using the 3x3 fused fiber coupler. $F_i$ ($i = 1, 2, 3$) indicates the output port of the coupler. $L$=lens, $D$= Detectors/Spectrometers.

Assuming a perfect reciprocity ($\alpha_{ab} = \alpha_{ba}$) and $\sum_a \alpha_{an} = 1$, for all $a, b$, based on the conservation of energy, the phase shift of the optical heterodyned signal satisfies the condition [19]:

$$\sum_n \sqrt{\alpha_{1n}\alpha_{3n}}\cos(\phi_n) = \sum_n \sqrt{\alpha_{1n}\alpha_{3n}}\sin(\phi_n) = 0$$

(4.13)

For quadrature FD-OCT, based on ideal 3x3 fused fiber couplers, Eq. (4.13) results in an interferometric phase shift between any two output ports to be $120^\circ$.

The complex conjugate artifact can be resolved by acquiring the complex interferometric signal and converting it to its quadrature components ($0^\circ$ and $90^\circ$). Defining the interferometric signal $I_n$ acquired at detector $D_n$ ($n = 1, 2, 3$) as the real part of the complex signal, the imaginary part can be obtained by using a trigonometric relationship [19]:

$$I_{im} = \frac{i_n\cos(\phi_m-\phi_n) - \beta_{mn}i_m}{\sin(\phi_m-\phi_n)}$$

(4.14)

where $i_n$ is the interferometric signal acquired at detector $D_m$ ($m = 1, 2, 3$, $m \neq n$), $\beta_{mn} = (\alpha_{1n}\alpha_{3n}/\alpha_{1m}\alpha_{3m})^{1/2}$ is the wavelength dependent power splitting ratio between detector ports $D_m$ and $D_n$. Equation (4.14) shows that the trigonometric relationship only works if the phase delay between the two interferometric signals is not an integer number of $180^\circ$. Sarunic et al. [7, 8] demonstrated the use of 3x3 fiber-based coupler to create quadrature interferometric signals in FD-OCT to suppress the complex conjugate artifact. As a result the unambiguous imaging depth is enhanced by a factor of two compared to conventional FD-OCT.

**Integrated optics 3x3 directional couplers**

Conventional 3x3 fused fiber couplers can be manufactured symmetrically in three dimensions. In contrast, in integrated optics, the 3x3 DC layout is in two dimensions. Therefore the coupling between the waveguides is inherently asymmetric. Furthermore, our calculations (not shown here) demonstrate that for integrated optics 3x3 directional couplers constructed using identical waveguides (similar width), the
interferometric phase shifts at the output waveguides are $0^\circ$, $180^\circ$ and $360^\circ$. Equation (4.14) shows that from a measurement at these angles it is impossible to create the quadrature components. Alternatively, Love et al. [20] proposed a 3x3 DC design based on varying waveguide width and varying gap width along the coupling region. In this design, the output power and phase at any output port can be designed to be not a multiple of $180^\circ$.

The structure of the integrated optics 3x3 DCs used by us is shown in Fig. 4.9. It consists of three waveguides in which the top (wg$_1$) and the bottom (wg$_3$) waveguides have identical widths and have the same gap width relative to the center waveguide (wg$_2$). In the coupling region, the widths of waveguide 1 and 3 ($w'$) are identical and differ from the width of wg$_2$ ($w$). In the integrated optics 3x3 DC geometry, power coupling only happens between two adjacent waveguides implying that $\alpha_{13} = \alpha_{31} = 0$.

The integrated optics 3x3 DC is fully characterized by the set of parameter ($w$, $w'$, $d$, $R$, $L$).

![Figure. 4.9: Schematic of an integrated optics 3x3 DC. wg$_i$ ($i = 1, 2, 3$) denotes the $i^{th}$ output waveguide.](image)

### 4.3.2 3x3 DC design, simulation and experiment

#### Waveguide design and simulations

Integrated optics 3x3 DCs are designed based on the two criteria:

- The waveguides are very weakly coupled
- The maximum power transfer between two adjacent waveguides is $66.7\%$ (i.e., the amplitude term $\kappa^2/\delta^2 = 2/3$ in Eq. (4.11))

The simulated power transfer coefficients of the integrated optics 3x3 DCs, $I_1:I_2:I_3$, is calculated by taking the ratio of the simulated light intensities at three output waveguides. Ideally, the power transfer coefficients for integrated optics 3x3 DCs are $1/3:1/3:1/3$, no matter which input waveguide is used.

BPM simulations are used to simulate the electric field (quasi-TE polarization) propagation in the directional couplers. Parameters such as the gap width $d$, coupling length $L$, S-bend radius $R$, waveguide widths $w$, $w'$ are optimized to adjust the
amplitude term and achieve the target power transfer coefficients. We investigate an integrated optics 3x3 DC structure with parameters \((w, w', d, R, L) = (2.0, 1.95, 2.3, 500, 623) \mu m\). The integrated optics 3x3 DCs are fabricated in SiON technology.

**Experiment**

Characterization and splitting ratio measurements of integrated optics 3x3 DCs are carried out similar to that of symmetric integrated optics 2x2 DCs as shown in Section 4.2.2. In the experiment, light from the swept source with TE polarization is coupled into either the top waveguide or the center waveguide and the output spectra are measured at the three output waveguides. Ignoring losses, the splitting ratios over the used bandwidth are calculated by taking the ratio between the output spectral intensities of a single component and the sum of the intensity of the three output spectra. The power transfer coefficient \((\alpha_{ab})\) at a certain wavelength is calculated by normalization of the measured splitting ratios at the same wavelength.

To investigate the inherent phase shift character of the integrated optics 3x3 DC, a fiber based swept source OCT is used with the integrated optics 3x3 DC at the output, as shown in Fig. 4.10. In the experiment, the back-reflected light from sample and reference arm can be coupled into any two input waveguides of the integrated optics 3x3 DC. Spectra at any two output waveguides of the integrated optics 3x3 DC are measured simultaneously. The phase shift of the interferometric signals at a particular wavelength is derived by measuring the wavelength shift between the two wave forms.

**4.3.3 Results and Discussion**

**Simulation results**

Figure 4.11 shows a BPM simulation of the electric field (TE polarization, \(\lambda_c=1300\) nm) propagating in the horizontal plane for the integrated optics 3x3 DC with the set of parameters \((w, w'; d, R, L) = (2.0, 1.95, 2.3, 500, 623) \mu m\). The dashed line indicates the boundary between the end-facet of the coupler (left) and the air region (right). As can
be seen in Fig. 4.11, for light launched from either the top input waveguide (a) or from
the center input waveguide (b), the light is split equally into the three output
waveguides of the integrated optics 3x3 DC. Since the integrated optics 3x3 DC is fully
symmetric with respect to light launched in waveguide 1 or 3, a simulation with light
launched from waveguide 3 is superfluous. The power transfer coefficients obtained
from the simulation are shown in Table 4.1.

![Figure 4.11: BPM simulation results of the electric field (TE polarization, \(\lambda=1300\ nm\))
propagating in the horizontal plane for an integrated optics 3x3 DC with \((w, w', d, R, L) = (2.0, 1.95, 2.3, 500, 623)\ \mu m.\)

<table>
<thead>
<tr>
<th>Light launched from</th>
<th>Power transfer coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Output waveguide 1 (top)</td>
</tr>
<tr>
<td>Waveguide 1 (top)</td>
<td>0.338</td>
</tr>
<tr>
<td>Waveguide 2 (center)</td>
<td>0.335</td>
</tr>
</tbody>
</table>

*Table 4.1: Simulated power transfer coefficients of an integrated optics 3x3 DC obtained from BPM simulations at \(\lambda = 1300\ nm.\)*

**Experimental results**

Figure 4.12 show the measured splitting ratio for the integrated optics 3x3 DC with set
of parameters \((w, w', d, R, L) = (2.0, 1.95, 2.3, 500, 623)\ \mu m.\) The measure power
transfer coefficients at 1300 nm wavelength are shown in Table 4.2. It can be observed
that the measured power transfer coefficients are not in good agreement with the
simulation results in Table 4.1.
Figure 4.12: Splitting ratio measurement as a function of wavelength for the integrated optics 3x3 DC. a) Light is launched into the top input waveguide. b) Light is launched into the center input waveguide.

<table>
<thead>
<tr>
<th>Light launched form</th>
<th>Power transfer coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Output waveguide 1 (top)</td>
</tr>
<tr>
<td>Waveguide 1 (top)</td>
<td>0.294</td>
</tr>
<tr>
<td>Waveguide 2 (center)</td>
<td>0.020</td>
</tr>
</tbody>
</table>

Table 4.2: Measured power transfer coefficients of an integrated optics 3x3 DC at 1300 nm

Figure 4.13 shows the interferometric measurements with the integrated optics 3x3 DC with parameters \((w, w', d, R, L) = (2.0, 1.95, 2.3, 500, 623) \ \mu m\). In this measurement, the back-reflected light from the sample and reference arm are coupled into the input waveguides 1, 2 respectively and the interference signals are collected at output waveguides 1 and 2. Due to the path length difference between the two arms in the interferometer a fringe can be observed in the spectrum. The phase shift between the two measured interference signals is clearly visible in the inset. At the center wavelength band \((\lambda_c = 1300 \ \text{nm})\) the measured phase shift is \(50^\circ\). The phase shift calculated from Eq. (4.13) using the measured power transfer coefficients of 3x3 DC in table 4.2 is \(68^\circ\).
Figure 4.13: Interferometric measurement performed with a Michelson interferometer and an integrated optics 3x3 directional coupler.

Discussion

A strong disagreement between the power transfer coefficients obtained from the simulation and from the measurement is attributed to either an inaccuracy of the effective refractive index used in the field simulations that are used as the input for the BPM simulation or due the fabrication errors. Moreover the measured phase shift is not in good agreement with the simulated phase shift. This difference is attributed to errors in determination of measured power transfer coefficients of the integrated optics 3x3 DC. However, with the current integrated optics 3x3 DC, the phase shift between the interferometric signals is 50° and the complex interferometric signals (0° and 90°) still can be calculated from the measured quadrature components for depth degeneracy removal using Eq. (4.14).

A balanced detection scheme in combination with depth degeneracy removal can be implemented simultaneously in integrated optics SS-OCT by using an integrated optics 3x3 DC combined with 2x2 DC as in Ref. [6]. In this way, the center output port of the 3x3 coupler is split using a 50:50 DC and two differential signals are constructed by combining two outputs of the 2x2 DC with the two remaining outputs of the integrated optics 3x3 DC. In this implementation an integrated optics attenuator can be used to balance the power between the outputs of the integrated optics 3x3 DC and the outputs of the 2x2 DC.
Chapter 4

4.4 Summary

In summary, we have designed, fabricated, and characterized symmetric 2x2 directional couplers for integrated-optics-based OCT. Our results show that a device with an average splitting ratio of 50:50 can be achieved, but that there is a rather strong dependence of the splitting ratio on wavelength. Using additional design and simulations we demonstrated that this problem can be solved by using an asymmetric DC geometry. We also present the design, fabrication, and measurements of an integrated optics 3x3 DC, which can be used in FD-OCT for depth degeneracy removal. The measured power transfer coefficients are not in agreement with the simulation results. The Interferometric measurements show a clear 50° phase shift between two output ports of the 3x3 DC at wavelength of 1300 nm. This phase shift can be remapped to the quadrature components, and clearly indicates that an integrated optics 3x3 DC can be applied in integrated optics SS-OCT for depth degeneracy removal.

4.5 References

Integrated-optics directional couplers for OCT


