Doctoral Thesis

Fabrication and System Integration of Single-Mode Polymer Optical Waveguides

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Fabrication and System Integration of Single-Mode Polymer Optical Waveguides

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for the degree of
Doctor of Science

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Abstract

The emergence of ever new user applications and advances in computing technology drive the growth of computational power and interconnection bandwidth. While traditionally down-scaling of the chip dimensions was sufficient to satisfy these needs, integration and interconnection aspects nowadays become more important as traditional electrical interconnects approach their performance limits. Since the 1980s, single-mode optical fibers have dominated the market for long distance optical communication. Current research efforts focus on short distances (mm – m) with optical technologies such as single- and multimode integrated polymer waveguides or active optical cables, as well as on very short distances (µm – mm) with silicon photonics.

In the present work, we identified direct laser written single-mode polymer waveguides as a promising solution for board-level optical interconnects with distances of cm – m. We demonstrate a range of building blocks to show the potential of the proposed waveguide technology. The success of this optical technology is, besides performance and reliability measures, mainly dependent on the implementation cost. A cheap fabrication technology, as well as smart and simple coupling concepts to active devices (e.g., lasers or photodetectors), to devices made in other fabrication technologies (e.g., silicon photonics chips) and to single-mode fibers (SMF) have to be available.

We studied two direct UV-patternable polymer materials, namely acrylates during the initial process development phase and polysiloxanes for the device fabrication. Together with Dow Corning Corporation, a novel polysiloxane material was developed with absorption losses as low as 0.2 dB/cm at the wavelength of 1.3 µm. Laser direct writing was selected as the most advantageous micro-patterning technique. Characteristics of laser writing include high flexibility, fast prototyping, scalability to large substrates and local position accuracy with respect to substrate.

By using a custom-built laser direct writing setup and optimizing the writing modes and fabrication parameters, we achieved the controlled fabrication of single-mode waveguides. A propagation loss of 0.28 dB/cm at the wavelength of 1.3 µm was achieved, including 0.2 dB/cm intrinsic material loss. We manufactured a range of well performing passive devices, including y-splitters, directional couplers, multimode interference
couplers and, for the first time with laser direct writing, an arrayed waveguide grating. The proper device functionalities and performances prove the feasibility of fabricating complex high-performance optical structures by laser direct writing.

We propose a novel integration concept of single-mode vertical cavity surface emitting lasers and polymer waveguides around the wavelength of 1.55 µm. The concept benefits from the unique advantages of the laser direct writing systems. By combining the writing head with a vision detection system, the waveguides were fabricated with a µm-accuracy relative to a VCSEL array, while using the contacts of the VCSEL as alignment marks. An estimated loss between 1.1 dB and 3.9 dB resulted as a combination between measured performance and simulated loss numbers.

When polymer materials are considered in optics, their reliability is often the decisive factor for the viability of the material. We performed a set of environmental tests on the polysiloxane materials and waveguide devices, including a relevant solvent compatibility study during the manufacturing process, a damp-heat test (85°C / 85% RH test conditions for 1000 h) and a temperature cycling test (with maximum temperature differences of 70°C). Neither the propagation loss nor the coupling ratio of a directional coupler showed significant changes during these tests.

We then developed a simple pluggable optical connector to interface the polymer waveguides with single-mode fibers. The concept relied on the accurate fabrication of alignment structures in the same fabrication step and layer as the core of the polymer waveguide. These sub-µm-precise alignment structures guided the placement of a silicon v-groove with a single-mode fiber embedded. A fiber-to-waveguide connector loss of 1.5 dB was measured.

All these building blocks combined show the potential of the proposed waveguide technology for the use in optical interconnects and potentially in other applications, such as sensing.
Zusammenfassung


Für die kontrollierte Fabrikation von Monomode-Wellenleitern verwendeten wir eine selbst entwickelte Laserdirektschreibanlage. Mit der Optimierung von Schreibmodi


Die Kombination aller dieser Bausteine zeigt das Potential der vorgestellten Wellenleitertechnologie für die Verwendung in der optischen Datenkommunikation und potentiell in anderen Anwendungsgebieten, wie z.B. in der Sensorik.
Chapter 1

Introduction

The emergence of ever new user applications and advances in computing technology drive the growth of computational power. For decades, the integration density of transistors in dense integrated circuits followed "Moore's law" by doubling approximately every two years [1]. With the integration density, other system aspects scale or be scaled accordingly, including the memory capacity and the interconnection bandwidth [2]. While traditionally down-scaling of the chip dimensions was sufficient to maintain the trend, nowadays new technologies and system architectural concepts must be developed to cope with electrical devices and interconnects reaching their physical limits. Integration and interconnection aspects become more important as traditional electrical interconnects approach the limits in terms of bandwidth and length. The demand for new technology to cover the bandwidth requirements affects interconnection networks at all levels of communication [3]. Tab. 1.1 illustrates how optical interconnects are employed at continuously shorter distances to replace electrical links. It is worth mentioning that with shrinking link length, the number of lines increases drastically. Since the 1980s, single-mode glass optical fibers are the standard for long distance communication (> 10 m), mainly due to very low propagation losses < 0.2 dB/km at the wavelength of 1.55 µm. Current research efforts focus on short distances (mm – m) with technologies such as single- and multimode integrated polymer waveguides or active optical cables, as well as on very short distances (µm – mm) with silicon photonics [4]. On chip level typically semiconductor based solutions are preferred, e.g. silicon or III-V semiconductors [5], due to the high refractive index contrast, compatibility with chip fabrication, and advanced fabrication techniques that can be adapted from the semiconductor chip technology. In the following research work, we focus on board-level optical interconnects with distances of cm – m.
Table 1.1: Deployment of optical links into shorter distance communication systems.

<table>
<thead>
<tr>
<th>Distance m – km</th>
<th>Distance mm – m</th>
<th>Distance µm – mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type</td>
<td>Technology</td>
<td>Status</td>
</tr>
<tr>
<td>Long-distance</td>
<td>Single-mode glass fibers</td>
<td>Established since 1980s</td>
</tr>
<tr>
<td>WAN, MAN, LAN</td>
<td>Single- and multimode integrated waveguides, optical fibers</td>
<td>Present time, near-future, research status</td>
</tr>
<tr>
<td>Rack, Board, Module, Chip-Chip</td>
<td>Silicon photonics</td>
<td>Research status</td>
</tr>
<tr>
<td>On-Chip Core-Core</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

1 Map of the submarine cables interconnecting the USA and Europe with optical fibers. [6]
2 Board-to-board optical link prototype applying embedded multimode polymer waveguides and a fiber bundle for the interconnection. [7]
3 Cross-sectional view of an IBM silicon nanophotonics chip combining optical and electrical circuits. [7]

1.1 Board level optical interconnects

Certain aspects, such as the integration density (connected to bandwidth), the power consumption, the reliability, and the cost determine the viability of integrating a board-level interconnection technology into a computing system [8], [9].

1.1.1 Key performance factors

Integration density On this scale, electrical data transmission is limited by high-frequency loss, channel crosstalk and bandwidth restrictions [3]. These restrictions lead to a limited bandwidth per channel and consequently, to a limited integration density. On the contrary, optical links with data rates up to 10 Gb/s/channel are currently the standard in many optical communication systems and efforts are targeting toward the implementation of 100 Gb/s (4 channels of 25 Gb/s). Optical links have been demonstrated with immensely high bandwidth densities, for example by applying a wavelength-
division multiplexing principle (e.g., 640 Gb/s within 80 µm of a printed circuit board [10]).
In our research, we exploited waveguide spacings of 62.5 µm which potentially allows
for high-density integration using waveguide arrays. The density limits for optics are fi-
nally given by packaging aspects. In terms of transmission distance, there are no limits
on board-level, aside from the attenuation of the signal caused by waveguide losses.

**Power consumption** An analysis of the power requirements for optical interconnects
can be found in [11]. Current estimates show that up to 200 times more energy is re-
quired to transport a bit in a computing system than to perform the logical operation
itself. The main argument why optical interconnects favor electrical links in terms of en-
ergy efficiency is centered around what capacitances have to be charged/discharged
for signal transmission. For electrical interconnections, sending a voltage pulse requires
the transmission line to be charged to the signal voltage. In optical interconnects, en-
ergy is required to charge the capacitance of the photodetector, which can potentially
be significantly below the one of the transmission line. Estimating the energy per bit
transmitted in an optical link is complex as it includes light generation, modulation,
transmission, and detection. The mentioned study argues that there are indications
that optical interconnects, starting from a link length of 50 µm, might be considered in
the future.

**Reliability** The reliability requirements for datacom devices are relatively high as com-
pared to other applications (e.g. sensors). Reasons include large component count in
systems, environmental operating conditions, and long lifetime. In Chap. 6 we discuss
the reliability standards in more detail.

**Cost** Finally, cost is the most important point that explains why optical interconnects
are not yet employed at all levels of communication. Transmission lines for high speed
electrical interconnects are produced at low cost and interfaced rather simply with signal
generation and detection. The components for an optical link are relatively expensive.
Additionally, the integration of the different optical system subparts is not trivial and a
range of sophisticated assembly and packaging concepts have to be developed to solve
this issue.

### 1.1.2 Waveguide technologies

Optical interconnects can be realized applying free space optics or guided optics. Free
space optics requires a clear transmission path between sender and receiver and there-
fore is applicable only to simple systems and systems without exposure to environmental influences (e.g., dust, fog, rain, etc.). Waveguide based interconnects, either fiber or integrated waveguide based, do not suffer from these disadvantages. Whether fibers or integrated waveguides are favorable, depends on the characteristics of the specific application, including, among others, criteria like link count, link length, density or technologies to interconnect. For example, for interconnects in the range of > 1 m, multimode fibers in combination with VCSELs around 850 nm are utilized in super computing systems and large data centers [4]. Systems based on single-mode glass fibers are also a potential solution. However, the manual connecting and the large fiber count disfavor this technology for smaller distances. An integrated waveguide solution prospects to reduce the manual assembly issue, fiber count and cost, similar to the introduction of printed circuit boards for electrical wiring [12]. Integrated waveguides are the favorable choice for systems, where the possibility of integrating complex light manipulation functions, such as power splitting, routing or wavelength filtering, is desirable.

A range of material systems are available for the integrated waveguide fabrication [13]. Based on the same material as glass fibers, silica-based integrated waveguides achieve very low propagation losses with high reliability. For board-level interconnects, the fabrication of modules in these dimensions is difficult and the costs are high. Semiconductor-based solutions, e.g. InP, are widely employed for waveguide devices, mainly due to their potential for integration with active devices, such as lasers and photodetectors. Similar to the silica-based waveguides, its utilization for dimensions up to 1 m is not feasible. We believe, that polymer is the material of choice, due to its rapid processability (potentially compatible to printed circuit board manufacturing), cost-effectiveness, high performance, and flexibility of material properties (e.g., refractive index tunability or possibility for doping) [14].

**Polymer waveguide technology** In terms of optical properties, cost effectiveness, and processing possibilities, integrated polymer waveguides are likely to play an important role in board-level interconnects [15]. Most of the research nowadays focuses on multimode waveguides providing data transmission around 850 nm [16]. Typical dimensions of single-mode waveguides in polymers are in the order of 2 – 8 µm, while multimode waveguides are an order of magnitude larger (30 – 100 µm), which makes multimode waveguides easier to fabricate. Around 850 nm, a range of high-performance VCSELs are commercially available and typical polymers show lower intrinsic material absorption as compared to longer wavelengths in the infrared [17]. However, long distance communication as well as on-chip integrated optical devices are usually single-mode and operate in the telecommunication frequency bands (around 1310 or 1550 nm). Additionally, single-mode technology allows for the integration of advanced multiplexing
1.2. Motivation and aim of this work

The aim of this thesis is to investigate the feasibility of single-mode polymer waveguides and devices for optical interconnects on board-level. The success of this optical technology is, besides performance and reliability measures, mainly dependent on the implementation cost being lower than electrical solutions. Both, the fabrication of the waveguides and devices and the packaging and system integration contribute to the total

concept, such as wavelength division multiplexing, helping to reduce the waveguide count [18]. Consequently, we focus on single-mode waveguides in this thesis.

Waveguide material and fabrication Particularly siloxanes exhibit many favorable properties including good thermal stability, tunable refractive index and mechanical properties, chemical resistance, and excellent photo-stability [19]. In consideration of these properties, Dow Corning Inc. [20] developed a new photo-patternable material set for characterization in a wide range of single-mode applications, which formed the basis for the presented waveguides. Various waveguide fabrication methods have been studied in the past, including non-photolithographic techniques (e.g. molding [21], [22]), indirect (e.g. photo-resist patterning combined with reactive ion etching [23], [24], [25]), and direct lithographic patterning (e.g. laser writing [26], [27] or mask lithography [28], [29]). Direct lithographic patterning methods are low-cost due to the absence of complex pattern transfer techniques, for example additional etching steps. We identified laser direct writing as the most versatile approach, with its favorable aspects of fast prototyping (no masks needed), scalability to large substrates, and local positional accuracy with respect to substrate.

The last point is of particular interest, as PCBs (manufacturing tolerances typically > 50 µm) are not compliant with the requirements for single-mode optics in terms of manufacturing precision. For instance, a lateral misalignment of two single-mode waveguides, as described in this thesis, of 1.7 µm leads to a simulated coupling loss of 1 dB. By combining the laser writing with a vision system, the position of the laser head can be adapted for substrate deformations and calibrated to local alignment marks.

The disadvantages of laser direct writing include the challenge of fabricating complex structures and the costs for mass production. The laser beam shape and size, as well as the mechanical properties of the positioner of the writing head, limit the range of possible structures. Laser direct writing is an inherently serial process; the fabrication time scales with the complexity and number of photonic devices, which then determines the costs for mass production.

1.2 Motivation and aim of this work

The aim of this thesis is to investigate the feasibility of single-mode polymer waveguides and devices for optical interconnects on board-level. The success of this optical technology is, besides performance and reliability measures, mainly dependent on the implementation cost being lower than electrical solutions. Both, the fabrication of the waveguides and devices and the packaging and system integration contribute to the total
cost. A cheap fabrication technology, as well as smart coupling concepts to active devices (e.g., lasers or photodetectors), to devices made in other fabrication technologies (e.g., silicon photonics chips) and to single-mode fibers (SMF) have to be available. An overview of the different aspects of the proposed board-level optical interconnect technology is given in Fig. 1.1. The fabrication of passive optical devices by direct laser writing, the polymer waveguides’ reliability, as well as system aspects for the integration of a passive optical link are studied, including the coupling of VCSELs to the waveguides and an interface to single-mode glass fibers. Despite this thesis’ strong focus on using waveguides in optical interconnects, other application fields are possible, such as sensing or interferometry. As particular example, an application in Fourier spectrometry is studied.

Figure 1.1: Schematic of the different parts of a board-level optical interconnects transmitter.

Chapter 2 gives an overview of the theory and the simulation of the optical waveguides and devices studied in the thesis. The simulations reveal the refractive index contrast targeted, minimum bending radius, and the dimensions for the passive optical devices, including y-splitters, directional couplers, multimode interference couplers, Mach-Zehnder interferometers, arrayed waveguide gratings and Bragg gratings.
1.2. Motivation and aim of this work

Chapter 3 exploits the fabrication of the above mentioned waveguides and devices by direct laser writing using a custom-build laser writing setup, including an introduction to the applied materials. Special emphasis is put on the fabrication challenges of the passive optical devices, such as directional couplers or arrayed waveguide gratings.

Chapter 4 focuses on a novel coupling concept of vertical cavity surface emitting laser arrays (VCSELs) to the presented single-mode polymer waveguide technology. We make use of the distinct advantages of direct laser writing over other fabrication techniques. The technology allows to locally position the laser writing head relative to alignment marks with sub-µm positional accuracy.

Chapter 5 discusses the measurements and analysis of the performances of the power splitting devices (Y-splitters, directional couplers and multimode interference couplers) and wavelength selective devices (Mach-Zehnder interferometers, Bragg gratings and arrayed waveguide gratings).

Chapter 6 looks at reliability testing in general and the specific measurements performed on the presented siloxane materials and laser direct written boards are discussed. The refractive index, waveguide propagation losses and the splitting ratio of a directional coupler are monitored during damp heat and temperature cycling tests.

Chapter 7 studies a mass-producible optical connector to the polymer waveguides using a passive alignment approach. The concept combines the precision of silicon v-grooves for alignment with the advantages of polymer waveguide laser direct writing.

Chapter 8 shows the fabrication and characterization of a Fourier spectrometer based on integrated waveguides and gold nanowires serving wave probes. A moving mirror mounted at the waveguide facet produces a standing wave pattern visualized by the optical antennas.
Chapter 2

Theory and simulation of optical waveguides and devices

Optical structures confining and guiding light, so called optical waveguides, are basic building blocks of integrated photonics. Various types of optical waveguides exist and are categorized according to, among others, the following criteria: number of modes (single-mode or multimode), geometry (planar, strip, ridge, or fiber waveguides), refractive index distribution (step or gradient index) and material (polymer, semiconductor, glass, etc.). In this chapter an introduction into the principles describing integrated dielectric waveguides and passive devices is given, as well as simulations thereof. First, the semi-analytical solution of a slab waveguide is calculated, starting off with the fundamental laws of electrodynamics, the Maxwell’s equations. Then the semi-analytical solution for rectangular waveguides is given applying the effective index approximation. The basics of the simulation algorithms used to describe the waveguides and devices in this thesis is shown. Using these tools, single-mode waveguides and a set of passive optical devices, including power splitting (y-splitter, directional, and multimode interference couplers) and wavelength selective devices (Mach-Zehnder interferometers, arrayed waveguide gratings, and Bragg gratings) are designed by simulation. The designs served as templates for the device fabrication and characterization discussed in the following chapters.

2.1 Description of light by electromagnetic fields

Electrical charges and currents generate electric and magnetic fields. James Clerk Maxwell was the first person to publish equations describing this phenomenon in 1861 [30], known as the Maxwell’s equations (see Eq. 2.1–2.4). $\vec{B}$ represents the magnetic flux density, $\vec{D}$ the electric flux density, $\vec{E}$ the electric field intensity, $\vec{H}$ the magnetic field...
intensity, $\vec{J}$ the free current density, $\vec{r}$ the space vector, $\rho$ the free electric charge density, $\nabla$ the divergence operator, $\nabla \times$ the curl operator, and $\frac{\partial}{\partial t}$ the time derivative.

$$
\nabla \times \vec{E}(\vec{r}, t) = -\frac{\partial}{\partial t} \vec{B}(\vec{r}, t) \tag{2.1}
$$

$$
\nabla \times \vec{H}(\vec{r}, t) = \vec{J}(\vec{r}, t) + \frac{\partial}{\partial t} \vec{D}(\vec{r}, t) \tag{2.2}
$$

$$
\nabla \vec{D}(\vec{r}, t) = \rho(\vec{r}, t) \tag{2.3}
$$

$$
\nabla \vec{B}(\vec{r}, t) = \vec{0} \tag{2.4}
$$

Materials are optically described by a set of material parameters; the permittivity $\varepsilon$, permeability $\mu$, and conductivity $\sigma$ of a material are complex valued and typically strongly frequency $\omega$ dependent.

$$
\vec{D}(\vec{r}) = \varepsilon(\vec{r}, \omega) \vec{E}(\vec{r}),
$$

$$
\vec{B}(\vec{r}) = \mu(\vec{r}, \omega) \vec{H}(\vec{r}),
$$

$$
\vec{J}(\vec{r}) = \sigma(\vec{r}, \omega) \vec{E}(\vec{r}),
$$

By applying the weakly guiding approximation [31] and by assuming stationary field components (see Eq. 2.5) and absence of charge and current sources ($\rho = 0$, $\vec{J} = \vec{0}$), the Helmholtz or wave equations can be derived (see Eqs. 2.6 & 2.7)\textsuperscript{1}. These partial differential equations describe the propagation of waves in optical waveguides. Its solutions are called the modes of the waveguide. The parameter $k$ is called wave vector and describes the phase velocity of the mode.

$$
\vec{E}(\vec{r}, t) = \vec{E}(\vec{r}) e^{j \omega t} \tag{2.5}
$$

$$
\Delta \vec{E} + \omega^2 \mu \varepsilon \vec{E} = (\Delta + k^2) \vec{E} = \vec{0} \tag{2.6}
$$

$$
\Delta \vec{B} + \omega^2 \mu \varepsilon \vec{B} = (\Delta + k^2) \vec{B} = \vec{0} \tag{2.7}
$$

$$
k^2 = \omega^2 \mu \varepsilon
$$

In this thesis, waveguides in polymer materials are studied, which belong to the material class of dielectrics. Dielectrics are electrical insulators, and thereby non-conductive; however they exhibit a characteristic permittivity and permeability. In photonics, a material’s optical properties are described by the refractive index, which is related to the two characteristics stated previously (see Eq. 2.8) and generally complex-valued. The

\textsuperscript{1}$\Delta$ represents the Laplacian operator. In the case of Cartesian coordinates, $\Delta = \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} + \frac{\partial^2}{\partial z^2}$
The real part indicates the phase velocity of light propagating through the medium. The imaginary part represents the light absorption.

\[ n = \sqrt{\mu \varepsilon} \]  

(2.8)

## 2.2 Optical waveguide fundamentals

Before going into details about the optical functionality studied in this work, the fundamentals of an optical waveguide are discussed. A basic optical waveguide is a structure consisting of two materials, whereas the core material exhibits a higher refractive index as compared to the surrounding cladding material. The light is mainly confined in the core and guided therein.

### 2.2.1 Slab waveguide

A dielectric slab waveguide is the most fundamental waveguiding structure and consists of a 3 layer stack, a core layer surrounded by two cladding layers. A sketch of the geometry is found in Fig. 2.1. The dielectric slab waveguide is analytically solvable and explains the basic principles of waveguides, such as mode field distribution or propagation constant [32].

![Figure 2.1: Schematic of a symmetric planar slab waveguide.](image)

Assuming propagation along the z-axis and to the homogeneity in this direction, the wave equation can be separated into a transversal and propagation direction dependent part.
\[ \Delta = \Delta_T + \frac{\partial^2}{\partial z^2} \]

The propagation direction solution corresponds to a plane wave ansatz (see Eq. 2.9).

\[ \vec{E}(\vec{r}, t) = \vec{E}_Te^{j(\omega t - k_z z)} \] \hspace{1cm} (2.9)

The problem is reduced to a set of partial differential equations for the transversal fields.

\[ (\Delta_T + k_T^2) \vec{E}_z(\vec{r}_T) = 0 \]
\[ (\Delta_T + k_T^2) \vec{H}_z(\vec{r}_T) = 0 \] \hspace{1cm} (2.10)

\[ k_T^2 = \omega^2 \mu \varepsilon - k_z^2 \]

The analysis of Maxwell’s equations leads to two distinct sets of linearly polarized solutions, TE modes \((E_z = 0, H_z \neq 0)\) and TM modes \((E_z \neq 0, H_z = 0)\). For TE modes the wave equations reduces further (see Eq. 2.11).

\[ \left( \frac{\partial^2}{\partial x^2} + k_i^2 - k_z^2 \right) H_z = 0 \] \hspace{1cm} (2.11)

\[ k_i = k_0 n_i \]

A solution ansatz for each region (top cladding, core, lower cladding) is chosen. The sine and cosine solutions in region 2 (core region) represent symmetrical and asymmetrical solutions).

- **Region 1:** \(x > d\)
  \[ H_z(x) = B e^{-(x-d)\sqrt{k_i^2-k_1^2}} \] \hspace{1cm} (2.12)

- **Region 2:** \(|x| < d\)
  \[ H_z(x) = A \begin{cases} \sin \left( x \sqrt{k_2^2 - k_z^2} \right) \\ \cos \left( x \sqrt{k_2^2 - k_z^2} \right) \end{cases} \] \hspace{1cm} (2.13)

- **Region 3:** \(x < -d\)
  \[ H_z(x) = -B e^{(x+d)\sqrt{k_i^2-k_1^2}} \] \hspace{1cm} (2.14)

The boundary conditions at the interfaces between region 1 and 2 and between 2 and 3 impose additional constraints for the solutions.
• Continuity \( H_z \) field:

\[
H_z(\pm d) = A \begin{cases} 
\pm \sin \left( d \sqrt{k_x^2 - k_z^2} \right) \\
\cos \left( d \sqrt{k_x^2 - k_z^2} \right)
\end{cases} = \pm B 
\]

• Continuity \( E_y \) field:

\[
E_y(\pm d) = j\omega \mu_2 A \begin{cases} 
\cos \left( d \sqrt{k_x^2 - k_z^2} \right) \\
\mp \sin \left( d \sqrt{k_x^2 - k_z^2} \right)
\end{cases} = \pm j\omega \mu_1 B \sqrt{k_x^2 - k_1^2}
\]

For the symmetric modes the calculations result in Eq. 2.15 and for the asymmetric ones in Eq. 2.16. The equations are solved using a numerical solver (e.g. MATLAB® [33]) or even a pocket calculator [34]. The solutions of the equation are the wave vectors \( k_z = k_0 n_{eff} \) in propagation direction of the different modes. Therewith and combining with Maxwell’s equations all field components can be determined for each mode. In Fig. 2.2 the electric field in y-direction \( E_y \) for the first 3 TE modes is sketched.

\[
tan \left( d \sqrt{k_x^2 - k_z^2} \right) = \frac{\sqrt{k_x^2 - k_1^2}}{\sqrt{k_x^2 - k_z^2}} \quad (2.15)
\]

\[
-cot \left( d \sqrt{k_x^2 - k_z^2} \right) = \frac{\sqrt{k_x^2 - k_1^2}}{\sqrt{k_x^2 - k_z^2}} \quad (2.16)
\]

**Figure 2.2**: Electric field \( E_y \) of the first 3 TE modes of a slab waveguide.

If only one solution for these equations exists, then the waveguide only supports one mode and is called single-mode. The structure parameter \( V(\omega) \) can be used to indicate
the cut-off frequency of the higher order modes (see Eq. 2.17, \( V < \frac{\pi}{2} \) for single-mode operation).

\[
V(\omega) = \sqrt{(dk_{T1})^2 + (dk_{T2})^2} = k_0 d \sqrt{n_2^2 - n_1^2}
\]  
(2.17)

The calculations are very similar for TM modes and lead to an equivalent set of equations.

### 2.2.2 Rectangular strip waveguide

Planar waveguides in practical implementations need in addition to the vertical (slab waveguide) a horizontal confinement to allow for several waveguides next to each other in a film. A rectangular strip waveguide, as used for the devices presented in this thesis, is shown in Fig. 2.3.

Unfortunately, no analytical solution exists for this structure [13]. Several methods using numerical tools (e.g. numerical mode solvers, as presented in Sec. 2.3.1) or approximations (e.g. the effective index approximation [35] or the Marcatili method [36]) exist.

#### 2.2.2.1 Effective index approximation

The effective index approximation assumes that the 2-dimensional geometry is separable into 1-dimensional geometries (see Eq. 2.18). The problem of a rectangular waveguide is split into 3 sections of slab waveguides stacked in x-direction (see Fig. 2.4, sections 1, 2 and 3). For each section, the effective refractive index \( n_{eff} \) (see Eq. 2.19)
2.2. Optical waveguide fundamentals

for the individual modes and polarizations is calculated assuming an infinite extension in y-direction. The semi-analytical method described in the previous section can be applied to find \( n_{\text{eff}} \). The effective refractive index \( n_{\text{eff}} \) of the rectangular waveguide results finally from a slab waveguide stacked up in y-direction (see Eq. 2.20). The ansatz for the field components are similar to Eq. 2.12-2.14. The resulting modes are labeled TE\(_{xy}\) and TM\(_{xy}\), where x stands for the mode order in the x-direction and y for the y-direction.

\[
E(x, y) = X_1(x)Y_1(y), \quad H(x, y) = X_2(x)Y_2(y)
\]

\[
n_{\text{eff}1} = f(n_{\text{core}}, n_{\text{clad}}, h)
\]

\[
n_{\text{eff}} = f(n_{\text{eff}1}, n_{\text{eff}2}, n_{\text{eff}3}, w)
\]

Figure 2.4: Effective index approximation: The rectangular waveguides is divided into 3 regions of slab waveguides (1,2,3) with effective refractive indices \( n_{\text{eff}1} \), \( n_{\text{eff}2} \) and \( n_{\text{eff}3} \).

The effective index approximation method is a very useful algorithm to estimate basic parameters of a waveguide, among others, the effective index, the cut-off wavelength for higher order modes or for a given structure the number of modes. As an example, the dispersion relation of a quadratic waveguide for 2 different material systems is shown in Fig. 2.5\(^2\).

\(^2\)The wavelength dependence of the refractive index is neglected and the data is chosen according to the siloxane material generation 1 and generation 2 introduced in Sec. 3.1
Figure 2.5: Dispersion relations and dependence of the effective index of quadratic waveguides on dimensions for the first 4 modes and TE polarization calculated with the effective index method: (top left) Dispersion relation of a $8 \times 8 \mu m^2$ waveguide with $n_{\text{core}} = 1.5100$ and $n_{\text{clad}} = 1.5055$, (top right) dispersion relation of a $5.5 \times 5.5 \mu m^2$ waveguide with $n_{\text{core}} = 1.3892$ and $n_{\text{clad}} = 1.3805$, (bottom left) effective index dependence on dimensions with $n_{\text{core}} = 1.5100$ and $n_{\text{clad}} = 1.5055$ at $\lambda = 1.55 \mu m$, and (bottom right) effective index dependence on dimensions with $n_{\text{core}} = 1.3892$ and $n_{\text{clad}} = 1.3805$ at $\lambda = 1.31 \mu m$.

For quadratic waveguides, the fundamental mode’s (TE$_{00}$) cut-off wavelength is indefinitely high and its refractive index changes from $n_{\text{clad}}$ for high wavelengths to $n_{\text{core}}$ for lower ones. This is explained by the higher confinement of the mode in the core region for lower wavelengths or higher frequencies. The higher order modes show distinct cut-off wavelengths, above which the modes are not guided. For the presented waveguide
material examples, the respective dimensions for single-mode operation are in case (left) around \(8 \times 8 \mu m^2\) for a wavelength of 1.55 \(\mu m\) and (right) around \(5.5 \times 5.5 \mu m^2\) for a wavelength of 1.31 \(\mu m\). These dimensions were used for the waveguide fabrication examined in the next chapter.

### 2.2.3 Bending loss

An important factor in the choice of refractive index contrast, structure and dimensions during the waveguide design is the bending loss. Marcuse derived an analytical approximation for the bending loss of 2-dimensional waveguides in [37], which was later studied and verified by several groups (e.g. in [38], [39]). The formula for the attenuation coefficient \(\alpha_{\text{bend}}\) is given in Eq. 2.21. Notice that 3-dimensional waveguides can be reduced by the effective index method to 2-dimensional ones. The transmission through a bend of radius \(r\) and angle \(\phi\) is given in Eq. 2.22, the corresponding loss in dB in Eq. 2.23.

\[
\alpha_{\text{bend}} = \frac{\alpha_y^2}{k_0 n_{\text{eff}} (1 + \alpha_y w/2) (n_{\text{eff}f_2}^2 - n_{\text{eff}f_1}^2)} e^{\alpha_y w} e^{-\frac{2\alpha_y^2}{n_{\text{eff}}^2 k_0^2 r}} \tag{2.21}
\]

\[
\alpha_y = k_0 \sqrt{n_{\text{eff}}^2 - n_{\text{eff}f_1}^2}, k_y = k_0 \sqrt{n_{\text{eff}f_2}^2 - n_{\text{eff}f_1}^2}
\]

\[
T_{\text{bend}} = e^{-\alpha_{\text{bend}} \phi r} \tag{2.22}
\]

\[
L_{\text{bend}} = -10 \log_{10} (T_{\text{bend}}) \tag{2.23}
\]

Figure 2.6 shows the estimated bending loss for a 90\(^o\) bend in function of the radius \(r\) for the two material systems considered. A significant bending loss is estimated to occur below a radius of 20 mm for case (left) and below 6 mm for case (right).

The center peak of the mode in a bent waveguide is shifted from the center towards the outside of the bend. Therefore the overlap of the mode with the sidewalls is increased, which is potentially an additional loss source if the sidewalls exhibit roughness.

Not only the loss in the bends, but also the loss at the transition from straight to bent waveguide has to be taken into account for minimum bending radius and loss determination. The transmission \(T\) through a transition between two different 2-dimensional waveguide sections with modes \(E_1\) and \(E_2\) is given in Eq. 2.24 (3-dimensional waveguide again can be simplified by the effective index approximation).

\[
T = \left| \int_{-\infty}^{\infty} E_1(y) E_2^*(y) dy \right| \left/ \int_{-\infty}^{\infty} E_1(y) E_1^*(y) dy \int_{-\infty}^{\infty} E_2(y) E_2^*(y) dy \right| \tag{2.24}
\]
Chapter 2. Theory and simulation of optical waveguides and devices

By approximating the mode of a straight waveguide by a Gaussian profile (see Eq. 2.25) and its radial dependence in a bend according to Eq. 2.26, a simple formula for the straight-to-bend transition $T_{sb}$ was found by [40]. The transition characteristics in dependence of the radius of the bent waveguide is shown in Fig. 2.7. The graph shows that for the considered material system, the bending radius is confined mainly by the bending loss and not by the transition loss. For the device design the transition loss therefore was negligible.

\begin{align*}
E_0(y) &= Ae^{-(y/(2\omega_0))^2} \\
E(y) &= E_0(y) \left[ 1 + \frac{1}{\rho^2} (k_0 n_{core} \omega_0)^2 y \right] \\
T_{sb} &= \frac{1}{1 + \left( \frac{k_0 n_{eff core} \omega_0}{2\rho^2} \right)^4 \omega_0^2}
\end{align*}

2.3 Optical simulation tools

Optical waveguide simulation tools are coarsely divided into mode solvers, wave propagators and transmission system simulators. Analytical solutions for the mode profiles
and effective indices exist only for a few simple structures. Therefore several mode solvers were developed based on different methods with different complexity and application fields. Among them are finite element method (FEM) based solvers (discussed in Sec. 2.3.1), plane-wave expansion [41], transfer-matrix [42], eigenmode expansion methods [43] and others. Wave propagation techniques are essential for the design of waveguide devices and describe the propagation of the modes in optical structures. Among these techniques are the beam propagation method (BPM) based tools (discussed in Sec. 2.3.2), finite difference time domain [44], FEM, transfer-matrix and eigenmode expansion methods. Transmission system simulators calculate the properties of systems composed of individual components at different levels, ranging from measured to detailed physical models, e.g. to calculate submarine communication systems.

### 2.3.1 Finite-element based mode solvers

The finite-element method is a technique for finding numerical solutions to boundary value problems for partial differential equations (PDE) [45]. In the case of 2-dimensional mode calculations for a dielectric waveguide, the PDE for the independent field component $H_z$ is shown in Eq. 2.27 (reformulation of the Helmholtz equations in Eq. 2.10).

\[
-\nabla \left( n^{-2} \nabla H_z \right) - k_0^2 H_z = -k_z n^{-2} H_z
\]  

(2.27)
The method divides the problem into small finite-size elements (meshing). For each of these elements a set of equations (the PDE describing the physics and boundary conditions) is assigned. The systematical recombination of the finite-elements approximate the behavior of the larger domain or problem. Starting from an initial solution, variational methods are typically iteratively used to minimize the error function for the solution [46].

Oftentimes, the physical problems have open boundaries, e.g. in the case of waveguide modes, the electro-magnetic fields decay exponentially and infinitely in the cladding material. The simulation domain is reduced to finite size by setting proper boundary conditions. A commonly used approach is the perfectly matching layer (PML). It absorbs waves without reflections back into the inner computation domain [47].

FEM mode calculation for a rectangular dielectric waveguide

In the specific case of a rectangular dielectric waveguide, the symmetry of the geometry can be used to reduce the calculation domain. The electro-magnetic fields in the xy-plane are symmetrical along the x- and y-axis (see Fig. 2.3). Therefore, the tangential component of either the electric field (perfect electrical conductor, see Eq. 2.28) or the magnetic field (perfect magnetic conductor, see Eq. 2.29) has to vanish at the symmetry axis.

\[
\vec{n} \times \vec{E} = \vec{0} \quad (2.28)
\]

\[
\vec{n} \times \vec{H} = \vec{0} \quad (2.29)
\]

We used the commercial FEM solver software package COMSOL Multiphysics ® [48] for the mode simulations of the polymer waveguides.

The fundamental mode (TE\(_{00}\)) of a typical quadratic waveguide simulated with the FEM mode solver is shown in Fig 2.8. Plotting the norm of the electric field along the horizontal and diagonal axis shows that the rotationally asymmetric refractive index profile only slightly distorts the mode as compared to a circular profile (used for example in single-mode glass fibers). The calculated effective index \(n_{eff00} = 1.50751\) is in good agreement to the effective index method based calculated \(n_{eff00} = 1.50760\).

FEM based simulations suffer from the fact that the number of elements scales with the size of the simulated object. Especially for 3-dimensional simulations the method is limited to small simulation spaces. For optical waveguide device simulations, other techniques are better suited.
2.3. Optical simulation tools

Figure 2.8: Fundamental mode profile for an 8 x 8 µm² waveguide with \( n_{\text{core}} = 1.5100 \), \( n_{\text{clad}} = 1.5055 \) and TE polarization at \( \lambda = 1.55 \mu m \) simulated with an FEM mode solver: (left) the norm of the electric field and its direction indicated by the arrows and (right) the norm of the electric field along the horizontal and diagonal axis.

2.3.2 Beam propagation method based simulations

The optical devices were simulated applying the beam propagation method (BPM). BPM bases on the paraxial or slowly varying envelope approximation of the Helmholtz equations [49]. Assuming propagation mainly in z-direction and slowly varying in that direction (see Eq. 2.32)\(^3\), the fields \( \phi \) are separated in a slowly (\( u \)) and a fast varying part (see Eq. 2.30)\(^4\). These expressions change the Helmholtz equations for scalar fields (see Eq. 2.31) to the paraxial form (see Eq. 2.33).

\[
\phi(x, y, z) = u(x, y, z)e^{jkz} \tag{2.30}
\]

\[
\frac{\partial^2 u}{\partial z^2} + 2jk \frac{\partial u}{\partial z} + \frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} + (k^2 - \bar{k}^2) u = 0 \tag{2.31}
\]

\[
\left| \frac{\partial^2 u}{\partial z^2} \right| \ll \left| \frac{\partial u}{\partial z} \right| \tag{2.32}
\]

\(^3\)The slowly varying envelope approximation reveals a shortcoming of the method; structures with abruptly changing properties in propagation direction, e.g., coupling of a polymer to a silicon waveguide, are inaccurately simulated.

\(^4\)\( \bar{k} \) is the reference wavenumber representing the average phase variation of the field \( \phi \)
\[
\frac{\partial u}{\partial z} = \frac{j}{2k} \left( \frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} + (k^2 - \bar{k}^2) u \right) = 0
\] (2.33)

Knowing the in-plane fields of a problem, the z-dependence of the fields can be determined by integration applying, e.g., a finite-difference approach [50], [51]. The finite-difference approach relies on discretizing the space and knowing the field in the xy-plane at the position \( z_0 \). Subsequently Eq. 2.33 determines the field at \( z_0 + dz \). By repeating this step, the field is propagated along the z-axis.

The simulation results presented were obtained by the BPM solver BeamPROP ® by RSOFT Design [52].

### 2.4 Passive waveguide devices

Besides simple waveguides, this project studied the fabrication of passive waveguide devices. Single-mode waveguides in boards can be used to form devices for power splitting or wavelength filtering. In the following sections, the design and simulation of several passive devices is shown.

#### 2.4.1 Power splitting devices

The basic waveguide device is a splitter, which functions as an input power distributor into power fractions at the output ports. This is used, for example, to divide the power from a laser over several waveguides or as basic block for more complex functionality (e.g. Mach-Zehnder interferometers).

##### 2.4.1.1 Y-splitters

**Theory**

The simplest waveguide geometry for 50:50 power splitting is a y-splitter. A waveguide at the input is branched out symmetrically into 2 output ports. An ideal y-splitter shows no wavelength dependence and a symmetric coupling ratio. By choosing a smooth transition in the branching region, the loss of the device can be minimized.
2.4. Passive waveguide devices

Simulations

From a laser direct writing fabrication point of view, the straightforward y-splitter implementation consists of a straight waveguide and two circular bends with radius \( r \) separating from the branching region (see Fig. 2.9). Using a BPM simulation, the behavior of the structure can be predicted. For the material system chosen in the simulations a minimum radius of 10 mm for the best performance of around 0.5 dB loss and symmetric coupling results.

![BPM simulations of a y-splitter with circularly spreading output branches with 5.5 x 5.5 \( \mu m^2 \) waveguides with \( n_{\text{core}} = 1.3892, n_{\text{clad}} = 1.3805 \) and TE polarization at \( \lambda = 1.31 \mu m \): (left) normalized modal power simulated in a y-splitter with \( r = 15 \text{ mm} \) and (right) output branch power in dependence of the radius of the branches.](image)

**Figure 2.9:** BPM simulations of a y-splitter with circularly spreading output branches with 5.5 x 5.5 \( \mu m^2 \) waveguides with \( n_{\text{core}} = 1.3892, n_{\text{clad}} = 1.3805 \) and TE polarization at \( \lambda = 1.31 \mu m \): (left) normalized modal power simulated in a y-splitter with \( r = 15 \text{ mm} \) and (right) output branch power in dependence of the radius of the branches.

2.4.1.2 Directional couplers

Theory

The coupling ratio for a power distributor is oftentimes required to be different from 50:50, e.g., 99:1 couplers can be applied for power monitoring without significant loss of signal power. A directional coupler is a 4-port device where 2 waveguides are fabricated in close vicinity to each other and power is coupled through the evanescent field components of the modes in the individual waveguides (the geometry is sketched in Fig. 2.10). Directional coupler allow tuning of the splitting ratio by choosing the proper length and waveguide separation of the device [53].
Using the coupling mode theory, the behavior of a directional coupler can be predicted semi-analytically [54]. In this approach the geometry is divided into a collection of individual waveguides with independent modes that are being perturbed by the refractive index profile of the surrounding waveguides. The perturbations lead to coupling and power exchange between the individual modes [55]. The coupling is characterized by the coupling coefficient $\kappa$, which is basically an overlap integral of the two waveguide modes over the region perturbed by $\delta n$ (see Eq. 2.34). The amplitude of the electric fields in the waveguides in dependence of the propagation distance in the coupler is shown in Eq. 2.36. The light power is coupled from one to the other branch with a $\sin^2(\kappa z)$-behavior. Considering the amplitude of one of the input fields (e.g. $E_{in,1}$), the transmitted branch $E_{01}$ is called bar state and the coupled branch $E_{02}$ the cross state.

$$\kappa_{12} = \frac{k_0^2}{2k_z} \int y E_1^*(y) \delta n^2 E_2(x) dx$$  \hspace{1cm} (2.34)

$$\begin{bmatrix} E_1(z) \\ E_2(z) \end{bmatrix} = \begin{bmatrix} \cos(\kappa z) & -j\sin(\kappa z) \\ -j\sin(\kappa z) & \cos(\kappa z) \end{bmatrix} \times \begin{bmatrix} E_{in,1} \\ E_{in,2} \end{bmatrix}$$  \hspace{1cm} (2.35)

### Simulations

BPM method based simulators are suitable for directional coupler geometries. A 50:50 directional coupler and the dependence of the coupler length and waveguide separation on the coupling ratio are simulated in Fig. 2.10. The results verify the mutual coupling calculated in Eq. 2.36 and show the exponential behavior of the coupling coefficient $\kappa$ in dependence of the waveguide separation.

#### 2.4.1.3 Multimode interference couplers

The performance of directional couplers is strongly dependent on the fabrication accuracy of the waveguide separation in the coupling region (see Fig. 2.10 for a given coupler length). Multimode interference (MMI) couplers on the other hand hold the advantage of reduced polarization and wavelength dependence and of relaxed fabrication accuracy tolerances [56].

### Theory

MMIs are based on the principle of self-imaging of an input field in a multimode waveguide structure (supporting a large number of modes), meaning that the field pattern is
2.4. Passive waveguide devices

![Figure 2.10: BPM simulations of a directional coupler with circularly approaching waveguides of 5.5 x 5.5 µm² with \( n_{\text{core}} = 1.3892, n_{\text{clad}} = 1.3805, r = 15 \text{ mm} \) and TE polarization at \( \lambda = 1.31 \text{ µm} \): (left) modal power of a 50:50 directional coupler with \( d_{\text{sep}} = 5.8 \text{ µm} \) and \( l_{\text{cpl}} = 3.7 \text{ mm} \) and (right) modal power of the bar state in dependence of \( d_{\text{sep}} \) and \( l_{\text{cpl}} \).]

reproduced in multiple images at periodic intervals along the propagation direction (see Fig 2.11). The input field excites a number of modes with different propagation constants that show interference patterns and at a specific length image again the input field. At the input of the device typically a single-mode waveguide produces the input field and at the end the imaged field is coupled again into single-mode waveguides, positioning and number according to the device function.

Simulations

This project focused on 1x2 MMIs, although the principles hold for arbitrary NxM configurations. BPM simulations were carried out to calculate the device dimensions and performance. In Fig. 2.11, a MMI structure with 30 µm output waveguide separation and a centric input waveguide was simulated. For 1x2 MMIs, although the principles hold for arbitrary NxM configurations. BPM simulations were carried out to calculate the device dimensions and performance. In Fig. 2.11, a MMI structure with 30 µm output waveguide separation and a centric input waveguide was simulated.

For a directional coupler a small change in coupling waveguide separation has an ex-
ponential effect on the coupling ratio. A variation of the waveguide separation in the coupling region of the directional coupler presented in Fig. 2.10 from 5.8 µm to 5 µm changes the coupling ratio from 50:50 to 10:90. The fabrication tolerances for MMI structures are significantly relaxed. Misaligning one of the output waveguides of the MMI shown in Fig. 2.11 by 1 µm changes the coupling ratio only by around 1.2 %.

Figure 2.11: BPM based simulations of a 1x2 multimode interference coupler with 30 µm output waveguide separation and 5.5 x 5.5 µm² waveguide cross sections with \( n_{\text{core}} = 1.3892 \), \( n_{\text{clad}} = 1.3805 \), TE polarization at \( \lambda = 1.31 \mu\text{m} \): (left) simulated modal power of a 50:50 MMI with \( w_{\text{MMI}} = 58 \mu\text{m} \) and \( l_{\text{MMI}} = 2.03 \text{mm} \) and (right) modal power of the output branches in dependence of \( w_{\text{MMI}} \) and \( l_{\text{MMI}} \).

### 2.4.2 Wavelength selective devices

Multiplexing and demultiplexing (filtering) of optical signals is essential for wavelength division multiplexing systems and is also applied in certain sensor applications. While many simple waveguide structures have a wavelength dependence (e.g. the directional couplers), a large range of wavelength selective devices exists for specific applications.

- Mach-Zehnder interferometers are typically used as active devices for the electrical modulation of an optical signal. Operated passively, they act as periodic wavelength filters.
- Bragg gratings are used as filters with very narrow bandwidth.
2.4. Passive waveguide devices

- Arrayed waveguide gratings are multiplexing devices for a specific number of wavelength channels with defined spacing.

2.4.2.1 Mach-Zehnder interferometers

Theory

A Mach-Zehnder interferometer (MZI) is built up of an input coupler (e.g. directional couplers) that divides the optical power at the input into two two waveguide arms (power splitting ratio $\varepsilon : 1 - \varepsilon$). After traveling through these separate arms the signal is recombined by an output coupler. The path length difference and therewith the phase difference acquired ($\Delta \phi = \phi_1 - \phi_2$) in the two arms is wavelength dependent and leads to a constructive/destructive interference pattern with changing wavelength. In an active configuration the path length difference is modulated. This is achieved by applying an electrical voltage and change of the refractive index by the electro-optical effect [53]. MZIs are mathematically described with a similar matrix formalism as the directional couplers.

\[
\begin{bmatrix}
E_{\text{out},1} \\
E_{\text{out},2}
\end{bmatrix} =
\begin{bmatrix}
\sqrt{1-\varepsilon} & j\sqrt{\varepsilon} \\
 j\sqrt{\varepsilon} & \sqrt{1-\varepsilon}
\end{bmatrix}
\begin{bmatrix}
e^{-j\phi_1} & 0 \\
 0 & e^{-j\phi_2}
\end{bmatrix}
\begin{bmatrix}
\sqrt{1-\varepsilon} & j\sqrt{\varepsilon} \\
 j\sqrt{\varepsilon} & \sqrt{1-\varepsilon}
\end{bmatrix}
\begin{bmatrix}
E_{\text{in},1} \\
E_{\text{in},2}
\end{bmatrix}
\]

Simulations

Figure 2.12 shows the power transfer function of a MZI and its dependence on loss in the delay line and coupling variations. Loss in the delay line reduces the extinction ratio as well as the transmission at constructive interference in the bar and the cross state. Asymmetric coupling, if for the input and output coupler equal, affect only the bar state with reduced extinction.

2.4.2.2 Arrayed waveguide gratings

Arrayed waveguide gratings (AWGs) are used as wavelength (de)multiplexers with the goal of combining multiple wavelength channels into a single waveguide in wavelength division multiplexed (WDM) systems [57], [58]. A typical configuration is illustrated in Fig. 2.13.
Figure 2.12: Power transfer characteristics calculated by a transfer matrix model of a MZI with $n_{\text{eff}} = 1.3848$ and $\Delta l = 50 \, \mu m$ at $\lambda = 1.31 \, \mu m$: (left) transfer function in dependence of delay line loss ranging from 0 to 3 dB in 0.5 dB steps (highest extinction in lossless case) (right) transfer function in dependence of coupling ratio of both couplers ranging from 50:50 to 60:40 in 2 \% steps (highest extinction with 50:50 coupling).

Figure 2.13: Schematic of an arrayed waveguide grating showing input and output waveguides, the input and output star couplers (free space propagation regions) and the arrayed waveguides.

Theory

The operation of an AWG can be described as follows: the light of one or several input waveguides is coupled into an arrayed waveguide section. In Fig. 2.13 a star coupler with a free space propagation region is used therefore (see Fig. 2.14), although also other implementations have been demonstrated (e.g. MMI couplers [59]). At the central wavelength $\lambda_0$ of the device, the path length difference $\Delta L$ between adjacent arrayed
waveguides corresponds to a multiple of the wavelength in the media (see Eq. 2.37, \( m \) is the order of the arrayed waveguides).

\[
\Delta L = \frac{m \lambda_0}{n_{\text{eff}}} \quad (2.37)
\]

The arrayed waveguides are recombined in a second identical star coupler into the output waveguides. For the central wavelength, the relative phases of the light in the arrayed waveguides are equal, causing a refocusing of the beam at the same position as in the input coupler. Other wavelengths exhibit a relative phase difference between the arrayed waveguides, leading to a tilted phase front and refocusing at a specific angle compared to the central channel. The output waveguides reconfine the light into waveguides and are placed at determined angles to collect the wanted wavelength range.

A detailed mathematical analysis of the operation of an AWG can be found in [59]. The most important characteristics are listed below.

![Figure 2.14: Schematic of a star coupler based on Rowland circles.](image)

The dispersion \( D \) describes the lateral displacement of a specific wavelength at the output plane of the output coupler and guides the spacing of the waveguides (see Eq. 2.38). \( n_{gr} \) stands for the ground index, \( n_{sc} \) for the index in the star coupler slab waveguide, and \( \Delta \alpha \) for the angular offset between two arrayed waveguides.

\[
D = \frac{ds}{df} = \frac{\lambda_0 n_{gr} \Delta L}{c n_{sc} \Delta \alpha} \quad (2.38)
\]
\[ \tilde{n}_{gr} = n_{gr} + f \frac{dn_{gr}}{df} \]

At \( \lambda_0 \) the arrayed waveguides exhibit all the same phase at the input of the output coupler, while a change of the wavelength can result in a change of the relative phase to a multiple of \( 2\pi \). This periodicity of the arrayed waveguides determines the free spectral range (FSR) (see Eq. 2.39).

\[ \Delta f_{FSR} = \frac{f_c}{m \tilde{n}_{gr}} \]

Insertion loss of the devices is dominated by coupling loss between the free space propagation region and the arrayed waveguides and by diffraction of light into undesired orders. The waveguides should therefore taper adiabatically and touch each other at the star coupler interface. The far-field intensity of the individual waveguides reduces from the center to the outer waveguides in the image plane, resulting in channel non-uniformity. The bandwidth of an individual channel depends on the overlap of the imaged field with the output waveguide mode field. The bandwidth therefore is related to the spacing of the output waveguides in the image plane of the output coupler. Approximate formulas for these parameters can be found in [59].

**Simulations**

AWGs have numerous design degrees of freedom and several design approaches are possible. The design approach chosen in this work is described below.

As a starting point the material system is given and determines the minimum bending radius in the device. First, the center wavelength \( \lambda_0 \) of the device, as well as the channel spacing and the number of wavelength channels is chosen. Therewith the number of input and output channels are given. An increase of channel uniformity is possible by selecting a higher number of wavelength channels than output waveguides. Choosing more than 4 times the number of channels as arrayed waveguide count has proven to be a solid rule of thumb [60]. Subsequently, the crosstalk level requirements set the spacing of the waveguides in the output plane of the output star coupler. The spacing of the arrayed waveguides is chosen so that the overlap of far-field at the image plane of the input coupler and the waveguide modes is maximal in order to couple all light into the arrayed section. This spacing is partly determined by the possibilities of the fabrication process. In a next step, the radii for the Rowland circles in the star couplers are set according to Eq. 2.40. Then, the length increment of the arrays is given from Eq. 2.37 using Eq. 2.41. This increment, together with the Rowland radii
and the waveguide spacing, sets the configuration of the AWG, e.g., the angle of the star couplers.

\[ r_o = \frac{n_{sc} d_i d_o}{m \Delta \lambda} \]  
\[ m = \frac{\lambda_0}{\#_{channel} \Delta \lambda} \]  

After setting the geometrical parameters and the desired characteristics, the device is simulated with the BPM software. Special attention is given to the star coupler design. As indicated in Fig. 2.14, the waveguides after fabrication tend to taper slightly approaching the free space propagation region, which affects the far-field pattern at the output plane.

\[ \text{Figure 2.15: BPM simulations of a 1 x 8 arrayed waveguide grating with } 5 \text{ nm channel spacing, 8 wavelength channels, 40 arrayed waveguides, grating order 33, 20 } \mu \text{m input and } 18.5 \mu \text{m output waveguide spacing, minimum bending radius of } 15 \text{ mm, device area of } 22.2 \times 7.2 \text{ mm}^2, 5.5 \times 5.5 \mu \text{m}^2 \text{ waveguide cross sections with } n_{\text{core}} = 1.3892, n_{\text{clad}} = 1.3805, \text{ and TE polarization around } \lambda = 1.3 \mu \text{m}. \]

The results from the simulations of an 1 x 8 AWG around 1.3 \mu m with 5 nm channel spacing and > 30 dB channel extinction for the central channels is shown in Fig. 2.15. The device shows an insertion loss of only 0.3 dB for the central channels, a non-uniformity
of 5.6 dB, and channel extinction of 34 dB for the central and 8.5 dB for the outer channels. The non-uniformity and channel extinction is greatly improved by using only the 6 central channels, that is using the device as a 1 x 6 AWG. The slight asymmetry of the device is due to the fact that the design is actually an 8 x 8 AWG (see Fig. 2.13), leading to an off-center input coupling.

2.4.2.3 Bragg gratings

Bragg gratings are the preferred choice for spectrally narrow single-wavelength filters. They are implemented by a periodical change of the effective refractive index of the waveguide, which can either be realized by changing the waveguide geometry through surface corrugations (e.g., periodical etching of the waveguide [61]) or variations in the refractive index itself (e.g., by UV-radiation as in fiber Bragg grating [62]). Each periodic variation of the refractive index causes a fraction of the mode to be reflected. For a specific grating period with fixed wavelength or a specific wavelength for a fixed grating period constructive interference occurs and the light is reflected.

Figure 2.16: Power reflection characteristics calculated by the coupled-mode theory of a 3rd-order Bragg grating: 8 x 8 μm² waveguides with 1 μm grating depth, \( n_{\text{core}} = 1.510 \), \( n_{\text{clad}} = 1.5055 \), duty cycle of 50% and 3500 periods with resonance at \( \lambda = 1.55 \mu m \).

Theory

Coupling-mode theory is used to describe Bragg gratings. A simple approximation formula can be derived for the coupling coefficient in the case of a rectangular grating
cross section of depth \( a \) in the core material, grating resonance wavelength \( \lambda_0 \) and grating order \( l \) [54].

\[
\kappa = \frac{2\pi^2 a^3}{3\lambda_0 d^3} \frac{n_{\text{core}}^2 - n_{\text{clad}}^2}{n_{\text{core}}} \left[ 1 + \frac{3\lambda_0}{2a\pi(n_{\text{core}}^2 - n_{\text{clad}}^2)^{0.5}} + \frac{3\lambda_0^2}{4a^2\pi^2(n_{\text{core}}^2 - n_{\text{clad}}^2)} \right] \tag{2.42}
\]

The spectral reflection response of the grating is given in Eq. 2.43 [63].

\[
R = \left| \frac{j\kappa \sin \left( \sqrt{\delta^2 - \kappa^2} L \right)}{\sqrt{\delta^2 - \kappa^2} \cos \left( \sqrt{\delta^2 - \kappa^2} L \right) - j\delta \sin \left( \sqrt{\delta^2 - \kappa^2} L \right)} \right|^2 \tag{2.43}
\]

\[
\delta = n_{\text{eff}} \left( \frac{2\pi}{\lambda} - \frac{2\pi}{\lambda_0} \right)
\]

**Simulations**

Using above formulas the spectral reflection of a Bragg grating can be predicted (see Fig. 2.16). The simulated Grating shows 97 % peak reflection, a full width at half maximum (FWHM) of 0.31 nm and side lobes of -6.4 dB.

### 2.5 Conclusions

Maxwell’s equations describe the behavior of electro-magnetic fields in matter in general, and can be applied to study the propagation of modes in optical waveguide structures in particular. The single-mode operation conditions for quadratic slab waveguides were studied, assuming the material parameters of the waveguide materials introduced in Chap. 3. A set of passive devices were studied analytically and by simulation using beam propagation algorithm based solvers, including y-splitters, directional couplers, multimode interference couplers, Mach-Zehnder interferometers, arrayed waveguide gratings and Bragg gratings. The simulation results formed the basis for the dimensioning and analysis of the waveguide devices fabricated and characterized in the next two chapters.
Chapter 3

Polymer waveguide and device fabrication

This chapter starts by introducing optical polymer materials experiencing low loss in the infrared telecommunication bands around 1.3 and 1.55 µm. Particularly, the focus is on acrylate and polysiloxane materials (see Fig. 3.1). In a collaborative work, Dow Corning Corporation® developed a novel UV-curable polysiloxane material set for waveguide fabrication in the near-infrared that combines several favorable properties (such as direct patternability) and is low-loss. Subsequently, the chapter describes the fabrication of single-mode waveguides and devices with direct photo-patternable polymers applying a custom-built laser direct writing setup. Special emphasis is put on the fabrication challenges of passive optical devices, such as directional couplers or arrayed waveguide gratings. To our knowledge, this is the first time that multimode interference couplers and arrayed waveguide gratings have been fabricated in polymers by laser direct writing. Parts of the work described in this chapter have been published in [64].

![Chemical formulas of acrylate and siloxane polymers.](image)

Figure 3.1: Sketch of the chemical formulas of acrylate and siloxane polymers.
3.1 Optical waveguide materials

The materials and fabrication techniques used in integrated optical circuits are numerous. Media in which optical waveguides have been demonstrated include dielectric materials, such as glasses (e.g. silica glass [65]), semiconductors (e.g. silicon [66]), crystals (lithium niobate [67]) and polymers (e.g. polysiloxanes [68]). While each material presents advantages and disadvantages, this work focuses on polymer waveguides in the near-infrared telecommunication bands. Particularly, waveguides have been fabricated applying acrylate and polysiloxane materials.

Optical polymers show distinct favorable characteristics as compared to other materials [69]. They offer flexible processability (fast processing, applicable on a diverse range of substrates and simple processing techniques available, i.e. laser direct writing), cost-effectiveness and advantageous optical properties (possibility for low optical absorption, a strong thermo-optic effect, and a large refractive index tunability) [70], [16].

Many different polymer classes have found attention in the integrated optics community. Among others, they include acrylates [71], [72], [73], [15] epoxy resins [28], olefins [74], polyesters [75], polyethers [76], polyimides [77], polysiloxanes [68] and hybrid sol-gels [78]. Each polymer class has its specific advantages and disadvantages and the large range of polymer materials shows that there is no agreement on the most suitable material for integrated optics, as silica is the standard material for single-mode fiber long distance communication. The material choice is therefore guided by combining the best overall characteristics among the following criteria:

- simple processability (including compatibility with printed circuit board manufacturing, direct patterning, large-area scalability (casting, no oxygen inhibition, adhesion properties, etc.), UV-curability)
- low optical absorption
- reliability during manufacturing and operation (see Chap. 6)

The optical absorption in polymer materials is dominated by vibrational absorption in molecular bonds. While in the visible many materials show low absorption loss (< 0.05 dB/cm), most polymers exhibit strong optical absorption (> 1 dB/cm) in the near-infrared optical telecommunication bands. Table 3.1 shows a list of the relevant molecular bonds causing absorption, and lists the central peak wavelengths (in brackets the overtone number), normalized intensities and resulting absorption losses [18]. The table shows that C–H and O–H bonds give the main contribution to absorption loss. Very low loss materials make use of fluorination or deuteration of the polymers in order to
3.1. Optical waveguide materials

Avoid these absorptive bonds. The lowest loss polymer waveguides in the near-infrared to date are based on completely fluorinated acrylates fabricated by indirect photolithography (0.04 dB/cm at 1.31 µm and 0.05 dB/cm at 1.55 µm wavelength) [79]. For optical waveguides of board level dimensions (30 – 100 cm) a material absorption of below 0.3 dB/cm is required and below 0.1 dB/cm desired.

Table 3.1: Selected optical absorption peaks of molecular bonds relevant for polymers in the near-infrared telecommunication bands.

<table>
<thead>
<tr>
<th>Bond</th>
<th>Wavelength [µm]</th>
<th>Rel. intensity</th>
<th>Absorption [dB/cm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>C–H</td>
<td>3.390 (1)</td>
<td>1</td>
<td>500</td>
</tr>
<tr>
<td>C–H</td>
<td>1.729 (2)</td>
<td>7.2 x 10⁻²</td>
<td>36</td>
</tr>
<tr>
<td>C–H</td>
<td>1.176 (3)</td>
<td>6.8 x 10⁻³</td>
<td>3.4</td>
</tr>
<tr>
<td>C–D</td>
<td>1.541 (3)</td>
<td>1.6 x 10⁻³</td>
<td>8.0 x 10⁻¹</td>
</tr>
<tr>
<td>C–D</td>
<td>1.174 (4)</td>
<td>1.3 x 10⁻⁴</td>
<td>6.5 x 10⁻²</td>
</tr>
<tr>
<td>C–F</td>
<td>1.626 (5)</td>
<td>6.4 x 10⁻⁸</td>
<td>3.2 x 10⁻³</td>
</tr>
<tr>
<td>C–F</td>
<td>1.361 (6)</td>
<td>1.9 x 10⁻⁷</td>
<td>9.5 x 10⁻⁵</td>
</tr>
<tr>
<td>C–F</td>
<td>1.171 (7)</td>
<td>6.4 x 10⁻⁹</td>
<td>3.2 x 10⁻⁶</td>
</tr>
<tr>
<td>C=O</td>
<td>1.836 (3)</td>
<td>1.2 x 10⁻²</td>
<td>6.0</td>
</tr>
<tr>
<td>C=O</td>
<td>1.382 (4)</td>
<td>4.3 x 10⁻⁴</td>
<td>2.2 x 10⁻¹</td>
</tr>
<tr>
<td>C=O</td>
<td>1.113 (5)</td>
<td>1.8 x 10⁻⁵</td>
<td>9.0 x 10⁻³</td>
</tr>
<tr>
<td>O–H</td>
<td>1.438 (2)</td>
<td>6.0 x 10⁻³</td>
<td>30</td>
</tr>
<tr>
<td>O–H</td>
<td>0.979 (3)</td>
<td>5.2 x 10⁻³</td>
<td>2.6</td>
</tr>
</tbody>
</table>

3.1.1 Acrylates

In a first phase of this thesis work, Norland Optical Adhesives (NOA) by Norland Products, Inc. were selected [80]. They are simple processable through direct UV-curing and patternability, low-cost and show good adhesion properties to all typical substrates. NOA materials are supplied in 20 different types for various applications. An intermixable pair was found with NOA 65 and NOA 71 for refractive index tunability. The refractive index in dependence of the mixing ratio NOA65:NOA71 by weight is illustrated in Fig. 3.2 (mixed with Thinky ARE-250). We targeted an index contrast of 0.005 for single-mode operation with waveguide dimensions of 8 x 8 µm² at 1.55 µm and for optimal matching with the mode of a standard single-mode fiber [81] (see simulations in Sec. 2.2.2). The measured refractive index data is shown in Tab. 3.2.

The material loss was determined by measuring the propagation losses of laser-written 50 x 50 µm² multimode waveguides and was around 0.03 dB/cm at 0.85 µm, 0.4 dB/cm
Table 3.2: Refractive index measurements of different NOA acrylates by ellipsometry.

<table>
<thead>
<tr>
<th></th>
<th>$\lambda = 0.85 , \mu m$</th>
<th>$\lambda = 1.31 , \mu m$</th>
<th>$\lambda = 1.55 , \mu m$</th>
</tr>
</thead>
<tbody>
<tr>
<td>NOA 65</td>
<td>1.519</td>
<td>1.514</td>
<td>1.513</td>
</tr>
<tr>
<td>NOA 71</td>
<td>1.540</td>
<td>1.535</td>
<td>1.534</td>
</tr>
<tr>
<td>Mix 3:1</td>
<td>1.525</td>
<td>1.520</td>
<td>1.518</td>
</tr>
<tr>
<td>Contrast NOA 65 - Mix</td>
<td>0.006</td>
<td>0.006</td>
<td>0.005</td>
</tr>
</tbody>
</table>

Figure 3.2: Dependence of refractive index on percentage of NOA71 content in a NOA65/NOA71 polymer mix.

at 1.31 $\mu m$ and 1.4 dB/cm at 1.55 $\mu m$. A further optimization of the material loss is not possible as NOA are off-the-shelf materials and the material supplier has no development activities ongoing to minimize the optical loss in the near-infrared. There is no proof of NOA acrylates to meet environmental stability requirements for integrated optical components (see Chap. 6). Additionally, the processing times of the acrylate materials were relatively long as compared to the siloxanes introduced in the following (see Sec. 3.3).

3.1.2 Siloxanes

Within this thesis, polysiloxanes have been identified to be the favorable material to meet the criteria mentioned above [16]. Siloxanes exhibit many favorable properties including, among others, good thermal stability, tunable refractive index and mechanical properties, chemical resistance, and excellent photo-stability [82]. In particular, within
3.1. Optical waveguide materials

a collaboration with Dow Corning Corporation® a new UV-curable polymer material has been developed [20] (here named generation Gen. 1a, Gen. 1b and Gen. 2). These material sets were loosely based upon previously reported siloxane materials [83] which proved to meet relevant industry reliability standards, i.e., solder reflow and 85°C/85% relative humidity (see Chap. 6 for more information). The viscosity was controlled by adding toluene as solvent.

The refractive index data of the different material sets is shown in Tab. 3.3. Generation 1 was produced in a low and a high refractive index contrast between the cladding and the core waveguide, as a slight reduction of the contrast was observed during waveguide manufacturing. For generation 2 the refractive index contrast of 0.0087 at 1.3 µm was adapted for device integration, as a compromise between minimum bend radius (15 mm) and tolerable loss due to modal mismatch with a SMF. Modal overlap calculations show a coupling loss of 0.25 dB between the waveguide of 5.5 x 5.5 µm² cross section and the SMF (Corning SMF-28) [81].

Table 3.3: Refractive index measurements of polysiloxane materials by the prism coupler method.

<table>
<thead>
<tr>
<th></th>
<th>λ = 0.632 µm</th>
<th>λ = 1.31 µm</th>
<th>λ = 1.55 µm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Core Gen. 1a</td>
<td>1.5225</td>
<td>1.5100</td>
<td>1.5083</td>
</tr>
<tr>
<td>Clad Gen. 1a</td>
<td>1.5174</td>
<td>1.5055</td>
<td>1.5040</td>
</tr>
<tr>
<td>Contrast Gen. 1a</td>
<td>0.0051</td>
<td>0.0045</td>
<td>0.0043</td>
</tr>
<tr>
<td>Core Gen. 1b</td>
<td>1.5278</td>
<td>1.5139</td>
<td>1.5123</td>
</tr>
<tr>
<td>Clad Gen. 1b</td>
<td>1.5150</td>
<td>1.5025</td>
<td>1.5010</td>
</tr>
<tr>
<td>Contrast Gen. 1b</td>
<td>0.0114</td>
<td>0.0113</td>
<td>0.0113</td>
</tr>
<tr>
<td>Core Gen. 2 (XX-2120)</td>
<td>1.3964</td>
<td>1.3892</td>
<td>1.3878</td>
</tr>
<tr>
<td>Clad Gen. 2 (XX-2121)</td>
<td>1.3873</td>
<td>1.3805</td>
<td>1.3795</td>
</tr>
<tr>
<td>Contrast Gen. 2</td>
<td>0.0091</td>
<td>0.0087</td>
<td>0.0083</td>
</tr>
</tbody>
</table>

The lower refractive index for the Gen. 2 materials is a result of the partial fluorination to reduce the optical absorption loss in the near-infrared range. The absorption loss of the Gen. 1 material was determined by spectrometer measurements of cured polymer samples with different thicknesses (see Fig. 3.3). The loss was measured to be < 0.1 dB/cm at 0.85 µm, 0.38 dB/cm at 1.3 µm and 1.32 dB/cm at 1.55 µm. For Gen. 2 the material absorption was evaluated by the material supplier, 0.20 dB/cm at 1.3 µm and 0.82 dB/cm at 1.55 µm. Currently, research on further reducing the intrinsic material absorption loss is ongoing.
Chapter 3. Polymer waveguide and device fabrication

3.2 Waveguide micropatterning techniques

Recent research on polymer integrated optics concentrates on multimode waveguides (~ 50 x 50 µm² waveguide cross sections), where fabrication tolerances are more relaxed as compared to single-mode (~ 6 x 6 µm²). Due to the availability of low-cost vertical cavity emitting lasers (VCSELs) around 0.85 µm, most of these multimode optical interconnect technologies focus on that wavelength range. While some of the processing steps are equal for multimode and single-mode manufacturing, especially the patterning of the waveguide core is more challenging due to the an order of magnitude smaller dimensions. Various single-mode polymer waveguide fabrication methods have been studied in the past, including non-photolithographic techniques, indirect, and direct lithographic patterning [84].

3.2.1 Non-photolithographic waveguide patterning

Molding or imprint are typical non-lithographic patterning methods which rely on the fabrication of preforms or masters and subsequent pattern transfer to the polymer. These methods mitigate the issue of directly micro-forming the waveguide polymer. Instead, the preform or master is produced first, where the material choice is arbitrary. Consequently, the fabrication technique in this first step can be adapted to the specific material
3.2. Waveguide micropatterning techniques

in order to meet fabrication tolerance requirements [85]. Typical material examples are
other polymers (e.g. PDMS [86]), glass [87] or silicon [88].

Advantages of these techniques include low-cost, wide variety of processable materials, not diffraction limited and three-dimensional structuring. On the contrary, these techniques are typically limited in terms of processing area and the pattern transfer step is oftentimes complicated.

3.2.2 Indirect photolithographic patterning

The process of indirect photolithographic patterning is closely adapted to standard semiconductor processing technology and is the most spread technique for single-mode polymer waveguide fabrication. The core layer is formed by first applying and structuring a photoresist on top of the waveguiding polymer and subsequent pattern transfer through etching (for example reactive ion etching) [89], [90], [68].

Using the maturity of state-of-the-art photolithography tools, fabrication of very precise structures with < 50 nm precision is possible. All polymers are structurable using dry etching techniques which allows to form waveguides in a wide range of polymer classes. The sidewall roughness, which typically is one of the limiting factors in waveguide propagation losses, is reduced to a minimum. Consequently, the lowest loss waveguides [79] and best performing devices are realized with this technology [91].

The disadvantages of the technology include the high production costs of the mask sets and the limitation in terms of scalability of the process.

3.2.3 Direct photolithographic patterning

Direct lithographic patterning methods are low-cost due to the absence of complex pattern transfer techniques, for example additional etching steps. Only UV-curable polymers can be used for these methods which limits the material choice. These polymers typically include a photo-active agent, which initializes the polymerization upon UV irradiation. While typically the waveguide layer is exposed, and later the exposed or unexposed material is chemically developed, also techniques inducing refractive index changes in the layer directly were studied in the past [92], [93]. 3D-integration of waveguides by a laser writing system was achieved [94]. Direct induction of refractive index based techniques typically suffer from long term and environmental stability issues.
Mask lithography  Patterning UV-curable polymers by mask lithography avoids the dry etching step of non-direct photolithography discussed in the previous section [95]. While being a simpler and lower cost process, the technique suffers from mask proximity effects.

Proximity and projection lithography are the two methods available for mask lithography. In proximity printing, a UV-light source is uniformly irradiating a mask, which is in close proximity to the exposed substrate, typically below 20 µm. The dependence of minimum feature size $w$, wavelength $\lambda$ and gap $g$ between mask and substrate is estimated by the so-called Fresnel number $\nu$ (see Eq. 3.1) [96].

$$\nu = \frac{w^2}{\lambda g}$$  (3.1)

The equation shows that with a given wavelength $\lambda$, the Fresnel number $\nu$ mainly depend on the gap size. In order to be able to produce waveguides in the order of $6 \times 6 \, \mu\text{m}^2$ with straight sidewalls, contact/close-contact proximity lithography needs to be applied [97]. With contact lithography, ultra-low loss single-mode waveguides with propagation losses below 0.1 dB/cm at 1.55 µm were demonstrated [98].

Contact between the mask and the sample leads potentially to damage of the mask or sample. Additionally, problems occur with the presence of defects, which can lead to a gap between mask and specimen. Out of these reasons, projection lithography is commonly used. In projection printing a lens is introduced between the mask and the sample that projects the mask image onto the sample. The projection is typically limited by sample size, as uniformity reduces towards the outside of the lens. In addition, precise alignment and depth of focus of the projection can be difficult.

The materials used in this work did not allow for contact lithography. Therefore close-contact proximity lithography was studied (refer to Sec. 3.3.3 for details).

Laser direct writing  Laser direct writing is a form of direct photolithography, but avoiding the expensive fabrication of masks. Several advantages make laser direct imaging a versatile method:

- High flexibility
- Fast prototyping (no masks needed)
- Scalability to large substrates
- Local position accuracy with respect to substrate
3.3. Process flow direct photolithographical patterning

The last item is of particular interest, as printed circuit board processing (manufacturing tolerances typically > 50 µm) is not compliant with the requirements for single-mode optics in relation to manufacturing precision. For instance, a lateral misalignment of two Gen. 2 single-mode waveguides of 1.7 µm leads to a coupling loss of 1 dB at 1.3 µm. By combining the laser writing head with a vision system, the local position of the laser head can be adapted for alignment mark inaccuracies or substrate deformations (the presented system allows for pattern recognition and relative positioning with an accuracy < 1 µm after pre-alignment on a 10 µm pinhole detector). This also enables a range of new alignment concepts. For instance, they can be applied to integrate lasers (see Chap. 4).

The numerous advantages of laser direct writing over mask-based methods are seen alongside the following disadvantages:

- Comparatively low fabrication throughput due to limited laser writing speed, as compared for example to mask lithography
- High cost per unit for large series production due to low fabrication throughput
- Fabricating complex structures challenging (Section 3.4 describes the fabrication challenges of complex passive waveguide devices by laser direct writing.)

Laser direct writing of polymer waveguides was pioneered by [73], among others. Propagation losses of around 1 dB/cm were reached in the visible wavelength range initially, which is significantly above the low material absorption loss of polymers in that range. Later, direct laser writing of low loss Gaussian-shaped rib waveguides was demonstrated (< 0.03 dB/cm at 0.84 µm [27]) [26].

### 3.3 Process flow direct photolithographical patterning

The process flow of direct photolithographical patterning based waveguide fabrication is illustrated in Fig. 3.4 and described in detail in the following sections.

#### 3.3.1 Substrate materials

Polymers yield the advantage that they are applicable on a wide range of substrates. This reports uses glass, silicon and glass-reinforced epoxy laminate (FR4) substrates. Borosilicate glass® is a transparent silica substrate with the thermal expansion coefficient matched to silicon. In Chap. 4 borosilicate glass is used due to its optical transparency in the visible as well as in the near-infrared. Silicon is the material of choice for
simple processability due to its very low surface roughness and compatibility with standard semiconductor processing steps, for example, to form metallic alignment marks. Most of the device performances shown in this thesis are from samples processed on silicon. FR4 is used as printed circuit board material and is used in Chap. 7 being the favorable material for mass production of electro-optical boards due to its low costs and standard PCB processing compatibility. FR4 that exhibits significant roughness, was planarized with the application of the lower cladding layer. A comparison of waveguide losses shows no significant dependence on the chosen substrate material. Considering the substrate size, the laser writing system allowed for fabrication of boards of up to \(0.5 \times 0.5 \text{ m}^2\), while most of the samples in this report were produced on 4 and 6 inch wafers.

Optical polymers exhibit thermal expansion coefficients (typically around \(100 \times 10^{-6}/K\) at room temperature) significantly above the one of many commonly used substrate materials, such as silicon (\(2.6 \times 10^{-6}/K\)) [84]. To reduce stress induced reliability issues, the silicon substrate in combination with the Gen. 2 siloxane was coated with a buffer layer. We used a 10 \(\mu\text{m}\) thick siloxane layer with improved adhesion and flexibility properties (also by Dow Corning Corporation®) in the presented waveguides and devices.
3.3.2 Lower cladding

For the casting of the lower cladding either spin coating (glass and silicon) or doctor blading (FR4) was used. Especially for large area processing, doctor blading is preferred although the set-up of the process is more time consuming. BPM simulations show that the waveguide modes are not affected by the substrate above a thickness of about 20 µm. Typical thicknesses for the substrate range therefore from 20 – 35 µm with an accuracy of ±1 µm. In case of the siloxane materials, the deposition step was followed by a pre-exposure step in order to evaporate residual solvent (2’, 110°C). The acrylate material is solvent free and this step was therefore skipped.

The photo-polymerization is initialized with a UV exposure step (LOT Thermo-Oriol UV source, peak at λ=355 nm). For the cladding layers, the sample was flood exposed with UV light for 2’ in case of the siloxanes (fluence of 1.2 J/cm²) and 15’ in case of the acrylates (fluence of 9.0 J/cm²). Post-exposure baking finalizes the polymerization (2’, 110°C for the siloxane and 30’, 90°C for the acrylate).

3.3.3 Core layer definition

The critical and most demanding step in waveguide fabrication is the definition of the core layer. As explained in the previous sections, direct patterning was identified as the most promising method. We explored mask lithography and laser direct writing, favoring the latter.

Similar to the lower cladding material, the core material can either be spun or doctor bladed on the sample. Spinning allows for a thickness control of ±0.1 µm while doctor blading exhibits measured tolerances of ±0.3 µm. Doctor blading is only possible with the siloxane materials and requires very precise alignment and adjustment of the blade to the substrate.

The siloxane materials require the same pre-exposure bake as for the lower cladding (2’, 110°C). After the exposure, post-exposure baking finalizes the polymerization of the core layer (2’, 110°C for the siloxane and 30’, 90°C for the acrylate).

3.3.3.1 Mask lithography

Traditional mask based photo-lithography applies UV-sources at 365 nm and 0.5 µm thick photo-resist layers. The method achieves feature sizes of around 500 nm with <100 nm accuracy. These systems use contact lithography in order to avoid proximity effects and quartz masks with a chromium layer defining the patterns. Contact lithogra-
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Phy requires very flat samples and is typically only applicable on small area samples.

We studied the fabrication of single-mode polymer waveguides with close-contact proximity lithography on 4 inch silicon wafers. Spinning the liquid polymer layers lead to typical increase of the layer thickness towards the edges of the wafers in the order of 50–100 µm (edge bead). This edge bead was removed by either selectively applying solvent to etch or by using a mask avoiding UV-exposure in the area of the edges. The exposure mask was prepared by applying spacers (5, 10 µm thick metal strips or 25 µm thick polymer tapes) at the edges compensating for the lower cladding and the core layer thicknesses.

Figure 3.5 shows the cross sections of proximity mask fabricated waveguides with different waveguide widths on the mask using Gen. 1 polysiloxanes (fluence of 1.2 J/cm²). The mask-to-sample distance was 18 µm ± 1 µm. A smaller spacing was difficult to achieve, as the material is not compatible with contact lithography and therefore contact to the mask through impurities and layer non-uniformities, especially at the edges, had to be avoided. The figure shows that the exposed waveguides are narrower than on the mask design; and, that the sidewalls are tilted, being wider on top as compared to the middle part and again slightly wider at the bottom. This distortion of the waveguide shape is accounted to proximity effects due to the distance between sample and mask.
The non-rectangular form does not necessarily cause high propagation loss. Nonetheless, this waveguide shape is not optimal, especially for the controlled fabrication of passive devices, such as directional couplers.

### 3.3.3.2 Laser direct writing

Besides mask based photo-lithography, the main focus of this study was on laser direct writing. A laser writing head focuses a laser beam with a diameter of 5 - 10 µm on the sample. The head is mounted on an xyz-positioner for laser head positioning and movement.

![Custom-built laser direct writing setup](image)

**Figure 3.6:** Custom-built laser direct writing setup: (left) photo of the setup (detailed description in Apx. A, (right) laser head on XYZ positioner, combining laser collimation optics, confocal distance measuring device and a vision system.

**Custom-built laser direct writing setup**  A photo of the custom-built laser direct writing setup and a close view on the laser writing head is shown in Fig. 3.6.

The output beam of a pulsed UV laser (Paladin Compact 355-2000) is coupled into a hollow core photonic crystal fiber. The laser is an air-cooled, mode-locked, pulsed UV laser with repetition rate of 120 MHz and ~15 ps pulse duration. The laser power is attenuated by a free-space acousto-optic modulator in order to keep the fiber-coupled power below the long-term damage threshold of the fiber. The fiber is guiding the UV light to the writing head consisting of a fiber port and laser beam collimation optics. A schematic thereof is shown in Fig. 3.7. The divergent beam is focused onto a 20 µm (for waveguide widths of 5 – 7 µm) or 25 µm (for waveguide widths of 7 – 9 µm) circular pinhole by using a distance adjustable fiber port and a lens system to optimize the
x/y-alignment. Through the pinhole the beam shape is corrected from a Gaussian-like profile to a flat-top circular one. The flat-top profile allows the fabrication of waveguides with straight sharp sidewalls, compared to Gaussian-like shaped waveguide data published previously [26], [27]. The position of the 1/3 projection lens between pinhole and substrate is adjustable and allows for tuning of the projection ratio. This allowed the tuning of the laser beam diameter and therefore the resulting waveguide core width. For the calibration, a larger pinhole (150 µm) is mounted. The projection ratio is calibrated by scanning the writing head over a detector with a 10 µm diameter opening pinhole.

![Figure 3.7: Schematic of the laser head and the collimation optics.](image)

After adjusting the writing head and the projection ratio, the distance between the writing head and the substrate is adjusted on the same 10 µm detector, mentioned earlier, to attain optimal beam focusing. The depth of focus of the beam hitting the sample is in the order of 100 µm. The writing head is adjusted to form a laser beam of 5–8 µm diameter and 500–1000 µW beam power. The limitation in maximum laser power by the long-term damage threshold of the hollow core fiber could potentially be mitigated by replacing the fiber connection by free-space optics. This would allow to increase the laser writing beam power by up to 2 orders of magnitude.

The laser head was mounted on a high-precision three-axis linear robot gantry system with <0.15 µm positioning accuracy over the range of 0.5 x 0.5 m² (see Fig. 3.6) [99]. A confocal optical distance measuring device allows initial correction of sample tilt and
keeps the distance between the head and the waveguide sample constant during laser writing (avoiding defocusing of the beam) [100].

**Dose dependence** Special care is taken to control positional and velocity inaccuracies during laser direct writing of the waveguides and devices. Both can lead to increased losses of the waveguides and device malfunctioning. Figure 3.8 illustrates a dependence of the width of the waveguides on the exposure fluence (inversely proportional to the writing speed), that was observed for Gen. 2 polysiloxanes. Underexposed, and thus narrow waveguides, exhibited an unconfined fundamental mode and increased propagation losses. For strongly underexposed waveguides (below 0.8 J/cm$^2$) the exposure was too low to cure the complete core layer. Significant broadening and multimode behavior was observed for overexposure (see Fig. 3.9). The sidewall roughness is very low for all waveguides and not visible in the scanning electron microscopy (SEM) pictures.

![Graph showing waveguide width in dependence of exposure fluence](image)

**Figure 3.8:** Waveguide width in dependence of exposure fluence for a 5.5 µm thick waveguide core layer and a 5.5 µm wide laser writing beam made of Gen. 2 siloxanes.

**Writing speeds** For low writing speeds (<1 mm/s) positional noise of the gantry system (in writing and transverse direction) is translated directly into waveguide width and off-center distance variations, leading to wavelike waveguides. Applying a multipass writing mode, the writing speeds can be increased and exposure and positional noise are averaged over the passes. For the Gen.2 siloxanes, a fluence of 1.8 J/cm$^2$ was achieved applying writing speeds around 15 / 30 mm/s in an 8 / 16 pass writing mode.

Waveguide width and thickness precisions of ±0.1 µm were achieved using direct laser writing in siloxanes after optimization of the fabrication procedures. Figure 3.10 shows
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Figure 3.9: (left) SEM images of an underexposed, narrow, (middle) a quadratic properly exposed waveguide and (right) overexposed, wide waveguide for a 5.5 µm thick waveguide core layer and a 5.5 µm wide laser writing beam made of Gen. 2 siloxanes.

cross sectional views of direct laser written waveguides in acrylate and siloxane. The sidewalls are nicely straight and waveguide dimensions quadratic.

3.3.4 Core layer development

After laser writing or mask exposure and subsequent post-exposure bake (30', 90°C for the acrylate and 2', 110°C for the siloxane materials), the unexposed material is developed and the waveguide formed by a wet chemical process. Acetone is used to develop the acrylate material (20'') and a mix of toluene and trifluorotoluene (TFT) for the siloxanes (2'). In case of the siloxanes, a post-development bake step follows in order to evaporate residual development chemicals (2', 110°C).

3.3.5 Upper cladding and final baking

The upper cladding is deposited following the same procedure as the lower cladding. Following the upper cladding processing, a final baking step concludes the procedure (60', 90°C for the acrylate and 30', 120°C for the siloxane materials).

3.3.6 Facet formation

The facets are formed with a standard wafer saw. The blade consists of a electroformed nickel matrix filled with diamond particles (Mitsubishi® Rigid Wheel FTB R46 45x130). Cross sectional pictures using a through-light microscope are used to inspect the waveguide dimensions and facet quality. Figure 3.10 shows such an optical microscope view. Especially for the acrylate material, the interfaces between the different
3.4 Laser direct writing of complex structures

Laser direct writing is especially suited for simple waveguides and passive devices built of individual waveguides (e.g. directional couplers). For the fabrication of complex structures, special procedures, such as variable writing speed or power, were applied. Using these techniques, a set of passive optical devices was successfully fabricated using the siloxane material. These devices include y-splitters for 50:50 power splitting, directional couplers for variable splitting, Mach-Zehnder interferometers, multimode interference couplers, arrayed waveguide gratings and Bragg gratings.

In general, structures with abrupt direction or acceleration changes should be avoided. The writing system utilized for the Gen. 2 siloxanes suffered from small oscillations at specific resonance conditions (writing angle/velocity) after such changes. For example, after a straight-bend transition and for low writing speeds, the gantry system shortly enters in a regime of positional oscillations (<3 µm) by trying to correct positional inaccu-
cies before resettling into stable writing. As workaround, we found that the resonances were avoidable by increasing the writing velocity by applying more writing passes.

### 3.4.1 Y-splitters

![Diagram of laser writing procedure](image)

**Figure 3.11:** (left) Schematic of the laser writing procedure of a y-splitter with the writing velocity $v$ and (right) microscope top view of a branching area of a splitter fabricated with Gen. 2 siloxane material.

The y-splitters were implemented using circular s-bends with a radius of 15 mm. They were fabricated by alternatingly writing one arm, and subsequently, the second arm. To keep the exposure in the individual waveguide parts constant, the writing speed was gradually doubled in the bends near the combining region. To achieve symmetric exposure, the branches of the device are written in alternating order and always in the same direction during the multipass exposure. A diagram of the writing directions and speeds is shown in Fig. 3.11, together with a microscope top view of the branching region of a fabricated y-splitter. Important for proper device function is the symmetry of the waveguides in the fan-out region (affecting splitting ratio) and an abrupt branching of the waveguides with low residual material in between (affecting loss values).

### 3.4.2 Directional couplers

Waveguides written closely to each other ($< 10 \mu m$) exhibit mutual exposure which leads to slight broadening of the individual waveguides. For even lower gaps ($< 5 \mu m$) residual material in between them emerges. Figure 3.12 shows a directional coupler with a
coupler separation of 6.5 µm compared to a separation of 5 µm. The waveguide broadening is in the order of 0.2 µm for the first and 0.5 µm for the second device. Ultimately, broadening can lead to multimode behavior of the waveguides and, thus, to coupling into higher order modes in the coupling region. For this case, the writing speed in the coupling region is slightly increased to compensate for this effect (around 5% faster writing as compared to isolated waveguides for a coupler separation of 6.5 µm). The residual material seen in the latter case leads to an increased coupling coefficient, but does not necessarily affect loss values. The device fabrication though becomes less predictable and device performance variations increase.

Figure 3.12: Cross sectional view of a directional coupler with 2 different waveguide separations fabricated in Gen. 2 siloxane material.

The mutual exposure can be reduced by using an anti-reflection coating (ARC) on the substrate to suppress the reflected laser beam. We successfully coated silicon wafers with an anti-reflection layer and fabricated waveguides therewith. However, it must be clarified that the ARC step was skipped for the devices presented, as the additional layer complicated the fabrication process and added reliability uncertainty with an additional material used.

3.4.3 Multimode interference couplers

Generally, many passive waveguide devices are not only built-up of single-mode waveguides, but require multimode (e.g., multimode interference couplers (MMIs)), or even free space propagation regions (e.g., star couplers), that are significantly wider than
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the waveguides. Even though for many fabrication techniques, such as mask exposure, these areas are producible in a similar fashion to simple waveguides, direct laser writing of wider structures proves to be challenging. The width of the laser beam is in general tunable by the projection lens distance adjustment and the choice of pinhole size. With the custom-built laser writing system waveguides ranging from $5 \times 5 \, \mu m^2$ single-mode to $50 \times 50 \, \mu m^2$ multimode dimensions were fabricated. In the presented process for single-mode waveguides the laser beam width is adjusted and fixed before the writing step. A change thereof requires repositioning of the lens and is therefore not possible during the writing process.

Figure 3.13: (left) Cross section of 4 waveguides written with 4.7 µm center spacing and 5.5 µm laser beam width in Gen. 2 siloxane. (right) Top view of the output section of a 1 x 2 MMI with 30 µm output waveguide spacing and 57 µm multimode section width.

Consequently, the wider multimode regions were written with the single-mode dimension beam with very closely spaced waveguides. The left side of Fig. 3.13 depicts a multimode region, written with 4 waveguides with center spacing of 4.7 µm, leading to a 20 µm wide section in Gen. 2 siloxane material. In Fig. 3.14 the theoretical relative exposure dose is illustrated assuming a circular flat top laser beam with 5.5 µm diameter. Although there are variations in exposure dose along the position in the multimode layer, no refractive index variations are seen in the through-light image. The writing speed is increased by a factor of 1.5 as compared to an isolated waveguide to avoid broadening and residual material outside the exposed region.

All, the precision of the width, the lateral uniformity of the layer, and the length of the MMI, are critical for proper device functionality. MMIs require a well-defined lengths of the multimode region and ideally an abrupt starting/ending thereof. There are two op-
3.4. Laser direct writing of complex structures

Figure 3.14: (left) Relative exposure dose of 4 passes written with 4.7 µm center spacing and 5.5 µm laser beam width assuming a circular flat top laser beam and (right) laser direct writing pattern of an MMI device.

...tions that can achieve this structure: either by moving the laser head along the device and selectively switching on and off the laser power; or, by accelerating and deaccelerating the gantry system at the borders of the multimode region. With writing speeds in the order of tens of mm/s a positional accuracy of 1 µm requires switching the laser with a timing below 0.1 ms. The system does not allow for switching position detection and triggering of the acousto-optic modulator within these timing constraints. We therefore implemented a technique to accelerate and deaccelerate the gantry at the start and end of the multimode section. The increased time at the extrema leads to overexposure which is compensated by smoothly adjusting the laser power when the writing velocity is reduced. By doing this, the exposure is kept constant. Below a threshold velocity ($1/10$ of the nominal writing speed), the laser was completely switched off.

The writing pattern of an MMI is illustrated in Fig. 3.14. For symmetry reasons, the writing direction is always kept in the same direction. Additionally, the multimode region is defined before the input and output waveguides in order to have minimal influence of the input/output y-splitter configuration. The right side of Fig. 3.13 shows a multimode region written in several passes with the single-mode dimension laser beam. The individual passes were spaced at close intervals of 4.7 µm. The figure demonstrates that the technique allows for very regular end facets. The blurring of the sidewalls at the beginning of the MMI is caused by the gantry systems instabilities at accelerating from zero velocity. After nearly 80 µm the positional accuracy is regained and the sidewalls...
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become straight.

A post-development UV step and bake was introduced to improve the uniformity of the core layer (30° UV flood exposure and 30°, 110°C for the siloxane materials), for devices with multimode or free space propagation regions.

3.4.4 Arrayed waveguide gratings

The fabrication of arrayed waveguide gratings by direct laser writing follows from the previous sections as the device consists of isolated waveguides and a free space propagation region (written in the same way as the MMIs). While the ideal device can be simulated (see Sec. 2.4.2.2), the fabrication capabilities define many design constraints. In particular, the spacing and separation of the waveguides at the input and output plane of the star couplers is critical for the device performance. On the one hand, the crosstalk between channels is given by the overlap of the interference pattern and waveguide modes at the output plane. On the other hand, the spacing between the arrayed waveguides at the star coupler should be minimal to couple maximum power into the array.

Figure 3.15 illustrates a typical waveguide spacing at the input and output plane of the star couplers. The small broadening of the waveguides observed, was accounted for in the device simulations. The widening of the input waveguides affects the aperture and the dimensions of the star couplers in the design. The figure also shows a complete star coupler based on Rowland circles and an array of AWGs next to each other, illustrating the arrayed waveguides.

To achieve a proper design and fabrication of the star couplers, the path length difference of the arrayed waveguides is very important. A multipass (14 passes) writing mode was applied in order to average potential positional inaccuracies of the individual passes. During the writing process the AWG was divided into substructures, consisting of: input waveguides, input star coupler, arrayed waveguides, output start coupler, and output waveguides. The individual substructures were fabricated sequentially, while within each pass the complete substructure was written, in order to keep exposure maximally uniform.

3.4.5 Bragg gratings

The periodic change of refractive index required to fabricate Bragg gratings is hardly writable with a direct laser writing system. The period of a first-order Bragg grating corresponds to half the wavelength in the medium. This period length is well below
3.4. Laser direct writing of complex structures

Figure 3.15: Microscope top views of direct laser written Gen. 2 siloxane AWGs: (left top) 8 input waveguides separated by 16 µm, (right top) 40 arrayed waveguides with 8 µm spacing, (left bottom) complete 8 x 40 star coupler and (right bottom) array of AWGs.

the spot size of the laser beam utilized. There are techniques though to introduce a grating structure into polymer waveguides by other means, including, among others, molding, embossing, electron-beam writing, photolithographic techniques or laser ablation. Perhaps the most common technique to introduce a refractive index change by photolithographic two-beam interference, was successfully demonstrated in polymers
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Figure 3.16: Focused-ion beam cross sectional view of laser ablated grating structures: view at $30^\circ$ showing $10 \mu m$ period and $12 \mu m$ projected depth (corresponding to $16 \mu m$); the dark material is the polymer, which was covered by a platinum layer before the cross section formation.

by [101]. The approach we chose applies an excimer laser mask imaging system. The laser operates at 248 nm (energy density of 600 mJ/cm$^2$ and 20 ns pulse duration); where polymers typically show very strong absorption and ablate well [102]. Ideally, the waveguide core material itself should be patterned. However, the fabrication procedure allowed only for ablation of the upper cladding of completely processed waveguide samples with reduced upper cladding thickness (20 µm). We used a mask with periodicity of 2, 4, 6, 8 and 10 µm and 50% duty cycle. In the Gen. 1a siloxane material system, the highest aspect ratios were achieved with a 10 µm period on the mask (5 µm wide and around 16 µm deep trenches). Figure 3.16 depicts a cross sectional view of this grating obtained in a focused-ion beam system.

3.5 Conclusions

We identified two material classes, namely acrylates and polysiloxanes, as viable direct UV-patternable polymers for the fabrication of single-mode waveguide. Laser direct writing was selected as the most advantageous micro-patterning technique for single-mode board-level optical interconnects. Characteristics of laser writing include high flexibility, fast prototyping (no masks needed), scalability to large substrates and local
position accuracy with respect to substrate.

The optimization of the fabrication parameters and equipment allowed for the controlled fabrication of single-mode waveguides, as well as a range of passive devices. While some devices consisted of individual waveguides only, such as the directional couplers, others required the fabrication of more complex structures, such as the free space propagation region of an arrayed waveguide grating. The optimization of the writing modes and sequences of these structures was demanding with laser writing, but crucial for accurate device fabrication. We successfully structured y-splitters, directional couplers, multimode interference couplers, Mach-Zehnder interferometers and arrayed waveguide gratings. Additionally, we demonstrated laser ablation of the siloxane materials using an excimer laser mask imaging system to fabricate gratings in the waveguides.
Chapter 4

**Coupling concept for VCSEL integration**

While monolithic integration techniques could potentially reduce the number of components and eliminate many packaging and integration issues in optical interconnects, current optical systems rely on various material systems. Hence, an important factor influencing the success of an integrated waveguide technology is the availability of low cost system integration possibilities of single-mode glass fibers, electronic and optoelectronic components for light generation, manipulation and detection (such as silicon photonics chips or lasers). In this chapter, we focus on a novel coupling concept of vertical cavity surface emitting laser arrays (VCSELs) to the presented single-mode polymer waveguide technology.

### 4.1 Overview coupling concept

Typical PCBs (manufacturing tolerances typically > 50 µm) are not compliant with the requirements for single-mode optics in terms of manufacturing precision. For instance, a lateral misalignment of two described single-mode polymer waveguides of 1.7 µm leads to a coupling loss of 1 dB (Gen. 2 polysiloxane at 1.3 µm). Many of the revised concepts for active device integration of multimode waveguides are not applicable to single-mode technology as the alignment tolerances for the latter are almost an order of magnitude more stringent [103]. To overcome this issue smart integration concepts have to be developed, which rely either on active or passive alignment. Active alignment procedures base on monitoring the coupling efficiency of the device, while optimizing the placement of the components and the interface, which requires electrical connection thereof. Passive concepts are preferred due to the less complicated and therefore cheaper process. In passive alignment processes alignment marks usually serve as guidance for
the position of the placed device, e.g. by visually detecting the alignment marks on the carrier and positioning and fixing of the device during the assembly relative to these marks [104], [105]. In order to ensure alignment between carrier, device, and waveguides, the waveguides are positioned using the same alignment marks. Regarding multimode polymer waveguides, literature has proposed many different passive alignment concepts [99], [106]. The typical alignment tolerances achieved are in the order of several µms, which is not sufficient for single-mode applications and therefore the concepts are not transferable to the technology presented here.

Coupling the output beam of a laser into an optical waveguide is normally achieved by either butt-coupling the VCSEL or laser to the waveguide facet directly (which can involve beam steering mirrors) or by the use of grating couplers [107], [108], [109]. Due to the non-triviality of fabricating these gratings with laser direct writing and of the angular and positional alignment, we focus on the butt-coupling approach.

Many concepts for passive alignment rely on self-writing of the waveguides. Yoshimura et al. [110] studied the use of the light in the waveguides and of the lasers directly as curing sources of the uncured polymer, referred to as UV-curable self-forming waveguides, to overcome alignment problems. The approach is not applicable for large-scale integration in PCBs, but has its applications, for example, in fiber-to-fiber coupling [111].

An interesting passive alignment approach bases on self-alignment due to the surface tension of solder joints or liquid polymers. This techniques has been studied by Arvidsson et al. [112] and Bernabe et al. [113], for example, where device alignment applying a rough initial alignment combined with the surface tension of the solder bumps during fixation was demonstrated, so called self-aligning flip-chip soldering. These techniques all rely on precise alignment marks and flat and stable substrates. Hence, the studied chip and waveguide carrier material is silicon, which is not compatible with large-scale production.

A different approach is pursued by [114] by embedding the optoelectronic components directly into the waveguide layer, whereas only the alignment to multimode waveguides has been studied.

In our approach, we took advantage of the distinct properties of laser direct writing of the waveguides. By combining the laser writing with a vision system, the position of the laser head can be adapted for substrate deformations and calibrated to local alignment marks. The presented system allows for pattern recognition and relative positioning with an accuracy < 1 µm after the calibration of the relative position of laser beam and vision system by pre-alignment on a 10 µm pinhole detector [115]. We placed the VCSEL and electrical contacts on one side of a thinned glass substrate; we then used the electrical contacts of the VCSELS as alignment marks to write the waveguides on the other side.
The $90^\circ$ deflection of the beam was achieved by forming $45^\circ$ total internal reflection mirrors in the polymer by a v-shaped blade, that was likewise aligned relative to the VCSEL contacts.

As laser sources we investigated 1 x 4 VCSEL arrays fabricated by Vertilas GmbH [116]. The single-mode VCSELs operate at a central wavelength $\lambda_c$ of 1.58 $\mu$m with modulation bandwidths above 10 GHz and up to 5 mW output power. By tuning the driving current we experimentally observed a tuning range of up to 8 nm (around 6 nm within the safe long-term operation conditions). They could be utilized for a 1 x 4 WDM link with 2 nm channel spacing, e.g., in combination with the polymer AWGs demonstrated in Sec. 5.5.3.

### 4.2 Process flow coupling concept

An overview of the process flow for the VCSEL integration is given in Fig. 4.1. The process started by choosing an optically transparent substrate; in the presented concept

**Figure 4.1:** Process flow of the VCSEL integration with direct laser written single-mode polymer waveguides using passive alignment and $45^\circ$ deflection mirrors.
we chose a 4 inch borosilicate glass wafer. The optical transparency was required in order to ensure the visibility of the VCSEL's electrical contacts through the substrate. Using picosecond laser ablation, we created a cavity for the VCSEL array on the backside of the glass aiming at a minimal thickness of the remaining lamella (step 1). Therewith, the distance between VCSEL and waveguide core layer was reduced and coupling losses due to divergence of the output beam of the VCSEL optimized. Then, an adhesion layer as well as the electrical contact and soldering metals were deposited in the groove. The metal patterning to match the contact structures on the VCSELs was achieved again by laser ablation (steps 2 - 3). With a standard pick-and-place tool the VCSEL array was positioned on these contacts, afterwards soldered and finally fixed using an optical underfill material (steps 4 - 5). The fact, that in this step the VCSEL array didn’t have to be precisely placed, but could exhibit rather large alignment inaccuracies of several µm shows one of the strengths of the described coupling concept. Although not studied in detail in this report, the placement and soldering of the VCSEL driver chip could also be performed in this processing step, or, alternatively, the driver chip and further connectivity could be introduced by an additional submount at a later time.

After completing the attachment of the VCSEL on the backside of the substrate, the processing of the optical waveguide layer stack-up on the front side began. The deposition and curing of the lower cladding, as well as the casting of the core layer, followed the same procedure as described in Chap. 3 (step 6). For accurate alignment between the VCSEL output beam and the waveguides, the optical vision system of the laser writing head was utilized. As described in Chap. 3, the presented system allows for pattern recognition of the VCSEL electrical contacts, and therewith the center of the VCSEL output beam, and relative positioning of the UV-laser beam with an accuracy < 1 µm. Using this method, the waveguides are written perpendicular to the VCSEL array’s main axis (step 7). Then, the optical waveguide layer stack-up was completed by the formation of the upper cladding layer and final baking. For the 90° deflection of the beam required for the coupling concept, we fabricated 45° mirrors using a standard waver saw utilizing a 90° sawing blade (step 9). Once more, the metallization of the VCSEL array guided the in-plane positioning of the sawing blade. The out-of-plane alignment or depth control of the sawing blade was adjusted by a calibration procedure described in Sec. 4.2.5. To finish the process, the mirror was passivated either by a metallic layer or a protecting enclosure. For the thermal management of the VCSEL array, a cooling block would have to be attached either in direct contact to the VCSEL or by connecting the VCSEL to the cooling block via the definition of the heat paths through the metallic contacts on the substrate.
4.2. Process flow coupling concept

Figure 4.2: Through light microscopy images of a pyrex lamella after laser ablation (left), after an additional 1 min buffered HF smoothing etch step (middle) and after 5 min buffered HF etch step (right).

4.2.1 Glass substrate pre-processing

Although we demonstrated that the choice of substrate material is not decisive on the waveguide performance (similar results for silicon, glass and FR-4 substrates, see Sec. 5.3.1.2), a clean and flat substrate is preferred. Hence, the integration and electrical connections of the VCSEL are located on one side of the substrate (backside), while the other side stays untreated until the polymer waveguide formation starts. The VCSEL output beam is optimized for single-mode fiber mode matching with a coupling loss of around 1 dB at 20 µm spaced from the output facet. A distance equal to the thickness of the chosen pyrex glass substrates of around 500 µm, would lead to intolerable coupling loss due to divergence of the VCSEL output beam. Consequently, the substrate needed to be thinned down to a minimal size. Applying pico-second laser ablation\(^1\), glass lamellas down to \(6 ± 1\) µm thickness with dimensions of 300 x 1000 µm\(^2\) were fabricated. The debris of the laser ablation process was partially removed in an ultrasonic bath step after laser ablation. The ablation introduced significant roughness to the glass surface which was reduced by an isotropic hydrogen fluoride etch step after ablation (HF, 50% buffered solution, etch rate: approx. 5 µm/min). Figure 4.2 shows finally a 6 µm thick glass lamella after laser ablation (left), with an additional 1 min HF smoothing etch (middle) and with 5 min etching (right). With a surface profiler analysis, we determined a surface non-uniformity below \(±1\) µm after the HF treatment in the central area of the groove (250 x 800 µm\(^2\), corresponding to the VCSEL array size). This flatness of the lamella guarantees minimal VCSEL array tilt with respect to the substrate surface after placement.

\(^1\)The laser ablation system consisted of a frequency-tripled Lumera Laser Super-RAPID pulsed laser at a wavelength of 355 nm and was operated at 300 mW, with 10 ps pulse duration, a repetition rate of 500 kHz and a 10 µm spot size. Beamsteering optics allowed for spot positioning with sub-µm precision and around 5 µm glass ablation per pass.
Figure 4.3: Transmission measurements through a laser ablated glass lamella scanning the lateral position; a SMF served as light input and a second SMF as light collector. (blue) Transmission for the case with HF treatment and index matching fluid between input fiber and lamella (around 6 µm thickness) and (green) without HF treatment and without index matching fluid (around 10 µm thickness) while moving the lamella and keeping the two SMFs stable.

The transmission characteristics were measured using a single-mode glass fiber as input spaced around 5 µm from the lamella (in case of the HF etched sample with index matching fluid between the fiber and the lamella, and in the case of laser ablated lamella without HF etch and index matching fluid). A second SMF at the other side of the glass substrate collected the light, again with index matching fluid in between substrate and fiber. The data was then normalized with a simple SMF to SMF reference measurement. We achieved a very low transmission loss of only 0.4 dB through the HF edged sample, while the untreated sample exhibited significantly increased loss (see Fig. 4.3).

4.2.2 Deposition and patterning of electrical contacts

The electrical contacts of the VCSEL array were located on the front side of the devices, which required the fabrication of interconnect wires in the glass substrate groove. For high speed VCSEL operation around 10 Gb/s, laser drivers are commonly designed to match the 50 Ω load resistances of the VCSELs. Hence, a contact resistance between driver and laser chip significantly below 50 Ω is desired [117]. This performance parameter guided the design of the wires in terms of length (as short as possible) and
cross-sectional dimensions (as large as needed). The VCSEL contact and high speed probe head structures allowed the design of the finger structure to exhibit contact finger lengths < 800 µm.

We applied a 3 layer metal stack consisting of approximately 5 nm chromium, 1.5 µm gold and 200 nm indium on top as conductive contact layer. All of these were processed in the same chamber of a thermal vapor deposition system. Chromium is commonly used as adhesion promoter for metal films on various substrates, such as gold on glass. Gold is a material of choice for electrical wires due to its favorable electrical and chemical properties (e.g., low electrical resistivity of 22.14 nΩ m at room temperature [118]). Indium serves as component of many indium-based solders that share the common characteristics of low melting point (e.g., indium melting point of 157 °C) and the mechanical properties of softness and ductility [119]. For the purpose of demonstrating the feasibility of the coupling concept, indium was chosen due to its availability in the thermal vapor deposition tool. However, indium would be replaced ideally by a more complex solder alloy.

After the deposition, the metal stack was patterned using the same laser ablation system as for the groove formation operating at the reduced power of 10 mW. The structured metals are illustrated in Fig. 4.4. The fingers were designed with minimum widths of 40 µm, which in combination with contact length and thickness resulted in an estimated wire resistance of < 1 Ω.

![Figure 4.4: (left) Microscope image of electrically probed VCSEL array coupled to a single-mode fiber; (middle) laser ablated metallic contact structure on flat glass substrate; (right) laser ablated metallic contact structure on glass lamella.](image)

### 4.2.3 Placement of VCSEL array

The placement of the VCSEL array in the groove was performed using a standard pick-and-place tool (Tresky FC3 T3000) with a custom made pick-up head matched to the
VCSEL chip's dimensions. After placement, the test board was placed on a 180 °C hot plate and soldered. We utilized an epoxy material (EpoTek 301) for the optical underfill, in order to match the refractive index of the gap in between the VCSEL and the lamella to the glass and waveguide material and to attach the chip. A microscopy image of a test chip placed in a laser ablated groove is shown on the left of Fig. 4.5. The image indicates that the optical underfill compensates the remaining non-uniformity of the lamella after HF etching and that the electrical contacts are clearly visible from the frontside of the glass substrate.

The lamella thickness unevenness of approx. ±1 µm combined with the VCSEL chip size of 250 x 800 µm², led to a maximum angular tilt of the chip relative to the substrate of 0.3 and 0.9° respectively. The angular tilt in combination with the distance between VCSEL and waveguide core described in the next section of 33 µm led to an additional dimensional offset of the VCSEL beam with respect to the waveguide core of 0.2 and 0.5 µm.

4.2.4 Fabrication of optical waveguide layers

In a next step, the waveguide layer stack-up was fabricated following the procedure described in Chap. 3. The output beams of the VCSELs are matched to the mode profile of a SMF at a distance of approximately 20 µm from the chip facet (datasheet specifications state a coupling loss of around 1 dB), with a measured 0.6 dB/10 µm penalty for additional separation. The connectorization and glass lamella caused a summed distance of approximately 10 µm, which added to the distance between substrate surface and waveguide core. Hence, the lower cladding thickness of 20 µm was chosen to be minimal, while still providing proper confinement and no additional waveguide propagation loss (verified by simulation). Finally, the overall estimated distance between VCSEL facet and waveguide core summed up to 33 µm. The refractive indices of the underfill, glass and polymer waveguide material (between 1.4 and 1.5) weakened the divergence of the VCSEL beam and allowed for good mode matching with the polymer waveguide. The crucial step here was the accurate positioning of the laser writing head with respect to the VCSEL’s output beams during core patterning. The main idea of the coupling concept lies in using the direct laser writer’s vision system to localize the VCSEL’s electrical contact structures and to achieve a precise local core definition with µm accuracy (precise in terms of writing position and direction). The coupling efficiency is rendered independent of the position of the initial VCSEL placement, which makes this approach especially interesting for large boards with a high count of VCSELs. There µm fabrication accuracies over the whole board are not achievable within the standard PCB manufacturing processes.
4.2. Process flow coupling concept

4.2.5 45 degree mirror fabrication

In planar optical circuits, 45° waveguide mirrors are critical components for the integration of surface coupled devices, such as photodetectors or VCSELs. As compared to grating couplers, the mirrors are wavelength insensitive and can achieve very low losses. Numerous fabrication techniques have been studied in the past, including tilted beam UV-curing [100], laser ablation [120], imprint [87], reactive-ion etching [23] or machining [121], among others.

We chose machining by a dicing saw (ADT 7100 Pro-Vectus) applying a 90° blade as a simple and straightforward fabrication process. After testing the surface roughness of different blade types, we identified a metal bonded blade with synthetic diamond particles as most promising (Disco Corporation, type B1E802-SD1000N75M42 [122]). SEM images of the fabricated mirrors in Gen. 1 polysiloxane are shown in the middle and on the right side of Fig. 4.5, showing a very low roughness of the surface. Microscopic investigations revealed that the blade’s angle combined with the dicing saw indeed formed 45° mirrors, while for a more precise evaluation of the angular accuracy a more sophisticated measurement method would have to be applied. The according sub-µm positional resolution of the stages of the dicing saw were evaluated by subsequently sawing increasingly deeper v-grooves and later analysis of the width and depth thereof. In Fig. 4.6, the estimated groove depths are compared between measuring the width of the groove from the top with the saw’s camera and the depth measured by microscopic cross section investigations. The agreement between the two measuring methods and the precision between the 10 µm-depth spaced grooves allowed for very accurate fabrication of the grooves (precision in terms of depth and positioning in the µm range). A shallower groove aside the VCSELs was used for

**Figure 4.5:** (left) Microscope image showing metal contacts of a VCSEL dummy sample placed in the laser ablated glass groove after the underfill application; (middle) SEM overview image of the 45° polymer mirror fabricated by a 90° dicing saw; (right) SEM image of the surface quality of the mirror.
Figure 4.6: Evaluation of the precision of the dicing saw’s vertical position: comparison between measured v-groove depth by using the width in the top view of the dicing saw’s microscope and in microscopic cross section investigations (vertical dicing steps 5 µm, 10 µm, ..., 10 µm, 15 µm).

Snell’s laws define the reflection and transmission behavior of a propagating wave hitting an angled material boundary. These laws define a critical angle in relation to the boundary surface above which all the light is reflected back into the material (see Eq. 4.1). Theoretically speaking, for the material system studied here, total internal reflection occurs for a 45° angle. For smaller refractive indices of the waveguide material the mirror could potentially be coated with a metal, such as silver, to ensure total internal reflection.

\[ \phi_{\text{crit}} = \arcsin\left(\frac{1}{n}\right) \]  

(4.1)

We fabricated optical samples with waveguide bundles adjacent to each other, where only one bundle was prepared with a 45° mirror. We then compared transmission characteristics of the two groups. An additional loss of only 0.5 dB was determined, which certifies the high quality of the fabricated mirrors in terms of roughness and angular precision.

In a final step, the mirror is covered and protected from the environment. Additionally a head sink for the VCSEL would have to be attached on the backside of the sample and the connectorization for the VCSEL driver implemented. These last steps were not studied in detail within this work, as they were not part of the optical, but rather the
4.3 Performance summary

Due to the time constraints of this project, we were not able to fabricate the complete coupling concept. Instead we tested the viability of each individual sub-step. Tab. 4.1 presents a summary of the estimated and measured losses of the different sub-parts of the concept are listed. These causes included the transmission of the lamella and the mirror, the mode mismatch between the waveguide and the VCSEL output, as well as positional and angular inaccuracies of the VCSEL, mirror and waveguide. Additional comments are added in the table to explain the numbers in more detail where needed. The loss estimations on angular and positional inaccuracies are based on simulations which are discussed in more detail in Chap. 7.

Table 4.1: Causes of estimated and measured optical coupling loss for the proposed VCSEL coupling concept.

<table>
<thead>
<tr>
<th>Cause</th>
<th>Loss [dB]</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transmission lamella</td>
<td>0.4</td>
<td>According to the VCSEL supplier an ideal spacing between VCSEL and SMF of 20 µm leads to 1.0 dB loss.</td>
</tr>
<tr>
<td>Spacing VCSEL – WG</td>
<td>0.1</td>
<td>Unevenness of lamella leads to an estimated maximum VCSEL tilt.</td>
</tr>
<tr>
<td>TIR mirror</td>
<td>0.5</td>
<td>Positional accuracy of laser direct writing head of 1 µm estimated.</td>
</tr>
<tr>
<td>Angle VCSEL placement</td>
<td>&lt; 0.1 + 0.6</td>
<td>Angle VCSEL placement leads to positional offset of beam with respect to waveguide core.</td>
</tr>
<tr>
<td>Pos. VCSEL placement</td>
<td>&lt; 0.1</td>
<td>Positional accuracy of laser direct writing head of 1 µm estimated.</td>
</tr>
<tr>
<td>Positioning core</td>
<td>&lt; 0.2</td>
<td>Estimated positional accuracy of &lt; 1 µm.</td>
</tr>
<tr>
<td>Positioning mirror</td>
<td>&lt; 0.2</td>
<td>Angular orientation of dicing saw relative to VCSEL array orientation &lt; 1° and blade angle of 90±1°.</td>
</tr>
<tr>
<td>Angle mirror</td>
<td>&lt; 0.8 + 0.8</td>
<td>Simulated mode offset between waveguide and SMF.</td>
</tr>
<tr>
<td>Mode mismatch</td>
<td>0.1</td>
<td>Simulated mode offset between waveguide and SMF.</td>
</tr>
</tbody>
</table>

The given total loss caused by the lamella, the mirror and the coupling of the VCSEL to
the waveguide summed up to only 1.1 dB. Mainly the positional and angular inaccuracies of the alignment contributed to the higher estimated maximum losses of 3.9 dB. In particular, the alignment, in terms of angle, was critical for a low loss coupling interface.

4.4 Conclusions

We proposed a novel integration concept of single-mode vertical cavity surface emitting lasers and polymer waveguide in the infrared communication band around 1.55 µm. The concept benefits from the unique advantages of the laser direct writing systems, especially, the possibility of local positioning of the laser writing head relative to alignment marks. By combining the writing head with a vision detection system, the waveguides are fabricated with a µm-accuracy relative to a VCSEL array, while using the contacts of the VCSEL as alignment marks. The VCSEL itself is embedded and connectorized face-down in a laser ablated groove of a glass substrate, while keeping the spacing of the VCSEL output beam plane and the substrate surface with the waveguiding layers below 10 µm. After fabrication of the waveguides, a 45° TIR mirror is fabricated using a conventional dicing saw with a 90° blade, where again the VCSEL contact structures serve as alignment marks.

An estimated loss between minimally 1.1 dB and maximally 3.9 dB resulted as a combination between measured performance and simulated loss numbers. These loss numbers are low for a passive alignment concept and therefore prove the viability of the proposed approach.
Chapter 5

Performance of laser direct written waveguides and devices

While in the last chapter the fabrication feasibility of waveguides and devices with laser direct writing was shown, ultimately the performance thereof is the main measure of the capabilities and limitations of the technology [123]. In the following, the study of the characteristics of individual waveguides in dependence of substrate choice and fabrication parameters is described, including birefringence and propagation loss. For single-mode waveguides, the integration of functionality into the polymer waveguide board is of particular interest. The performances of power splitting devices (Y-splitters, directional couplers and multimode interference couplers) and wavelength selective devices (Mach-Zehnder interferometers, Bragg gratings and arrayed waveguide gratings) are measured and analyzed. Parts of the work described in this chapter have been published in [64].

5.1 Optical characterization setup

The setup to determine the before mentioned characteristics is depicted in detail in App. B. The light of a tunable lasers is coupled into a single-mode fiber, which is aligned to the waveguide board input using XYZ alignment stages and a controlled polarization state. For transmission measurements the light is similarly coupled back into a single-mode fiber and analyzed. For the polarization state and birefringence measurements, free space optics is used to manipulate and detect the polarization. The alignment of the fiber relative to the waveguide board is assisted by a camera vision system and optimized by an automatized power coupling optimization procedure. By applying the index matching fluid Glycerol between the SMF and the waveguide board, reflections at the interface are reduced [124].
5.2 Birefringence

For phase-sensitive devices built of planar waveguides, such as Mach-Zehnder interferometers or arrayed waveguide gratings, the birefringence is of high importance. For planar waveguides, the birefringence is defined as the difference in effective refractive index of the fundamental modes with horizontal TE and vertical TM polarization (see Eq. 5.1). In polymer waveguides, sources of birefringence include geometrical and stress-induced birefringence, as well as polarization dependence caused by the orientation of the polymer chains during curing. In polymer waveguides, the main contribution to the birefringence is typically accounted to the stress in the layer stack, particularly caused by the different thermal expansion coefficients of the substrate and polymer material [84]. Numerous techniques to minimize birefringence in optical waveguides have been studied in the past, including among others, waveguide geometry tailoring [125], introducing stress-reducing grooves [126] or choice of substrate material or additional layers with matching thermal expansion coefficients.

\[ B = n_{TM} - n_{TE} \]  

(5.1)

Figure 5.1: Sketch of the birefringence measurement setup.

The geometrical birefringence of the material system used in this thesis work was calculated using the FEM solver software described in Sec. 2.3. The asymmetry of the waveguide dimensions affects the overall birefringence by less than \(2 \times 10^{-6}\) assuming a waveguide width control of 0.1 µm during manufacturing (see left side of Fig. 5.2). Al-
though the prediction of stress-induced and polymer chain orientation dependent birefringence has been studied in the past, these procedures hold many uncertainties and assumptions on the material system [127].

\[ B = \frac{1}{2\pi l} \frac{d\delta}{d(1/\lambda)} \quad (5.2) \]

Figure 5.2: (left) Geometrical birefringence calculated with the FEM solver software COMSOL for a waveguide height of 5.5 µm and variable width. (right) Retardation between TM and TE polarization of fundamental order mode versus wave number for 3 different 7 cm long waveguides processed on silicon and FR-4 substrates. Both graphs apply Gen. 2 siloxane material at the wavelength around 1.3 µm.

Consequently, the birefringence of the waveguides was experimentally determined using a setup as illustrated in Fig. 5.1 [128]. The light of a tunable laser is coupled through a SMF into waveguides of length \( l \) with light linearly polarized at 45° relative to the horizontal waveguide axis. Therewith, the TE and TM modes are excited with equal phase and power at the waveguide input. The elliptically polarized light at the waveguide output (due to retardation of TE and TM mode) is transformed back to linearly polarized light at an angle \( \delta \) by using a \( \lambda/4 \) waveplate also at the angle of 45° relative to the horizontal waveguide axis. The birefringence \( B \) is extracted by calculating the wavelength-dependence of the angle \( \delta \), which we measured by a polarization analyzer (see Eq. 5.2).
0.8 \times 10^{-4} \text{ on FR-4}. The significance of these numbers will be discussed later in the sections on the phase sensitive device performances. The reduced birefringence on FR-4 indicates lower mechanical stress in the waveguide material, which results from the better match of the thermal expansion coefficient (CTE) between the polysiloxane and the FR-4 as compared to silicon [22]. The in-plane CTE of FR-4 \((11 - 15 \times 10^{-6}/\text{K})\) is about a factor of 4 above the one of silicon \((2.6 \times 10^{-6}/\text{K})\). The CTE of the polymer waveguide material was not measured, although similar materials exhibit coefficients >100 \times 10^{-6}/\text{K} (e.g., \(310 \times 10^{-6}/\text{K}\) for polydimethylsiloxane PDMS) [129]. The birefringence could be reduced further by choosing a substrate material with a thermal expansion coefficient even closer to the polysiloxane (e.g., polyimide).

### 5.3 Insertion loss measurements

The total insertion loss of an optical board consists of coupling loss to the sample and on-board loss (waveguide or device loss). The coupling loss is determined by the modal overlap of the light to the connecting device, which in our case was a standard single-mode glass fiber (SMF-28). The on-board loss results from the propagation losses of the waveguides and device loss.

#### 5.3.1 Propagation loss

The overall loss budget for the specific optical link sets the requirements on the propagation losses. For board-level optical interconnects in the cm–m range, a limit to the attenuation of 10 dB is typically tolerated [99]. Within this work, we defined the target of propagation losses of < 0.3 dB/cm as required and < 0.1 dB/cm as desired. The lowest loss single-mode polymer waveguides in the near-infrared to date have been reported with propagation losses of 0.05 dB/cm with waveguides structured by mask lithography combined with reactive ion etching applying highly fluorinated acrylate materials [18], [79].

##### 5.3.1.1 Sources of waveguide propagation loss

Absorption, scattering and radiation losses of the light in the waveguide reduce the transmitted optical power [63], [130]. In Sec. 3.1 the intrinsic optical attenuation of the waveguide polymers caused by vibrational absorption of molecular bonds was discussed. This intrinsic absorption for a specific material sets a lower limit for the waveguide propagation losses.
Scattering losses resulting from waveguide imperfections introduced by the waveguide fabrication process can be minimized by the manufacturing optimization. Scattering losses are subdivided into an extrinsic and intrinsic group. Extrinsic scattering can be caused by impurities (e.g., dust, bubbles, unreacted polymer), surface roughness and cracks in the polymer waveguide. All waveguide samples presented in this thesis are processed under cleanroom conditions to minimize the effect of impurities. Intrinsic scattering can result, for example, from inhomogeneities of the material itself. Waveguide bends or irregularities can lead to coupling into higher order modes or unconfinement of the modes, and therewith to radiation losses.

5.3.1.2 Propagation loss measurements

The cut-back method is a standard technique in determining the waveguide propagation loss by measuring the total transmission of the waveguide sample repeatedly while reducing or cutting back its length. Both, coupling loss and on-board loss, can be determined by this method. The device under test (DUT) was mounted on a automated 7-axis end-fire alignment setup, which is illustrated in more detail in Apx. B. A summary of the measured propagation losses of the different material sets is presented in Tab. 5.1. The propagation loss for the acrylate waveguides significantly exceeded the maximum tolerable loss and therefore was used only as prototype material for initial process adjustment of the laser writer. The samples fabricated with the polysiloxane materials show waveguide propagation losses close (< 0.1 dB/cm) to the material absorption loss. This fact indicates that the additional loss introduced by the fabrication process is indeed very low, by sidewall roughness for instance. A further reduction of the material absorption through fluorination could improve the performance potentially to below 0.1 dB/cm. The lowest propagation losses, achieved with the Gen.2 silox-

<table>
<thead>
<tr>
<th>Material</th>
<th>Material absorption / Propagation loss @ 1.3 µm in dB/cm</th>
<th>Material absorption / Propagation loss @ 1.55 µm in dB/cm</th>
<th>Coupling loss to a SMF in dB</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acrylate NOA</td>
<td>– / –</td>
<td>– / 2.5</td>
<td>–</td>
</tr>
<tr>
<td>Polysiloxane Gen. 1</td>
<td>0.30 / 0.37</td>
<td>1.30 / 1.42</td>
<td>0.35</td>
</tr>
<tr>
<td>Polysiloxane Gen. 2</td>
<td>0.20 / 0.28</td>
<td>0.82 / 0.92</td>
<td>0.7</td>
</tr>
</tbody>
</table>
ane material, are illustrated in Fig. 5.3. Structures processed on glass substrates (e.g. BK7) and FR-4 (typical printed circuit board material) showed comparable performance, proving that the choice of substrate material was not decisive.

Figure 5.3: Propagation loss of single-mode waveguides applying Gen. 2 siloxane material measured around 1.3 µm (left) and 1.55 µm (right) using the cut-back method.

5.3.2 Coupling loss to a standard single-mode fiber

The cut-back method also allows for determination of the coupling loss of the waveguides to the input and output single-mode fiber. The modal overlap integral of the waveguide and the fiber mode, as well as the refractive index difference between the different material systems, determine the coupling loss (see Eq. 2.24). The measured coupling losses to a single-mode fiber are listed in Tab. 5.1. An index matching fluid was applied between the single-mode fiber and the polymer waveguide in order to avoid light reflection. The numbers are determined by normalizing the linear fit of a zero length waveguide of the cut-back experiments to a SMF-SMF transmission measurement. For the Gen. 1 siloxane waveguides a negligible loss and for Gen. 2 a 0.25 dB modal overlap loss are expected from the simulations. The residual coupling loss was introduced by the dicing process that formed the facets.

5.4 Power splitting devices

In the following, the characterization results of the y-splitters, directional couplers and multimode interference couplers are discussed. They all serve as power splitting de-
vices and, if not stated otherwise, were fabricated in Gen. 2 siloxane material and characterized at the wavelength of 1.3 µm.

5.4.1 Y-splitters

The Y-splitters were implemented using S-bends with a radius of 1.5 cm. The BPM-based simulations described in Sec. 2.4.1.1 show an expected excess loss of 0.3 dB over the 3 dB splitting and propagation loss at the wavelength of 1.3 µm. A splitting ratio of 50:50 ± 5% and an additional loss of 0.7 dB compared to the simulated loss was measured. The additional loss was accounted to increased roughness and aberrations in the splitting region. Moreover, vibrations of the positioner of the writing head caused by changing acceleration at the transition between straight and bend waveguides were observed.

5.4.2 Directional couplers

The splitting ratio of a directional coupler can be tuned by varying the length of the coupling region for a given waveguide spacing. Figure 5.4 shows the measured and simulated relative branch powers of a directional coupler in dependence of the coupling length fabricated in Gen. 1a polysiloxane. The measurements show good reproducibility (±3% for a 50:50 coupler) and a coupling length of 2.2 mm at the wavelength of 1.3 µm.

![Figure 5.4: Coupling ratio of a directional coupler with waveguide cross sections of 7 x 7 µm² and 4 µm coupling separation applying Gen. 1a siloxane material measured around the wavelength of 1.3 µm (left) and 1.55 µm (right).](image-url)
1.3 µm. The presented couplers show on average an additional loss of 0.1 dB compared to an equivalent straight waveguide. Potentially, the couplers could also be used as wavelength filter; the presented coupler with a length of around 2.2 mm couples light at 1.3 µm in the coupled branch, while at 1.55 µm the light is coupled back into the transmitted branch. An extinction ratio of > 10 dB is achieved for this specific device. The devices fabricated in Gen. 2 polysiloxane showed similar reproducibility of the coupling ratios, with an additional device loss of 1.3 dB on average. The additional loss resulted from using the laser writing system with positional oscillations during acceleration and deacceleration phases, as described in Sec. 3.4.

5.4.3 Multimode interference couplers

As described in Sec. 2.4.1.3, the performance of multimode interference couplers is less dependent on fabrication inaccuracies as compared to directional couplers and therefore the device attractive for direct laser writing. So as to analyze the interference pattern of the modes in the multimode region of the device, we scanned a SMF along the output facet of a 1 x 2 MMI with varying lengths. We then plotted the resulting coupled power in dependence of the length and lateral offset on the left side of Fig. 5.5. The size of the fiber mode limits the lateral resolution of this measurement technique, while still allowing to see that indeed an interference pattern as predicted by simulation results (compare to Fig. 2.11). The right side of the same figure shows the transmission characteristics in dependence of the multimode region’s length for a 58 µm wide

Figure 5.5: (left) Coupled power to a SMF scanned along the cross section of the output facet (46 µm width, 30 µm output waveguide separation, Gen. 1b siloxane) and (right) transmission characteristics of a 1 x 2 MMI (58 µm width, 40 µm output waveguide separation, Gen. 2 siloxane) in dependence of the device length.
and approximately 2 mm long MMI – fabricated in Gen. 2 siloxane with 40 µm output waveguide separation and waveguide cross sections of 5.5 x 5.5 µm². The total transmission follows the simulated data, while for longer devices the measured data shows lower total loss compared to the simulations. Further investigations by simulation revealed that it is probably caused by broadening of the output waveguides at the output facet as compared to ideal waveguides assumed in the simulations. The best devices with lengths of approximately 2 mm exhibit a total device loss of 1.0 dB and coupling asymmetry of around ±5%. On the one hand, the device performances show that the fabrication with direct laser writing is feasible. On the other hand, the slightly increased device variations as compared to the directional couplers express the difficulty of the fabrication of precise multimode regions with a single-mode laser beam.

5.5 Wavelength selective devices

Besides power splitting, the integration of passive devices for wavelength division multiplexing (WDM) is of high interest for board-level applications. We present the characterization results of the Mach-Zehnder interferometers, Bragg gratings and arrayed waveguide gratings. All devices were fabricated in Gen. 2 siloxane material by laser direct writing.

5.5.1 Mach-Zehnder interferometers

We fabricated Mach-Zehnder interferometers (MZI) consisting of 2 directional couplers and 50 µm length difference between the two paths in Gen. 2 polysiloxane. The couplers had a coupler length of 3.5 mm and a separation of 6.5 µm, which corresponds to nearly a 50:50 splitting. The spectral response of the device is shown in Fig. 5.6. A total loss of 3.0 dB and an extinction ratio of up to 28 dB for the cross and 23 dB for the bar state was measured. The previously described birefringence of 1.8 x 10⁻⁴ caused a theoretical resonance shift of 0.17 nm between TE and TM polarization. Experimentally, we determined a shift of 0.21 nm, which showed good agreement with the birefringence data, considering wavelength inaccuracies of the tunable laser. Fitting the measured transmission characteristics to a transfer matrix based model showed a coupling ratio of 49:51 %, a loss of 1.4 dB for the directional couplers, and an additional loss in the delay line of 0.7 dB. The loss in the directional couplers was confirmed by the characterization of individual couplers.
Chapter 5. Performance of laser direct written waveguides and devices

5.5.2 Bragg gratings

We measured the transmission and reflection spectra of the Bragg gratings described in Sec. 3.4.5 with the setup illustrated in Apx. B. No resonance in either the transmission or reflection was observed; however, a decreased transmission as compared to unablated straight waveguides implied that the grating indeed affects the propagation. A possible explanation thereof is the fact that the angle of the grating was not 90° compared to the wave propagation axes (see Fig. 3.16) which significantly reduces the back-coupling of the reflection into the waveguide. This assumption is supported by the observation of high out-of-plane scattering of the grating. In a next fabrication run, we would preferably ablate the core layer directly rather than ablating the cladding until reaching the evanescent field of the mode. Additionally, targeting towards a first order grating with reduced perturbation periodicity would be advisable.

5.5.3 Arrayed waveguide gratings

Furthermore, we successfully fabricated a 1 x 6 AWG with 4.8 nm channel spacing (5 nm simulated) around 1.3 µm for coarse WDM in Gen. 2 polysiloxane. The design, simulation and fabrication of the device are described in Chap. 2 and Chap. 3. The left side of Fig. 5.7 depicts the spectral response of the 6 channels for TE polarization. The central channels show a total loss of 4.1 dB, which is mainly attributable to the following causes: 1.9 dB simulated device loss and 1.7 dB propagation loss. We believe that the
additional loss results from aberrations in the star coupler interfaces and phase errors in the arrayed waveguides. We determined a channel isolation of up to 15 dB for the central channels (above 12 dB for all channels) and a loss non-uniformity below 4.0 dB (simulations show 2.2 dB due to the AWG design and around 1 dB due to wavelength dependent material absorption). TM polarization measurements show channel resonance wavelength shifts of < 0.3 nm, which reflects the low birefringence presented.

The performance of the devices, especially in terms of insertion loss, is comparable to AWGs produced by indirect photolithographic patterning techniques [91], [131]. We identified the star coupler input waveguide spacing as one of the main factors for performance optimization. On the one hand, the output waveguide spacing should be chosen in a way that the individual waveguides are in contact and no light is lost at the transition from star coupler to arrayed waveguides (see right top image of Fig. 3.15). The input waveguides on the other hand, should be significantly spaced from each other to minimize cross talk and broadening due to mutual exposure during fabrication (see left top image of Fig. 3.15). Assuming no broadening of the input waveguides at the star coupler interface, the full width at half maximum (FWHM) of the central channel was simulated (simulation and design following procedure in Sec. 2.4.2.2). The right side of Fig. 5.7 illustrates the simulated compared to the measured FWHM in dependence of the input waveguide spacing (center to center distance). While for large spacings (>20 µm) the simulation and measurement concur, for smaller spacings the FWHM is significantly increased in the measurement case. This discrepancy indicates that the closely spaced input waveguides exhibit significant broadening which was confirmed by optical microscopy inspection. The best performing device described above was
consequently chosen with an 18 µm spacing. The increased spacing comes with the disadvantages of higher channel non-uniformity and small penalties on central channel insertion loss and device area.

The second limiting factor to the device performance is the device size largely determined by the minimum bending radius in the arrayed waveguides. We chose an input waveguide radius of 25 mm and star couplers at a 45° angle, which resulted in a minimum arrayed waveguide radius of 17 mm. While the fundamental mode confinement would theoretically allow for significantly lower bending radii, the chosen minimum radius results from a compromise between writing speed and safe and precise laser writing operation. Phase errors in the arrayed waveguides are given by the precision of the laser writing system and influence the channel isolation. In addition, shortening the length of the arrayed waveguides by decreasing the minimum bending radius would potentially benefit the device performance.

Taking into account the wavelength dependence of the refractive index during device design could also improve the device performance, as the material dispersion over the 30 nm device operation wavelength window is significant.

5.6 Conclusions

We successfully proved low-loss single-mode propagation in the near-infrared of polymer waveguides fabricated by direct laser writing. A waveguide propagation loss of 0.28 dB/cm was achieved, where 0.2 dB/cm was accounted to intrinsic material loss. The low loss introduced by waveguide imperfections and sidewall roughness is less than 0.1 dB/cm. We measured a low birefringence of 0.8 x 10⁻⁴ for waveguides processed on FR-4 substrate. The comparison of the birefringence of waveguides processed on silicon and FR-4, combined with predictions from simulations, indicated that this birefringence was mainly caused by stress introduced by thermal expansion coefficient differences between the polymers and the substrate. Applying the laser direct writing fabrication procedure described in Chap. 3, we fabricated a range of well performing passive optical waveguide devices, including y-splitters, directional couplers, multimode interference couplers and arrayed waveguide gratings. In particular, we demonstrated for the first time the fabrication of a 1 x 6 arrayed waveguide grating applying laser direct writing. The AWG exhibits a 4.8 nm channel spacing and an insertion loss of 4.1 dB for the central channels. The proper device functionalities and performances prove that the positioning accuracy of the laser direct writing system is excellent; and, overall, the feasibility of fabrication of complex high-performance optical structures.
Chapter 6

Reliability aspects of single-mode polymer waveguides

Many different materials are used for integrated waveguides, including glasses, semiconductors or polymers. Polymers exhibit on one hand a range of favorable properties (see Sec. 3.1), while on the other hand being known to have inferior environmental stability as compared to the other material systems. While in this thesis, as well as in the research community, a lot of attention is put on material development, fabrication techniques, characterization methods and system integration aspects, also environmental stability has to be addressed for the commercialization of the technology. This chapter presents an general overview of reliability investigations and discusses the specific measurements performed on the presented siloxane materials and laser direct written boards.

6.1 Overview reliability investigations

6.1.1 Theory reliably testing

Reliability is a characteristic of an item, expressed by the probability that the item will perform its required function under given conditions for a stated time interval. From a qualitative point of view, reliability can be defined as the ability of an item to remain functional [132]. The term "remain functional" has to be defined for each individual device or system. For optical waveguide devices, a typical criteria is the maximum allowed change of transmission as compared to the specifications. The time of optoelectronic devices in operation is in the range of years, which makes accelerated testing a necessity. Under certain assumptions it is possible to estimate the mean failure-free operat-
ing time, and connected therewith the failure rate, of a device by testing under harsher
operating conditions as compared to the operating conditions (stress, temperatures, hu-
midity, voltage, etc.). For example for temperature testing, many mechanical properties
of polymers follow approximately the Arrhenius relationship expressed in Eq. 6.1 (e.g.,
stress relaxation, and tensile properties) [133]. The equation describes the acceleration
factor $A_f$ of the failure rate. The relation shows the exponential influence of the
test temperature $T_{test}$ and the reference temperature $T_{ref}$ (e.g., operation temperature)
on the acceleration factor for a failure with a given activation energy $E_a$ ($k$ stands for
the Boltzmann constant). Therefore, accelerated testing under elevated temperature
shortens the time to failure and therewith the mean time to failure. Similarly, models
describing the conditions for accelerated humidity testing can be applied [134]. In or-
der to take meaningful estimations on the lifetime by accelerated testing, a statistically
significant number of samples have to be tested. An extensive study of the required
sample counts can be found in [132].

$$A_f = e^{\frac{E_a}{kT}} \left( \frac{1}{T_{ref}} - \frac{1}{T_{test}} \right) \quad (6.1)$$

### 6.1.2 Reliability requirements for telecom devices

For standardization purposes, Telcordia Telecommunication Inc. regularly releases
generic requirements and industry standards that most of the telecommunication in-
dustry and the research community apply [135]. Considering passive optical wave-
guide devices in particular, the documents Telcordia GR-326 "Generic Requirements
for Single-Mode Optical Connectors and Jumper Assemblies", GR-1209 "Generic Re-
quirements for Passive Optical Components", and GR-1221 "Generic Reliability Assur-
ance Requirements for Passive Optical Components" are often referred to. These files
include requirements on the insertion and return loss after mechanical (mechanical
impact and vibrations) and environmental tests (dry heat storage, damp heat storage,
low temperature storage, medium temperature storage, temperature cycling, temper-
ature/humidity cycling, rapid temperature cycling, corrosive atmosphere, water immer-
sion, and industrial atmosphere). For each individual field-application, the relevant tests
have to be selected or additional tests introduced (e.g. solder reflow test for devices un-
dergoing a soldering process during manufacturing or degradation under high optical
power operation). We identified the most important procedures for the interconnected
polymer waveguide board, which are listed in Tab. 6.1. These tests focus on the optical
loss characteristics of the devices after the device fabrication. The optical performance
changes of the devices are often caused by modifications in the material during test-
ing, e.g. change of the refractive index or the birefringence. We therefore monitored in
6.1. Overview reliability investigations

our tests refractive index stability, optical waveguide loss, and the device performance, particularly, of a directional coupler. Already during device fabrication, as compared to later system operation, these performance indicators are subject to environmental influences.

Table 6.1: Relevant reliability test procedures for the interconnected polymer waveguide board prototype.

<table>
<thead>
<tr>
<th>Test condition</th>
<th>Value (ideal)</th>
<th>Value (required)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Connector plugging cycles</td>
<td>1000</td>
<td>100</td>
</tr>
<tr>
<td>Vibrations</td>
<td>4 cy / min 4 axis, 20 G, 20 to 2000 Hz</td>
<td>–</td>
</tr>
<tr>
<td>Mechanical shock</td>
<td>5 x 6 dir @ 500 g, 1.0 ms</td>
<td>–</td>
</tr>
<tr>
<td>Damp heat 85°C / 85% RH</td>
<td>2000 h</td>
<td>500 h</td>
</tr>
<tr>
<td>Temperature cycling</td>
<td>500 cycles @ -40 – 85°C</td>
<td>100 cycles @ 0 – 70°C</td>
</tr>
</tbody>
</table>

6.1.3 Polymer specific reliability

The characteristics of a polymer are tailored by its chemical structure and method of synthetization. Consequently, a vast amount of polymer materials exist, which can be categorized according to a wide range of characteristics, including thermal, mechanical, chemical or crystalline properties. Similarly, also the failure mechanisms can be diverse and are separated into thermal, photo-induced, and chemical degradation, as well as oxidation. For polymer waveguide devices all these failures result in a change of optical transmission and are monitored by measuring this property.

An important figure for a polymer is the glass transition temperature, where the material’s mechanical and chemical properties change drastically. Therefore, for constant device operation, the glass transition temperature should be below or above the temperature operation range of the device.

Polysiloxanes in particular are hybrid organic/inorganic materials, whose chemical backbone consists of silicon and oxygen atoms forming a highly cross-linked network. The chemical structure is comparable to silicon dioxide-based materials such as quartz glass. Hence, these silicon-based polymers are expected to exhibit excellent environmental resistance. The polysiloxanes for the waveguide devices were selected because they combine easy processability, favorable optical properties and durability. The glass transition temperature for the commonly applied polydimethylsiloxane is -125°C and therewith is significantly below typical operation temperature ranges of photonics devices.
While UV-light is used to initialize the polymerization, many polymers degrade when exposed to high intensities of UV-light over time (e.g. bleaching [84]). Consequently, a high optical power injection test over time needs to be performed for devices operating in high optical power operation regimes before they are put into operation.

### 6.2 Polymer waveguide reliability in literature

Many publications in literature apply acrylate polymers as material for single-mode waveguides in the infra-red. The lowest propagation losses to date of <0.05 dB/cm have been reported by Yeniay et al. using fluorinated acrylates [18]. However, many research groups have observed refractive index and propagation loss changes in their material systems during environmental tests, e.g., [136], [137] or [138]. The acrylate materials utilized within this thesis, for process optimization and laser direct writing prototyping, have previously been investigated by the group at IBM Research Labs Zurich. Measurements on multimode waveguides raised concerns of the refractive index and absorption loss stability at high temperature and humidity (85°C / 85% RH). The material specifically has not proven to meet the relevant industry standards mentioned before and the supplier was not willing to optimize the materials in terms of optical propagation loss or environmental stability. Though, Eldada et al. claimed to fulfill Telcordia standards with their fluorinated acrylates with decent optical performance [139].

In contrast, for polysiloxane material systems, a large range of studies proving environmental stability exist. Usui et al. demonstrated single-mode waveguides without degradation at temperatures as high as 200°C for short-term (30 min) and 120°C for long term testing (1000 h), as well as at increased humidity (75°C and 90% RH for 1000 h). Similarly, high environmental stability of polysiloxane materials have been observed by Wantanabe et al. [140] or Zhang et al. [141]. Although not directly comparable, siloxanes have proven excellent environmental stability in multimode waveguide technologies [19] (2000 hours 85% RH/85°C as well as 500 thermal cycles between -40°C and 120°C at 850 nm), in solder reflow tests [142] or in multiple other test scenarios [143], [144].

### 6.3 Reliability tests of siloxane materials

We fabricated waveguide samples on silicon and FR-4 substrates for propagation loss measurements, as well as cladding and core layers on silicon for refractive index measurements, all applying Gen. 1 polysiloxanes. If not stated otherwise, the timing and
curing doses applied followed the fabrication procedure introduced in Chap. 3. A typical waveguide sample consisted of 3 waveguides and a directional coupler in parallel with several centimeters length. The refractive indices were measured on films with thicknesses of 5–8 µm using a prism coupler.

6.3.1 Refractive index stability

The refractive index stability acted as a primary indicator for the stability of a polymer material during waveguide fabrication and accelerated testing. A polymer’s refractive index can change significantly during the different curing stages and should ideally settle to its final value after the processing is completed (in the presented case after the final baking step).

**Refractive index stability during fabrication** We observed changes of the refractive index of the core material during fabrication and especially for partially cured waveguide stack-ups. We therefore investigated the refractive index stability during fabrication dependent on the curing dose and chemical exposure. The refractive index measurements are illustrated in Fig. 6.1. The dose dependence measurement, which is presented on the left side, showed that the refractive index stabilized after the first final baking step (110°C for 1 h). Before this final bake, the values were not significant. An insufficient UV-curing dose led to a reduction of the final refractive index, while in optical microscope investigations the layer seemed cured and the chemical development didn’t dissolve the layer.

![Figure 6.1](image)

**Figure 6.1:** Refractive index stability with (left) varying curing dose of the core material and (right) different chemical exposure of the core and cladding material.

During a regular waveguide fabrication procedure and before the final bake, the core and cladding materials were exposed to solvent (toluene) and developer (mesitylene).
Consequently, we examined the refractive index stability in combination with exposure to these chemicals. The materials were processed according to the recipe described in Chap. 3, then exposed to the chemicals (1 min bath) and finally underwent the final baking steps (right side of Fig. 6.1). As in the previous experiment, we observed that only the final bake set the refractive index to its end value. The cladding material showed no refractive index changes, neither to developer nor to solvent exposure. Though, the refractive index of the core material decreased after bathing it in the solvent, which explained the effect we observed for partially cured waveguide cores. The work of Lee et al. studied the solvent compatibility of PDMS, a special type of polysiloxane [145]. Toluene shows a high swelling ratio, which indicates low compatibility with siloxanes.

**Refractive index stability during operation** Subsequently, we investigated the refractive index stability in a damp heat test (85°C / 85% RH). Both materials, core and cladding, were spin coated on a silicon substrate with thicknesses of 6 and 8 µm and cured following the standard curing recipe. The materials showed a slight (<0.001) change in refractive index during the first 50 test hours and subsequently constant values. The refractive index contrast was constant over the whole test duration of 500 h. Most probably, the final curing step was not yet fully completed before the test started.

![Graph](image)

**Figure 6.2:** (left) Refractive index and (right) refractive index contrast of Gen. 1 polysiloxane films of the core and cladding material (6 and 8 µm thickness) during an 85°C / 85% RH test.
6.3.2 Waveguide and device performance stability

Despite the refractive index being a good indicator for the material stability, the waveguide and device performance of the boards have to be stable during the reliability tests. We fabricated samples by direct laser writing with 3 single-mode waveguides with 4 cm length in parallel, and adjacent a directional coupler on FR-4 and silicon substrates.

**Long term humidity and temperature tests** After a reference measurement right after fabrication was performed, the samples were put into a humidity controlled oven with $85^\circ\text{C} / 85\% \text{RH}$ conditions. After a specific amount of time, they were removed from the oven, rested for approximately 1 h, and their propagation characteristics were measured. The measurement results of the FR-4 samples with testing times of up to 100 h are illustrated in Fig. 6.3, the ones up to 1000 h for silicon in Fig. 6.4. The performance of the silicon samples stayed constant during the whole testing time, including constant straight waveguide transmission and directional coupler coupling ratio. For the case of the FR-4 substrate, we observed a strong decay of the transmission values. We accounted this fact to the instability of the FR-4 substrate under these conditions, which affected the polymer material. A potential issue could have been the degradation of the epoxy and subsequent outgasing of the specific FR-4 substrate material chosen. For board level applications, where silicon is not suitable as substrate material, a further study of the substrate material selection is needed (e.g., other types of FR-4).

![Figure 6.3: Transmission of a 4 cm long waveguide sample fabricated on an FR-4 substrate during an $85^\circ\text{C} / 85\% \text{RH}$ test.](image)
Figure 6.4: Transmission of (left) a 4 cm long waveguide sample fabricated on a silicon substrate and (right) of a directional coupler during an 85°C / 85% RH test.

6.3.2.1 Temperature cycling tests

Besides the damp heat measurements discussed in the previous section, we selected temperature cycling as the second type of relevant environmental stability test category (see Tab. 6.1). Two temperature ranges were studied: a hot cycle (10 – 80°C, 2 – 4°C/ min temperature ramps, 10 min holding time) and a cold cycle (-60 – 10°C, 10 – 20°C/ min temperature ramps, 10 min holding time). Both cycles exhibited a maximum temperature difference of 70°C. The samples were put into the chambers at the starting temperature of 10°C flooded with air of around 20°C and 50% RH. After a specified number of cycles, the samples were exposed to room temperature for around 1 h before the measurements were performed.

Waveguide and device performance The results of the temperature cycling experiments are shown in Fig. 6.5 for the cold and hot cycles and for samples processed on FR-4 (7 cm length) and silicon (4 cm length). The transmission results were normalized by the calibration measurement performed before the samples underwent the first temperature cycle (time = 0 cycles). For the cold, as well as the hot cycles the waveguides on silicon substrate showed a variation of less than 0.8 dB for 200 cycles. The transmission values of the FR-4 waveguides exhibited a slightly increased variability (below 1.4 dB for 200 cycles).

The measurement error was slightly increased as compared to the other measurements performed in this thesis. Residuals of the index matching liquid, used between the
6.3.2.2 Mechanical tests

In Tab. 6.1 we listed 3 relevant mechanical tests of a SMF-pluggable optical waveguide board (connector plugging cycles, vibrations, and mechanical shock). By the time of the completion of this thesis, the test boards were not yet completely fabricated and therefore no tests performed.

6.4 Conclusions

When polymer materials are considered in optics, as well as in other applications, their reliability and durability are often the decisive factors for the feasibility of the material. The Telcordia generic requirements and industry standards give the optical communication community a common set of tests to prove the reliability of its devices. A literature
study for the two material systems considered in this thesis shows that many acrylate based polymer waveguide technologies have problems passing relevant environmental tests of the material system, while polysiloxanes proved to be more stable.

We performed a set of environmental tests on the polysiloxane materials and waveguide devices. Both materials, core and cladding, showed stability for 500 h in an 85°C / 85% RH test. During fabrication, we showed that the refractive indices of the investigated polysiloxane materials exhibited instabilities when not sufficiently cured and in contact with solvent. Additionally, the final bake was essential for the full polymerization of the material and for the refractive index to reach a stable value.

We were able to prove that the polysiloxane material system was stable under 85°C / 85% RH test conditions for at least 1000 h. Neither the propagation loss nor the coupling ratio of a directional coupler showed any changes for devices produced on silicon substrate. The devices produced on the FR-4 substrate couldn’t withstand these environmental conditions, which showed the importance of considering not just the waveguides and devices, but also the surrounding materials (e.g. substrate or packaging) for overall system reliability and lifetime.

Temperature cycling tests revealed that the materials were able to comply with the Telcordia standards. For a cold and a hot temperature cycling test with maximum temperature differences of 70°C the performance varied in a range below 0.8 dB for straight waveguides.
Chapter 7

Single-mode optical fiber connector

An optical link is constituted by a light source, an optical modulator (which can be combined with the laser or external), waveguides and devices to transport and manipulate the light, and finally a detector to convert the optical to an electrical signal for further processing. Single-mode glass fibers are the preferred medium for waveguiding in many applications, especially at longer distances, due to their very low propagation losses below 0.2 dB/km at the wavelength of 1.55 µm. The coupling of any optical technology (e.g., the presented single-mode polymer waveguides) to these single-mode fibers is crucial for the potential success thereof. While numerous coupling concepts exist for integrated waveguides, we propose a mass-producible optical connector to the polymer waveguides using a passive alignment approach and which is compatible to standard fiber connectors. The concept combines the precision of silicon v-grooves for alignment with the advantages of polymer waveguide laser direct writing. The work was conducted within a project funded by the Commission for Technology and Innovation in Switzerland, where Huber+Suhner AG [146] (lead by Roger Krähenbühl) developed the concept and fabrication of the connector, vario-optics AG [147] (lead by Tobias Lamprecht) was responsible for the waveguide fabrication and the Swiss Federal Institute for Material Science for simulations, measurements and reliability aspects. The results of the project have been published in [148].

7.1 Introduction to fiber connectors

Connecting an optical fiber to another optical fiber or an integrated waveguide requires precise alignment of the cores, as well as a maximum mode overlap to ensure low coupling losses. For the optical measurements performed within this work, we mounted cleaved single-mode fibers on motorized XYZ-positioning stages and automatically aligned the cores to each other by monitoring the coupling efficiency. For practical field
applications this alignment procedure is not feasible and simpler passive alignment concepts are required. While for optical fibers fusion splicing can be applied for long-term fixed interfaces, commercially available connectors are the preferred choice. These connectors mechanically join and align the cores with fiber to fiber coupling losses of potentially below 0.2 dB, while offering a flexible connect/disconnect option. Their joining mechanism is typically made out of a precisely manufactured ferrule (e.g., of ceramic material and of either 1.25 or 2.5 mm circular cross sections) surrounding the fiber, which is mounted in a housing. A multitude of different assemblies and housings exist, including FC, ST, LC, SC, among others, where each one has its specific advantages and application fields. In a fiber to fiber adapter, a mating sleeve, is used to align two ferrules for the coupling [149].

Important key performance figures for connectors are the insertion and reflection loss. Besides dirt and defect fiber endfaces, the main cause of insertion loss in fiber to fiber connectors is given by positional and angular misaligned fiber cores. The fabrication precision of the fibers themselves (centricity of the core, cladding diameter and uniformity), the ferrules and the mating sleeves determine this misalignment. Current day manufacturing precision of these parts guarantees dimensional accuracies below 1 µm, which makes the before mentioned loss below 0.2 dB possible. A refractive index change at the fiber interface due to a gap between the two fibers or due to misalignment leads to typically unwanted reflections. Angled fiber facets are commonly utilized in systems where back-reflections are of importance. In the presented concept we focused on the interconnection between the polymer waveguides and a duplex LC connector with a 1.25 mm ferrule (see Fig. 7.1). At project start we defined a coupling loss of 1.5 dB as maximum loss target.

### 7.2 Alignment tolerances for optical fiber connectors

We experimentally determined the influence of lateral misalignment between a laser direct written single-mode polymer waveguide and a cleaved standard single-mode glass fiber. At both input and output facets of the polymer waveguides, a fiber was mounted on a motorized XYZ-stage and the mutual alignment was optimized by monitoring the coupled power. An index matching fluid was applied to minimize the coupling loss. In order to determine the alignment tolerances, the input fiber was gradually misplaced horizontally and vertically from its optimal position and the transmitted power observed. The resulting 2-dimensional coupling profile of a single-mode fiber to a polymer waveguide is illustrated in Fig. 7.2, while normalizing over the aligned transmission power. A coupling loss below 1 dB is achieved with a total lateral misalignment below 2.2 µm.
Besides the lateral displacement of the fiber, also the angular misalignment and the gap between the fiber and the waveguide lead to additional loss. We conducted simulations to estimate the losses caused by these two sources. The results are illustrated in Fig. 7.3. While the distance offset between the fiber and the waveguide is not very critical (70 µm distance lead to 1 dB loss), especially angular inaccuracies lead to transmission penalties ($1.2^\circ$ angular misalignment leads to a 1 dB loss).

### 7.3 Existing fiber-waveguide alignment concepts

The problem of coupling single-mode fibers to integrated waveguides has attracted a lot of attention in the research community and various different concepts have been proposed.

The lowest coupling losses were achieved with active alignment; losses below 0.1 dB were demonstrated by Zhang et al. [150]. With precise stages the previously explained alignment tolerances in the sub-µm range are readily achievable. To fix the fiber after active alignment, different adhesives were utilized. The study focused on the mechanical properties of these adhesives, which showed high stability under elevated temperatures ($100^\circ$C).

The use of microelectromechanical systems (MEMS) allows for a flexible active tuning of the aligning device, e.g. by the use of micro-mirrors [151]. As stated before, active

Figure 7.1: *Schematic of a duplex LC adapter integrated into a polymer waveguide board.* (drawing provided by Huber+Suhner AG)
alignment is not feasible for the mass-production of optical boards with a high fiber connection count.

Other efforts focus on relaxing the alignment constraints, for example, by introducing grating couplers [152] or tapered waveguides [153]. Grating couplers are typically used when difficulties in fabricating high quality waveguide facets occur. Laser direct writing
is not the best suited method to fabricate gratings though. Tapered waveguides help to transform the modal profile of the integrated waveguides to match the fiber mode. In the waveguide technology studied within this thesis, a maximal modal overlap between the waveguides and an SMF was a main constraint for waveguide and refractive index choice.

Evanescent field coupling of a polished SMF to a waveguide was demonstrated by Woong-Gyu et al. [154]. The coupling showed strong temperature dependence due to the thermal refractive index dependence of the applied polymers. Hence, the effect was used to implement an optical temperature sensor.

The majority of the activities focused on end-fire coupling, where the design of the alignment features is crucial, which guarantee the positioning and fixation. The SMF is typically placed in an alignment groove and the waveguide positioned relative to it [155]. Due to its diamond cubic crystal structure, the chemical etching of silicon occurs at defined crystal axes and allows for the fabrication of v-grooves with precisely defined sidewall angles [156]. Low coupling losses were demonstrated using silicon substrates for the waveguide fabrication with v-grooves in the silicon for fiber placement. Pre-structured silicon carriers [157], silicon structuring in the same step as the waveguide fabrication [158] or after the waveguide fabrication [159] were utilized. The waveguide core structuring was performed by mask lithography where the masks were positioned using alignment marks on the silicon carrier. The resulting coupling losses can be as low as 0.4 dB. Similarly low losses were achieved by forming the grooves in the polymer directly by using a molding process [160], [161] or RIE [162]. Therewith the silicon etching step could be avoided. Unfortunately, the use of silicon carriers for optical interconnect on board-scale is not feasible.

The usage of waveguide substrates other than silicon is possible with the approach chosen by Kim el al. [163]. First, several alignment grooves for the fibers and the optical waveguide device are pre-fabricated by molding in a polymer on glass carrier. The alignment structures are produced in the same processing step as the waveguide core patterning in order to ensure precise manufacturing. The molding process is suitable for small substrates and not a preferred fabrication process for large-scale board-level integration.
Chapter 7. Single-mode optical fiber connector

7.4 Novel coupling concept

7.4.1 Concept overview

The coupling concept developed within the before mentioned collaboration is sketched in Fig. 7.4. First, the polymer waveguide board was fabricated according to the recipe described in Chap. 3. During the core layer definition, also alignment structures running parallel on each side of the waveguide core and with a precisely defined spacing to the actual waveguide were fabricated. During the upper cladding deposition, only the actual waveguide cores were covered in the area of the connector, in order for the alignment structures to remain uncovered. Then, a precisely fabricated (angle and width) silicon v-groove was utilized to fix the fiber. One side of the polished fiber facet interfaced the polymer waveguide, while the other end was embedded in a specially prepared ferrule for the mounting of the fiber adapter with a mating sleeve. The polymer alignment structures guided the positioning of the fiber in respective to the waveguide core.

![Figure 7.4: Schematic of the coupling concept including (blue) the glass fiber, (white) the ferrule, (gray) the silicon v-grooves, (green) the waveguide board and (red) the waveguide core layer and adjacent alignment structures. (drawing provided by Huber+Suhner AG)](image_url)

7.4.2 Fabrication and assembly procedure

The fabrication of the connectorized optical board started by fabricating the lower cladding on an arbitrarily chosen substrate. For the prototype a FR-4 substrate was chosen due to its compatibility with large-scale board manufacturing. During the core layer definition by laser direct writing, also the alignment structures were fabricated besides
the actual waveguide core layer, applying similar processing parameters for both. Fabricating both structures in the same laser-writing step guarantees positional accuracy between the alignment structures and the core in the sub-µm range. The optical board fabrication was concluded by a selective curing of the upper cladding, which could either be performed using mask lithography or direct laser writing. Three selectively covered waveguides with alignment structures are shown in the SEM image of Fig. 7.5.

In parallel, an optical fiber was mounted on one hand in the ferrule and on the other in the silicon v-groove. Then, the groove was positioned on the board and optical glue applied for fixation of the parts. During the assembly step, the alignment structures were joined to the angled facets of the silicon groove. A cross sectional view of the fabricated coupling interface is illustrated on the right side of Fig. 7.5. The cross sectional through light image shows the waveguide core guiding the light, as well as the selective cladding and the alignment structures also made of core polymer. These structures were in contact with the angled sidewalls of the silicon groove. The width of the groove was chosen during the externally made silicon etching and chosen in a way that the optical fiber’s core would align with the waveguide core.

![Figure 7.5:](image)

**Figure 7.5:** (left) SEM image of 3 adjacent waveguides covered by the upper cladding, each with alignment structures on both sides; (right) cross sectional view of a silicon v-groove on top aligned and glued to the waveguide board with the waveguide in the center and its alignment structures joined to the v-groove. (cross sectional image provided by Huber+Suhner AG)

Subsequently, a mating sleeve was placed interfacing the fiber ferrule and encapsulated in adapter housing. The housing was mounted and fixed on the waveguide board, for which the board had to be machined in a matching shape to ensure stability and minimal mechanical stress during plugging cycles (visible in Fig. 7.4).
7.4.3 Performance results

The performance of the connector was evaluated by Huber+Suhner AG in a transmission measurement where a white-light source was coupled in a near-infrared single-mode fiber and connected to the waveguide board (length around 3 cm). The output facets of the waveguide board were again coupled to a single-mode fiber which then was connected to a detector. The transmission results of 3 coupling interfaces after a calibration by a fiber to fiber measurement are illustrated in Fig. 7.6. The waveguides were optimized for the wavelength of 1.3 µm with a propagation loss around 0.5 dB/cm for the specific sample. At this wavelength, a total transmission loss of 3.0 dB was measured which was composed of the waveguide propagation and the coupling loss. Hence, the loss attributed to the coupling interface was 1.5 dB. Considering this being a first prototype of the coupling concept and that further calibration of the laser writing speeds and doses for the alignment structures have to be performed, the loss of only 1.5 dB is remarkable and within the loss budget targeted towards.

![Graph showing fiber to fiber transmission measurement through 3 different connectors and a 3 cm long straight waveguide board.](image)

**Figure 7.6:** Fiber to fiber transmission measurement through 3 different connectors and a 3 cm long straight waveguide board. (data provided by Huber+Suhner AG)

7.5 Conclusions

By using simulations and measurements we showed that the requirements of alignment tolerances between a single-mode fiber and an integrated polymer waveguide are in the µm-range in order to ensure coupling losses below 1.5 dB for an optical connector. We developed an simple pluggable optical connector for any type of standard ferrule based optical connector technology to interface both technologies. The concept relied on the
accurate fabrication of alignment structures in the core layer of the polymer waveguide, where in the same laser direct writing step the waveguide core and the alignment structures were fabricated, guaranteeing precise positioning relative to each other in the sub-µm range. These alignment structures guided the placement of a silicon v-groove with a single-mode fiber embedded. That way, the position of the single-mode glass fiber relative to the polymer waveguide core was fixed. The glass fiber was encapsulated within a customized ferrule that afterwards allowed for the mounting of a mating sleeve and a adapter housing. The measured fiber-to-waveguide connector loss of 1.5 dB proves the feasibility of the coupling concept and fulfills the typical loss requirements for a connector. These results demonstrate the potential of the integrated polymer waveguide technology for simple connectivity to fibers or fiber coupled devices.
Chapter 8

Optical properties of waveguide-coupled nanowires

Within a collaboration of the Swiss Federal Laboratories for Materials Science and Technology, Micos Engineering GmbH, the Swiss Federal Institute of Technology Lausanne, and the Politecnico di Milano, we developed an integrated waveguide standing wave probing spectrometer. The work was partially funded by the Swiss Space Center within the "Nano Antennas for Optical Micro Instruments" (NAOMI) project. Initially, the project was meant to utilize single-mode polymer waveguides with epoxy materials produced by Micro Resist Technology GmbH (EpoCore / EpoClad) [164]. During the project, we realized that these specific polymers were incompatible with the electron beam lithography process we applied. Therefore, the polymer waveguides were replaced by femtosecond laser written glass waveguides. Parts of the work described in this chapter have been published in [165].

8.1 Introduction

A demand for controllable light out-coupling from optical waveguides on the sub-wavelength scale has been growing over the past years [63, 166–169]. One of the recent applications that rely on this effect is stationary-wave integrated Fourier transform spectrometry (SWIFTS) [167, 168]. Its most interesting feature is a high spectral resolution in combination with a small device size: a typical length is several centimeters and spectral resolutions reaching a few picometers have been shown in the visible and near-infrared wavelength ranges [168]. These characteristics make SWIFTS interesting for applications in chemical and biological analysis, metrology, space, and beyond [169].

The working principle of such a spectrometer is as follows. Light is coupled into a
single-mode optical waveguide terminated by a mirror. The reflection created by the mirror induces a stationary wave. Detectors of sub-quarterwavelength size are placed on top of the waveguide to measure the intensity of the evanescent field locally. This detection approach allows for a proper sampling of the standing wave. The resulting signal is known as Lippmann’s interferogram. The light spectrum is extracted by the Fourier transform of such an interferogram. The sub-quarterwavelength detectors are usually metallic nanowires out-scattering the light into a camera detection system. The distance between the scatterers has to be larger than the resolution set by the imaging diffraction limit. This sets a limitation on the interplay of spectral bandwidth and spectral resolution. The use of arrays of superconducting nanowire detectors placed on top of the waveguide has been proposed to overcome the diffraction limited detection. The functionality of 40 nm wide NbN nanowire arrays with a sampling period of 160 nm has been successfully demonstrated at 4.2 K [170]. Guldimann et al. have carefully analyzed the specific advantages of modifying SWIFTS by implementing a moving mirror as waveguide termination [171, 172]. This modification is especially important for the realization of a focal plane array spectrometer (FPAS), allowing to reduce the number of detectors and to miniaturize the system. A technological challenge of this approach is that the mirror requires a sufficient moving range to fill-in the increased gap between the detectors, without introducing significant back-coupling losses at the waveguide termination. To solve this issue, optical waveguides with low numerical apertures (NA) can be chosen.

We hereby propose the use of fs-laser written waveguides in glass [173]. These waveguides can be produced within a few micrometers distance from the surface of the fused-silica substrate. The metallic nanowires placed directly onto the surface scatter a sufficient amount of light for detection. The scattering properties of the metallic nanowire are complex [174] and crucial to understand in order to achieve a successful device operation. We experimentally studied the out-coupling efficiency and the angular distribution dependent on the geometrical size of the nanowires, on the position of the waveguides under the surface, and on the light polarization. We also characterized the nanowires in terms of the plasmonic scattering spectrum. Finally, we demonstrate the successful operation of a modified SWIFT spectrometer, using a movable mirror with a stroke of more than 10 µm.

8.2 Waveguide and nanowire fabrication

A sketch of the device under consideration in this paper is shown in Fig. 8.1. Essentially, it is a standard SWIFTS configuration [167] with a moving mirror. Femtosecond-
laser written single-mode optical waveguides are used as the main component of the device. Gold nanowires fabricated on top of the waveguides are applied as local sub-quarterwavelength light out-couplers. The fabrication details and exact geometry of the structure are presented in the following sub-sections.

![Figure 8.1: Sketch of the spectrometer device, including the waveguide, gold nanowires, and movable mirror.](image)

### 8.2.1 Femtosecond laser written waveguides

We investigated different material systems (photo-patternable epoxies, LiNbO$_3$, and fused-silica glass) and fabrication processes (photolithography and laser direct writing) for the integrated optical waveguides. We identified the system of fs-laser written waveguides in glass as the most promising candidate [173]. The advantages of this waveguide technology include a very low propagation loss in a wide wavelength range (visible and near-infrared), the close proximity to the substrate surface (a few micrometers), the high chemical stability of glass, and the very smooth surface. The chemical stability and the surface smoothness are a pre-requisite for the precise gold nanowire fabrication on the waveguide surface.

The fabrication process was based on a regeneratively amplified Yb-based fs-laser system (HIGHQLaser FemtoREGEN) with a wavelength of 1040 nm, a pulse duration of 400 fs, a repetition rate of 960 kHz, and an equivalent continuous power of 60 mW. The beam was positioned at focus points of 5, 6 and 7 µm underneath the glass surface. Focusing the light closer to the surface led to significant surface damage and malfunctioning waveguides. The substrate could potentially be polished to bring the waveguides even closer to the surface. The glass substrate was mounted on a translational stage (Aerotech FiberGLIDE), which moved with a speed of 40 mm/s in order to write straight waveguides. An optical microscope image of the waveguide facet is shown in Fig. 8.2.
At the wavelength of 850 nm, the $1/e^2$ dimensions of the single-mode beam were measured at $10 \times 10 \mu m^2$. The introduced refractive index change of $1 - 5 \times 10^{-3}$ allowed the fabrication of very low NA waveguides, which exhibited low back-coupling losses to the waveguides at the mirror termination.

Figure 8.2: (left) Optical microscope image of the waveguide facet, (middle) measured field distribution of the fundamental mode at 810 nm, and (right) a set of SEM images of the gold nanowires (50 nm scale bar).

8.2.2 Gold nanowires

Patterning gold layers to create nanowires can be achieved by a range of fabrication techniques, including optical lithography, electron beam lithography, nano-imprint lithography, focused ion beam milling, or shadow mask deposition. We identified the electron beam lithography as the most viable method to fabricate nanorods with widths below the sub-quarterwavelength criteria described in the introduction (< 150 nm for the wavelength range around 850 nm). In the fabrication process, we applied a bilayer positive resist sequence of a 70 nm thick copolymer P(MMA-MAA) and a 50 nm thick PMMA layers. The bilayer lithography created an undercut profile in the resist, which helped mitigate the problem of sidewall coating during the metal evaporation process and allowed for smaller feature sizes [175]. An 8 nm thick layer of copper was deposited on top of the resists for electrical discharge during the electron beam lithography process. After 30 keV electron beam exposure, the copper was removed in nitric acid and the resists were developed in a standard MIBK/isopropanol-based developer. A 1 nm thick chromium layer was evaporated to improve the adhesion between the glass substrate and the deposited gold layer (25 nm thickness). Subsequently, a standard lift-off process in acetone was performed resulting in nanowires exhibiting widths in the range of 40 – 130 nm. Top view scanning electron microscope images of a set of such nanowires are shown on the right side of Fig. 8.2.
8.3 Measurement setup

We used two different experimental setups to quantitatively study the optical properties of the nanowires and the spectrometer.

8.3.1 Evanescent-field waveguide-coupled nanorod scattering

The first setup, which is illustrated in Fig. 3, was based on an automated fiber-coupled end-fire configuration that injected polarized laser light, at a wavelength of 850 nm (New-Focus TLB-6316), through a single-mode glass fiber into the laser written waveguides. At the output of the waveguide, we either positioned a second single-mode glass fiber to detect the transmitted power; or, a movable mirror mounted on a high precision piezo stage (PI P-517.3CL), in the case of the spectrometer application. The light scattered by the nanowires was collected by a microscope objective (NA \(\sim 0.1\), 5 × magnification) and its intensity measured with a CCD camera (Sumix SMX 11-Mx). A custom-made software program synchronized the mirror movement with the optical signal acquisition. The output scattering efficiencies were calculated by normalizing the measured signal with the light intensity coupled into the waveguide.

![Figure 8.3: Experimental setup for the nanowire characterization and the spectrometer.](image)

8.3.2 Nanowire scattering spectra

For the spectral response measurement, a halogen lamp was used to illuminate the nanowires with polarized light in the wavelength range of 450 to 1100 nm. We col-
lected the scattered light spectrum with an inverted microscope (Olympus IX-81) and recorded it by a spectrometer (Andor Shamrock 301i, iDUS DV420A camera). A calibration procedure was applied to correct for the spectral response of the measurement configuration itself, including camera spectrum, filters, substrate without nanorods, and spectrometer [176].

8.4 Nanowire scattering properties

8.4.1 Scattering efficiency

In Fig. 8.4, the CCD image of an array of nanowires of varying width, on top of a waveguide, is shown (25 nm thick and 30 µm wide). The scattering intensities were extracted by integrating the signal in a square around the nanowire (∼50 × 50 µm²). We observed a near-linear trend of the out-coupling efficiency in relation to the nanowire width. The widest wire (130 nm) displayed an approximate 7-fold increase in out-coupling efficiency as compared to the narrowest wire investigated (40 nm). By fabricating the waveguides closer to the surface (5 µm), as compared to the deeper writing (7 µm), we improved the out-coupling efficiency by a factor of 1.5. This effect can be explained by the increased interaction of the nanowire with the exponentially decaying evanescent field of the mode outside the waveguide core. The maximum total out-coupling efficiency of the current device is in the order of 10⁻⁶. According to our estimates, further optimization of the device could improve this value by several orders of magnitude.

8.4.2 Angular dependence of radiation pattern

A small spacing between the nanowires in an array can potentially lead to crosstalk. We therefore studied the angular radiation patterns of the wires in waveguide direction for TE and TM polarization with a 15° angular spacing in between the measurement points (see Fig. 8.5). For both polarizations we measured a relatively wide radiation pattern (at 45° the intensity was approximately half as compared to 0°), whereas the effect was slightly more pronounced for the TM mode. As predicted by Arnaud et al. [174]'s simulations, we observed a trend of scattered fields oriented in the forward direction for TE and in the backward direction for TM polarization. Also matching these simulations, the influence of the nanowire width on the scattering signal amplitude was significantly more pronounced for the TM polarization. We measured around two orders of magnitude difference in the signal intensities between the widest and narrowest wires. A potential explanation is the fact that, for different polarizations, a different set of plasmonic
8.4. Nanowire scattering properties

Figure 8.4: (left top) CCD image of an array of 25 nm thick and 30 µm long nanowires with varying widths, (left bottom) relative intensity extracted from the CCD image by integrating over a 50 µm wide window across the waveguide, and (right) out-coupling efficiency for nanowires with width 40 – 130 nm and 5, 6, and 7 µm waveguide depths, all measurements with TE polarization and at the wavelength of 850 nm.

modes in the nanowires was excited. In the case of the electric field in the propagation direction, mainly the widths of the rods determined the resonance. In the case of the field perpendicular to the propagation direction, the nanowire thickness was decisive.

Figure 8.5: Measured angular radiation pattern dependence along the waveguide on the nanowire width for (left) TE and (right) TM polarizations (5 µm waveguide depth).
8.4.3 Spectral dependence

The strong dependence of these plasmonic resonances on the dimensions of the wires has been described by Link et al. [177]. To experimentally verify the spectral behavior of these nanowires, we measured their scattering spectra with the above described spectrometer setup with a polarization in direction of the waveguide (shown on the left side of Fig. 8.6). As expected and predicted by the Mie-Gans theory [177], the resonance wavelength of the wires was red-shifted for wider wires. A resonance wavelength shift of up to 260 nm between the narrowest and widest wire was observed, which is illustrated in the middle of Fig. 8.6. The right side of the figure shows the increasing resonance intensities for wider wires due to their larger scattering cross section. For the specific wavelength of 850 nm, the same trend of decreasing intensity for decreasing width was observed, resulting in two orders of magnitude signal difference between widest and narrowest nanowire. This ratio between the scattered signals coincides with the data presented in Fig. 8.5 for TM polarization. It indicates the validity of the argument explaining the strong scattering intensity dependence on the incident polarization. For SWIFTS applications, on the one hand, the narrowest nanowire should be chosen to probe the interference pattern of the waveguide mode with a maximal spatial resolution. On the other hand, the measured data shows that there is a trade-off between out-coupling efficiency and nanowire size. Spectrometers operating further in the near-infrared wavelength range would potentially benefit from increased out-coupling efficiencies, while having relaxed constraints on the nanowire size due to the longer wavelength.

![Figure 8.6](image)

Figure 8.6: (left) Scattering spectra, (middle) resonance wavelength and (right) relative intensity at resonance and at the wavelength of 850 nm of the gold nanowires illuminated by a white light source polarized parallel to the waveguide for different nanowires widths.
8.5 Movable mirror for SWIFTS

In order to demonstrate the feasibility of these nanowires in combination with the laser written waveguides for the use in SWIFTS, we fabricated an array of 150 nanowires on top of a waveguide and placed a mirror at the output facet of the waveguide (see Fig. 8.3). The nanowires were 25 nm thick, 30 µm long, 40 nm wide, and spaced by 10 µm. The piezo mounted mirror was moved in 2 nm steps over a range of 10 µm. The acquired signal (50 ms detector integration time) of one nanowire, probing the standing wave pattern, is illustrated on the left side of Fig. 8.7. The signal showed the pattern of the standing wave and proved the feasibility of back-coupling the light into the low-NA waveguides using a mirror termination. The spectrum of the injected laser light (∼850 nm wavelength) was extracted by the Fourier transform of the combined signal of the nanowire array (right side of Fig. 8.7). Without further calibration or data processing, we were able to measure a peak at 850 nm with a full-width at half maximum below 2 nm. This peak corresponded to the laser wavelength used. To our knowledge, this is the first experimental demonstration of an integrated mirror back-coupled SWIFT spectrometer, following the theoretical proposition of such a device by Guldimann et al. [171]. The resolution of the measurement could be further improved by scanning the mirror over a larger range, by decreasing the acquisition time between subsequent frames and by optimizing the calculation of the spectrum, for example, by implementing a calibration procedure [167]. In addition, the measures suggested here, to increase the out-coupling efficiency, could potentially lead to a better signal-to-noise ratio and allow lower integration times for the camera acquisition.

Figure 8.7: (left) Relative signal amplitude of a single wire versus moving mirror position showing the standing wave pattern and (right) Fourier transformed signal spectrum of the concatenated response of the 150 nanowires with an 850 nm laser as light input.
8.6 Conclusions

Using metallic nanowires as scatterers is a promising technique for the probing of the electro-magnetic fields in integrated waveguides. We identified the system of close-surface fs-laser written single-mode waveguides as the most promising candidate for this application. They offer a very low propagation loss in a wide wavelength range, can be fabricated in close proximity to substrate surface (a few micrometers), and exhibit a very smooth and chemically stable surface. We successfully proved the viability of combining these waveguides with gold nanowires, fabricated by electron beam lithography, to analyze the scattering properties of the nanowires in the wavelength range of around 850 nm. In order to understand the complex waveguide-nanowire coupling and scattering behavior of the wires, we characterized the scattering efficiencies dependent on the proximity of the waveguide to the wires, the waveguide mode polarization state, the nanowire dimensions, the scattering angle, and the wavelength. Out of these results, we were able to extract guidelines for the dimensional design of the nanowires for an optimal coupling efficiency and wavelength range. With this knowledge, we demonstrated, for the first time, a stationary-wave integrated Fourier-transform spectrometer applying these low-NA waveguides and nanowires, in combination with a moving mirror as device termination. We were able to probe the standing wave pattern generated by the moving mirror and to reconstruct the spectrum of a laser at the wavelength of 850 nm as spectrometer input with FWHM of 2 nm. With this demonstration, we reached a milestone towards the realization of a focal plane array spectrometer based on the SWIFTS principle.
Chapter 9

Conclusions and Outlook

9.1 Summary

Throughout the process of this research work, we identified single-mode polymer waveguides as a promising candidate for board-level optical interconnects. The success of this optical technology is, besides performance and reliability measures, mainly dependent on the implementation cost being lower than electrical solutions. Both, the fabrication of the waveguides and devices and the packaging and system integration contribute to the total cost. A cheap fabrication technology, as well as smart coupling concepts to active devices (e.g., lasers or photodetectors), to devices made in other fabrication technologies (e.g., silicon photonics chips) and to single-mode fibers (SMF) have to be available.

The polymer material selection is guided by low absorption loss in the NIR, large-area processability, low-cost due to process compatibility with established printed circuit board manufacturing, and reliability during manufacturing and system operation. We studied two direct UV-patterenable polymer materials, namely acrylates during the initial process development phase and polysiloxanes for the device fabrication. Together with Dow Corning Corporation, a novel polysiloxane material was developed with absorption losses as low as 0.2 dB/cm at the wavelength of 1.3 μm. Laser direct writing was selected as the most advantageous micro-patterning technique for single-mode board-level optical interconnects. Characteristics of laser writing include high flexibility, fast prototyping (no masks needed), scalability to large substrates and local position accuracy with respect to substrate.

By using a custom-built laser direct writing setup and optimizing the fabrication parameters, we achieved the controlled fabrication of single-mode waveguides, as well as a range of passive devices. The optimization of the writing modes and sequences of these structures was demanding for the laser writing, but crucial for accurate device fab-
Chapter 9. Conclusions and Outlook

Fabrication. We successfully proved low-loss single-mode propagation in the near-infrared of these waveguides. A waveguide propagation loss of 0.28 dB/cm was achieved at the wavelength of 1.3 µm, including the 0.2 dB/cm intrinsic material loss. The low loss introduced by waveguide imperfections and sidewall roughness was less than 0.1 dB/cm. We measured a low birefringence of 0.8 x 10^{-4} for waveguides processed on FR-4 substrate. The comparison of the birefringence of waveguides processed on silicon and FR-4, combined with predictions from simulations, indicated that this birefringence was mainly caused by stress introduced by thermal expansion coefficient differences between the polymers and the substrate. We fabricated a range of well performing passive optical waveguide devices, including y-splitters, directional couplers, multimode interference couplers and arrayed waveguide gratings. We demonstrated for the first time the fabrication of a 1 x 6 arrayed waveguide grating applying laser direct writing. The AWG exhibits a 4.8 nm channel spacing and an insertion loss of 4.1 dB for the central channels. The proper device functionalities and performances prove that the positioning accuracy of the laser direct writing system is excellent; and, overall, the feasibility of fabricating complex high-performance optical structures.

Considering system integration, we proposed a novel integration concept of single-mode vertical cavity surface emitting lasers and polymer waveguides in the infrared communication band around 1.55 µm. The concept benefits from the unique advantages of the laser direct writing systems, especially, the possibility of local positioning of the laser writing head relative to alignment marks. By combining the writing head with a vision detection system, the waveguides were fabricated with a µm-accuracy relative to a VCSEL array, while using the contacts of the VCSEL as alignment marks. An estimated loss between 1.1 dB and 3.9 dB resulted as a combination between measured performance and simulated loss numbers. These loss numbers were low for a passive alignment concept and therefore proved the viability of the proposed approach.

When polymer materials are considered in optics, as well as in other applications, their reliability is often the decisive factor for the feasibility of the material. The Telcordia generic requirements and industry standards give the optical communication community a common set of tests to prove the reliability of its devices. A literature study for the two material systems, considered in this thesis, showed that many acrylate based polymer waveguide technologies had problems passing relevant environmental tests of the material system, while polysiloxanes proved to be more stable. We performed a set of environmental tests on the polysiloxane materials and waveguide devices, including a relevant solvent compatibility study during the manufacturing process, a damp-heat test (85°C / 85% RH test conditions for 1000 h) and a temperature cycling test (with maximum temperature differences of 70°C). Neither the propagation loss nor the coupling ratio of a directional coupler showed significant changes during these tests.
We then developed a simple pluggable optical connector for any type of standard ferrule-based optical connector technology to interface the polymer waveguides with single-mode fibers. The concept relied on the accurate fabrication of alignment structures in the core layer of the polymer waveguide. In the same laser direct writing step, the waveguide core and the alignment structures were fabricated. This guaranteed precise positioning relative to each other in the sub-µm range. These alignment structures guided the placement of a silicon v-groove with an embedded single-mode fiber. A fiber-to-waveguide connector loss of 1.5 dB was measured. These results demonstrate the potential of the integrated polymer waveguide technology for simple connectivity to fibers or fiber coupled devices.

In summary, we developed a range of building blocks to show the potential of the proposed direct laser written single-mode polymer waveguide technology. Besides low-loss waveguides and well performing devices, we demonstrated ways of integrating active devices and connectorizing the technology. These results can be seen as a step towards the commercialization of a board-level single-mode polymer waveguide technology.

9.2 Outlook

Compared to long-distance optical communication, where optical fibers made of glass are the standard, the search of the ideal material for board-level interconnects is ongoing. The development of suitable polymers is far from completed, and characteristics such as absorption loss, mechanical flexibility, reliability, or processability show room for improvements. Optimized materials will allow for better performing waveguides and devices, and will open a range of new possibilities (e.g., longer link lengths). During this research work, we were continuously reminded that these developments can only occur when polymer chemists and optical engineers work in close collaboration.

After having proven the viability of subsystems of an integrated polymer waveguide technology, in a next step, the integration into a complete optical link would be of particular interest. Successfully demonstrating a fiber-connected wavelength-division multiplexing link, based on the proposed direct laser written waveguide technology, would be a next milestone towards real-world applications. The demonstrator would combine the fabrication of waveguides and complex devices (e.g., the AWG de-/multiplexers), the integration of electrical layers into the waveguide substrate and active light sources (e.g., VCSEL arrays), and the pluggable optical connector proposed.

As a follow-up towards the commercialization of the proposed waveguide system, it is crucial to identify specific applications where these polymer waveguides are superior to
other technologies. The deployment of the waveguides in server or supercomputing sys-
tems could be such an application. The use in integrated spectrometers, as proposed in
Chap. 8, is another possibility. For more wide-spread deployment and mass-fabrication
of polymer waveguides, many larger volume applications have to be found.
Appendices
Appendix A

Custom-build laser direct writer

The custom-build laser direct writing setup is illustrated in Fig. A.1. The setup has been built mainly by Dr. Folkert Horst at IBM Research Zurich.

Figure A.1: Custom-built laser direct writing setup: (left) photo of the setup including, 1. LabVIEW® control software, 2. controller positioner, 3. controller confocal distance measuring device, 4. controller detector power (detector used for laser power calibration and beam focusing), 5. laser direct writing head mounted on xyz-positioner with pneumatic suspensions, 6. sample table with vacuum plate for fixation, 7. pulsed UV-laser (Paladin Compact 355-2000), 8. acousto-optics modulator for laser power control and fiber coupling optics, 9. laser controller.
Appendix B

Waveguide characterization setup

Figure B.2: Schematic of the optical characterization setup.
Bibliography


List of publications


Curriculum vitae

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2010 – 2014 PhD Candidate in Electrical Engineering & Information Technology, ETH Zurich – Working on "Fabrication and System Integration of Laser Direct Written Single-Mode Polymer Optical Waveguides" sponsored by the Swiss Federal Institute of Material Science and Technology, Duebendorf and in collaboration with the IBM Research GmbH, Rueschlikon, Switzerland.

2009 Masters thesis on "Design and Optimization of a Silicon Electro-Optic Modulator", Research Laboratory of Electronics, Physical Optics and Electronics Group, MIT, Cambridge, USA.

2004 – 2009 BSc and MSc in Electrical Engineering & Information Technology, ETH Zurich – Focus on Micro- and Optoelectronics as well as Optical and Wireless Communication.
