Optical temperature sensing on flexible polymer foils

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Optical temperature sensing on flexible polymer foils

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I hereby confirm to have written the following thesis on my own, not having used any other sources or resources than those listed.

Freiburg, August 9, 2017

Stanislav Sherman

To my beloved parents Elena and Grygoriy and my brother Dmitrij

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Notation

List of symbols

symbol	meaning	unit
A	forward propagating mode number	—
B	backward propagating mode number	—
d	rib etch depth of a waveguide	m
D	lateral offset of the interferometer arms	m
DC	duty cycle of a grating	%
$\vec{E}$	electric field vector	—
GD	etch depth of a grating	m
h	height	m
h_{bend}	offset of an S-bend	m
H	core height of a waveguide	m
I	relative intensity	—
k	wave vector	—
L	length	m
m	mode number	—
m_g	diffraction order of a grating	—
M	number of segments	—
n	refractive index	—
N	effective refractive index	—
$\frac{\partial n}{\partial T}, \frac{\partial N}{\partial T}$	thermo-optic coefficient	K ⁻¹
r	reflectivity	—
S_{AMZI}	sensitivity of an AMZI sensor	% K ⁻¹
S_{Bragg}	sensitivity of a Bragg sensor	m K ⁻¹
t	transmission	—
T	temperature	°C / K
w	width of a waveguide	m
α	linear coefficient of thermal expansion	K ⁻¹

symbol	meaning	unit
β	propagation constant	m^{-1}
δ	detuning	m^{-1}
ϵ_0	permittivity of free space	—
ϵ_r	dielectric constant or relative permittivity	F/m
$\epsilon_i = \epsilon_{ri} \epsilon_0$	absolute permittivity of material i	F/m
κ	coupling coefficient	—
λ	wavelength in medium	m
λ_{Bragg}	Bragg wavelength	m
λ_0	wavelength in vacuum	m
Λ	grating period	m
ω	angular frequency	rad/s
ϕ	phase	rad
R_a	arithmetic average of absolute surface roughness	m
θ	angle	rad
ξ	single-mode criterion correction factor	—

List of abbreviations

abbreviation	meaning
2D	two-dimensional
3D	three-dimensional
a. u.	arbitrary unit
AFM	atomic force microscope
AMZI	asymmetric Mach-Zehnder interferometer
API	application programming interface
CCD	charged coupled detector
CMOS	Active pixel sensor in complementary metal oxide semiconductor technology
CMT	coupled-mode theory
DFG	German Research Foundation (Deutsche Forschungsgemeinschaft)
DI	deionized
FBG	fiber Bragg grating
FEM	finite element method
FFT	fast Fourier transform
HMDS	hexamethyldisilazane
LED	light emitting diode
SLED	superluminescent light emitting diode
MZI	Mach-Zehnder interferometer
OLED	organic light emitting diode
PDMS	polydimethylsiloxane
PECVD	plasma enhanced chemical vapor deposition
PMMA	polymethyl methacrylate
POF	polymer optical fiber
RIE	reactive ion etching
rpm	rounds per minute
SAMIM	solvent-assisted microcontact molding
sccm	standard cubic centimeters per minute (flow unit)
SEM	scanning electron microscope
SOI	silicon on insulator
TE	transverse electric
TEC	thermal expansion coefficient
TIR	total internal reflection

abbreviation	meaning
TM	transverse magnetic
TMM	transfer matrix method
TOC	thermo-optic coefficient
UV	ultraviolet wavelengths
WBG	waveguide Bragg grating

Abstract

This thesis presents the design, fabrication, and characterization of two novel types of optical temperature sensors. In contrast to existing devices, the components presented here were for the first time demonstrated as all-polymer systems on thin flexible foils. The fabrication techniques for both sensor concepts were optimized for large-scale mass-production, realizing a significant step towards low-cost manufacturing of optical devices.

The first approach described in this thesis is based on Bragg gratings integrated into single-mode and multi-mode inverted rib polymer waveguides. These sensors convert temperature changes of the environment into a shift of the output spectral features. Therefore, they can be used with broad band light sources, such as organic light emitting diodes (OLEDs), and do not require a laser source.

Theoretical modeling of the sensors, confirmed by experimental results, showed a narrower spectral bandwidth for single-mode sensors as opposed to multi-mode devices. Although this fact potentially simplifies the signal detection, larger structure sizes of multi-mode sensors can further simplify the manufacturing processes. Therefore, multi-mode sensors can be used in systems where temperature resolution is less critical. An experimentally determined sensitivity of $-87 \pm 24 \text{ pm K}^{-1}$ and a temperature resolution of $\approx 0.55 \text{ K}$ for single-mode sensors with a nearly linear response was demonstrated.

The second approach is based on asymmetric Mach-Zehnder interferometers sharing the same waveguide technology as Bragg sensors. A novel asymmetric layout of the developed structures greatly simplifies the manufacturing procedure. In contrast to the Bragg sensor concept, the developed interferometric sensors incorporate an intensity read-out and can, therefore, be used with a simple photodiode. They showed a linear temperature-dependent intensity shift of $0.98 \pm 0.33 \% \text{ K}^{-1}$ and a resolution of $\approx 0.66 \text{ K}$.

For the aimed use as parts of larger optical networks in the future, both sensor types are easily interchangeable due to the same waveguide technology and can be chosen for the desired application by the appropriate read-out concept.

Keywords: temperature sensor, Bragg grating, polymer waveguide, Mach-Zehnder interferometer, all-polymer sensor, large-scale manufacturing, flexible substrate.

Zusammenfassung

Die vorliegende Arbeit präsentiert den Entwurf, die Fertigung und die Charakterisierung zweier neuartiger Temperatursensoren. Im Gegensatz zu existierenden Lösungen, werden die hier gezeigten Komponenten erstmals als reinpolymerbasierte Systeme auf dünnen flexiblen Folien demonstriert. Die Herstellungstechniken für beide Sensorkonzepte wurden für eine großflächige Serienfertigung optimiert, womit ein signifikanter Schritt in Richtung kostengünstiger Herstellung von optischen Komponenten realisiert wurde.

Der erste beschriebene Ansatz basiert auf Bragg-Gittern, welche in monomodige und mehrmodige, invertierte Polymerrippenwellenleiter integriert sind. Diese Sensoren übertragen Temperaturänderungen der Umgebung in Verschiebungen ihrer spektralen Transmissionscharakteristik. Aus diesem Grund können sie mit breitbandigen Lichtquellen, beispielsweise organischen Leuchtdioden (OLEDs), betrieben werden und benötigen keine Laserquellen.

Die theoretische Modellierung der Sensoren zeigte eine schmalere spektrale Bandbreite für die monomodigen Sensoren im Vergleich zu ihren mehrmodigen Pendants, was auch experimentell bestätigt wurde. Obwohl diese Tatsache zu einer potentiellen Verbesserung der Signaldetektion beiträgt, ermöglichen größere Strukturbreiten von mehrmodigen Sensoren eine weitere Vereinfachung der Herstellungsprozesse. Daher können mehrmodige Sensoren in Systemen eingesetzt werden, für welche die Temperaturauflösung weniger kritisch ist. In der vorliegenden Arbeit wurde eine experimentell bestimmte Empfindlichkeit von $-87 \pm 24 \text{ pm K}^{-1}$ für monomodige Sensoren mit einer nahezu linearen Antwortkennlinie und einer Temperaturauflösung von $\approx 0.55 \text{ K}$ erfolgreich demonstriert.

Der zweite Ansatz beschreibt asymmetrische Mach-Zehnder-Interferometer, welche auf der gemeinsamen Wellenleitertechnologie mit den Bragg-Sensoren basieren. Das neuartige asymmetrische Design der entwickelten Strukturen trägt dabei erheblich zur Vereinfachung des Herstellungsprozesses bei. Im Gegensatz zum Bragg-Sensorkonzept, basieren die entwickelten interferometrischen Sensoren auf Intensitätsmessungen und können somit mit einer einfachen Fotodiode als Detektor realisiert werden. Sie zeigten eine lineare temperaturabhängige Intensitätsverschiebung von $0.98 \pm 0.33 \% \text{ K}^{-1}$ mit einer Auflösung von $\approx 0.66 \text{ K}$.

Für die zukünftig beabsichtigte Verwendung der vorgestellten Sensoren als Teile größerer optischer Netzwerke, sind beide Sensortypen aufgrund der gemeinsamen Wellenleitertechnologie leicht austauschbar und können basierend auf dem entsprechenden Auslesekonzept für die gewünschte Anwendung gewählt werden.

Stichwörter: Temperatursensor, Bragg Gitter, Polymerwellenleiter, Mach-Zehnder Interferometer, reinpolymerbasierter Sensor, großflächige Serienfertigung, flexibles Substrat.

1 Introduction

1.1 Temperature sensing

Being one of the basic quantities in the international system of units, temperature belongs to the most frequently measured environmental parameters. A wide variety of natural and industrial processes, covering such fields as structural health monitoring, scientific research, engineering, food and beverage control, and healthcare rely on the exact knowledge and timely recognition of temperature changes. Different processes, however, require appropriate temperature resolutions and measurement ranges, stimulating the ongoing research of novel temperature sensors.

Optical temperature sensors, hereby, offer significant advantages in various situations compared to their electronic equivalents. These advantages include electrical passiveness and insensitivity to electromagnetic interference. Therefore, optical temperature sensors evolved to a popular subject of research over the last decades [1]. Of particular interest in sensing applications are optical fully-integrated waveguide-based sensors as they allow an easy combination of multiple optical components into complex measurement systems.

One example with a high potential for optical sensing is the online health monitoring of lithium-ion batteries. Such batteries are widely used in consumer electronics and were additionally modified for use in electric vehicles and battery storage power plants in the recent time [2–4]. They typically consist of multiple power cells and support high energy densities. However, their temperature can rapidly increase in case of failure and affect the neighboring cells of the battery pack, resulting in a fire or explosion. A precise and independent temperature monitoring of each single cell is, therefore, required to ensure the immediate shutdown of the damaged cell. However, electronic sensors currently used in these batteries often suffer from high electric fields and degradation under harsh working environments [5]. These issues can be solved by optical temperature sensors in the future.

The concept of planar optronic systems is especially attractive for such applications, as it allows a combination of multiple sensor types for a simultaneous monitoring of several environmental parameters.

1.2 Planar optronic systems

Planar optronic systems are optical components, which can be combined to fully integrated spatially distributed sensor networks. The concept of “optronics” involves a broad rejection of electronic components in favor of their optic equivalents. This approach includes the signal generation, transfer, and processing to be realized mainly optically. Combining multiple sensor types, such systems can monitor one or more attributes of their environment. The manufacturing can be easily tuned for the desired application, adjusting the required sensor types.

For such optical components to become even more attractive, they should be made compact and easily manufacturable at low-cost and on a large area. The main effort of this work is, therefore, the realization of the required optical elements as highly integrable polymer components on planar foils with a thickness of several hundred micrometers. This approach includes research and characterization of polymer optical materials and tuning of their thermal, mechanical, and optical properties. Furthermore, concepts for signal generation, transport, and detection are in demand.

Reduction of the fabrication costs is necessary to keep the developed systems competitive to the state-of-the-art products. Another important goal of this thesis is, therefore, also compatibility of the manufacturing processes for all required components to mass-production and roll-to-roll techniques.

With these requirements in mind two novel polymer temperature sensors, based on waveguide Bragg gratings (WBGs) and Mach-Zehnder interferometers (MZIs) respectively, were developed in the scope of this thesis and optimized for use in planar optronic systems.

Both sensor types are based on inverted rib waveguides and are for the first time demonstrated as fully-polymer devices on thin and flexible substrates. Sharing one common waveguide technology, they can be easily combined, interchanged or extended by new sensor types in the future. Additionally, due to different read-out concepts they cover a wide range of possible applications.

1.3 Waveguide and fiber Bragg gratings

Fiber Bragg gratings (FBGs) are periodic modulations of the core refractive index in an optical fiber, designed to reflect a certain spectral region around the Bragg wavelength λ_{Bragg} , as shown in Figure 1.1. The spectral position of λ_{Bragg} shifts if the Bragg grating period or the refractive index of the optical fiber change. This effect is used in a wide range of optical filters and for various sensing applications.

Figure 1.1 Basic principle of a fiber Bragg grating sensor. A periodic modulation of the refractive index in the fiber core acts as a wavelength-selective mirror and can be optimized for the reflection of a narrow spectral region around the Bragg wavelength λ_{Bragg} . The spectral shift of the reflected wavelength band is detected and used for sensing applications.

Research on fiber Bragg gratings started with the generation of a permanent refractive index modulation in Germanium-doped silica fibers in the end of 1970s. In 1978 Hill et al. [6] reported the presence of a photosensitive effect in such fibers by generating an interference pattern between the forward and backward propagating waves inside the fiber core. It, however, took eleven years until Meltz et al. [7] published the modified method of grating generation utilizing a side-exposure of the fiber to a holographic ultraviolet (UV) two-beam interference pattern. This work is considered to be a milestone in the fiber Bragg sensor development [8].

Subsequently, fiber Bragg gratings became one of the most important passive fiber optic components, used for dispersion compensation [9–12], fiber laser pump reflectors [13–15] and in various sensing applications. Sensing fields such as strain [16], pressure [17–19], ultrasonic waves [20–22], force [23–25], acceleration [26,27], magnetic field [28,29], and temperature [30–32] were covered by FBGs over the years.

This popularity of Bragg-based sensors has practical reasons. They offer an attractive alternative to electronic sensors wherever small size and low weight as well as resistance to harsh environments and electromagnetic interference are an issue. Additionally, such sensors typically incorporate a spectral read-out, which makes them insensitive to intensity fluctuations of the light sources.

Up to now Bragg gratings were realized as sensor structures mainly in inorganic materials (silica fibers and semiconductor waveguides). Also, UV-inscription of Bragg gratings into polymer optical fibers (POFs) has been reported. These state-of-the-art devices will be discussed in more detail in the subsequent sections.

1.4 Interferometric sensors

Interferometric sensors represent the second measurement concept discussed in this thesis. Waveguide and fiber-based interferometric sensors generally utilize the interference between two or more beams after propagation through different optical paths. They transfer a phase difference change between the interferometer arms into an intensity change or into a shift of the interference pattern at the output. These sensors, therefore, generally require beam splitting and beam combining elements. Furthermore, single-mode waveguides are necessary to prevent distortions of the output signal due to multi-mode interference. Also, an asymmetry between the interferometer arms is needed to obtain a different phase shift of the propagating light waves with the change of the measured quantity.

This kind of sensors is used in a wide range of commercial and industrial applications, including strain [33,34] and pressure [35,36] sensors, bio-sensors [37], and temperature sensors [38, 39].

Fiber and waveguide-based interferometric sensors offer some important advantages for various applications, as they can be made highly compact and lightweight while maintaining high accuracy and sensitivity. They, furthermore, offer multiplexing capabilities and thus allow distributed sensing [1].

As in case of Bragg sensors, state-of-the-art interferometric sensors exist mostly as discrete optical fiber elements in inorganic materials. Additionally, hybrid material systems with polymer waveguides on inorganic substrates have been reported. However, all-polymer systems, such as the ones demonstrated in this thesis, were not shown in the literature until now.

1.5 State of the art

As optical sensors gained increased popularity in the past decades, a large number of optical temperature sensing devices was reported over the years. This section gives an overview on these developments and shortly describes some of the devices. The approaches are divided by their working principle into Bragg and interferometric sensors.

1.5.1 Waveguide and fiber Bragg grating sensors

As shown in Figure 1.2, Bragg grating sensors can be subdivided into volume and surface gratings by the type of the refractive index modulation, on the one hand. On

Figure 1.2 Fiber and waveguide Bragg gratings can be divided into two basic types. A volume grating, shown in (a), is a direct modulation of the core refractive index. This modulation is most frequently done via UV-exposure of the core to a holographically generated line pattern and is mainly fabricated in photosensitive silica and polymer fibers [7, 40–42]. A surface grating, shown in (b), is a physical modulation of the core size resulting in a modulation of the effective refractive index N_{eff} . Although such modulations were also shown in silica fibers by the direct etching of the fiber core [43, 44], they are mainly the fabrication technique of choice in planar waveguides.

the other hand, the type of the light guiding structure plays an important role in the sensor realization, resulting in the division into fiber and waveguide Bragg gratings. Based on these classifications, this section describes the current development state of fiber and waveguide Bragg sensors in general and temperature sensor specially.

Silica fiber Bragg gratings

Silica fiber Bragg gratings were the first Bragg-based sensors developed. Their manufacturing incorporates an exposure of the photosensitive fiber core to a binary UV pattern. The typical grating periods Λ for the standard telecommunication wavelength of $\lambda_{\text{Bragg}} = 1550 \text{ nm}$ are in the region of 530 nm according to the basic Bragg equation

$$\Lambda = \frac{\lambda_{\text{Bragg}}}{2N_{\text{eff}}}, \quad (1.1)$$

taking into account the effective refractive index of fused silica fibers $N_{\text{eff}} \approx 1.46$. The manufacturing of these small grating periods requires a holographic UV pattern generation by interference lithography or a phase mask, described in Figure 1.3. Switching the Bragg wavelength into the near infrared range around 850 nm , as realized in this thesis, would require an even smaller feature size.

Figure 1.3 Conventional writing techniques for fiber Bragg gratings. The refractive index of a Germanium-doped fiber can be locally modified by UV-exposure. Interference lithography (a) or phase masks (b) can be used to generate a line pattern with a required period of typically 530 nm for the telecommunication wavelength of 1550 nm.

These techniques are well established but have certain drawbacks. Due to small grating periods, the mechanical and thermal stability of the writing setup needs to be maintained during the entire exposure time, increasing the costs of the manufacturing facilities. Additionally, if the writing is not performed directly during the fiber pulling step, the protective buffer layer of the fiber needs to be removed prior to exposure as it shows a high absorption in the UV-range [45]. Fibers, thus, become fragile and require a recoating after the grating inscription. Finally, only specific UV-sensitive types of optical fibers can be processed.

Another possibility for the generation of a Bragg grating in an optical fiber is the physical periodic modulation of the core dimensions, for example by etching of the fiber core. The result is a surface grating, sketched in Figure 1.2 (b), and a modulation of the effective refractive index of the fiber. Several research groups fabricated sensors by this technique [43,44]. However, chemical etching of the core makes it directly exposed to the environment as the process additionally requires a local removal of the cladding layer from the fiber. Therefore, this technique is mainly suitable for chemical and refractive index sensing where a direct interaction of the sensor with the surrounding medium is desired.

The main advantages of inorganic FBG sensors are the high resistance of silica fibers to chemicals and their high temperature stability allowing temperature monitoring in a broad measurement range. Values from 4–300 K [46] up to 1000–1800 °C with silica and sapphire fibers [47] were reported in the literature. However, the temperature range of commercially available FBG-sensors is limited to ≈ -50 to 300 °C.

Silica FBGs, although well developed, also have considerable limitations. The narrow refractive index range of the available core materials restricts the design freedom. Their low thermal expansion coefficient (TEC) and thermo-optic coefficient (TOC) additionally restrict the thermal sensitivity of silica-based Bragg temperature sensors. As fibers are discrete optical elements, they are generally not suited for 2D spatially distributed networking, miniaturization, and large-scale mass production.

Polymer fiber Bragg gratings

Polymer optical fibers (POFs) are not as well developed as silica fibers, but there are several POF types available commercially. They mainly consist of polymethyl methacrylate (PMMA) and typically have a low Young's modulus (about 25 times lower than silica fibers) and also a high elastic limit of about 10 times higher than silica [48], which makes POF-FBGs especially attractive for strain sensing.

Bragg gratings were reported in PMMA POFs [40–42] and fluorinated CYTOP™ POFs [49, 50] fabricated using the same techniques as for their silica counterparts. The mechanism of refractive index change in polymer fibers is, however, not fully understood and multiple processes were reported to be involved into this effect [51–54].

One of the most widely accepted hypotheses says that the refractive index increase in PMMA occurs due to the photo-induced polymerization of the unreacted monomers [51–53]. However, laser-induced heating was also reported as a possible effect [54]. This assumption corresponds with the reported thermal stress in POFs due to the fabrication process, which can be released by thermal annealing [55, 56].

As in case of silica fibers, POFs are also discrete optical elements sharing the same disadvantages as described previously. The utilization of holographic exposure techniques, used in silica fibers for Bragg grating generation, additionally requires custom-made POFs with increased photo-sensitivity [41, 53, 57] or results in long exposure times of 60–180 minutes [58].

Planar waveguide Bragg gratings

State-of-the-art planar waveguides incorporate silicon on insulator (SOI) waveguide technology where a silicon rib structure is developed on top of a silicon oxide layer

by deposition or ablation techniques. The surface type of Bragg gratings is normally applied to such waveguides. The fabrication of the whole structure can be done with high precision. Additionally, highly integrated and miniaturized structures are possible. This case, however, requires a clean-room environment, limiting the mass-production capability of the processes and the maximal area of the sensor networks. Furthermore, sensors based on silicon waveguides are naturally restricted to the middle infrared region and rigid substrates.

Attempts to transfer the existing semiconductor waveguide technology to polymer materials were made in recent years. Thermally tunable WBG-based filters were presented in hybrid technology [59]. They consist of a silicon substrate with a silicon nitride layer patterned as a binary grating. Polymer waveguides from a UV-curable optical adhesive were deposited on top of the grating. The thermal tuning efficiency of the filter was reported to be -0.212 nm K^{-1} .

Another research group demonstrated a Bragg grating patterned SU-8 inverted rib waveguide [60]. The waveguide trench was etched into a standard silicon wafer, which was then coated by a silicon oxide layer serving as a lower cladding for the SU-8 core. The core was patterned with a Bragg grating via solvent-assisted microcontact molding (SAMIM) prior to UV-cross-linking of the SU-8.

In contrast to the sensors presented in this thesis, no fully polymer-based realization of planar WBG-sensors has been demonstrated up to now.

1.5.2 Interferometric sensors

Interferometric sensors for various physical quantities, such as refractive index, strain pressure and temperature, were also widely investigated over the past decades [61–65]. The most widespread interferometer types for temperature sensing applications are Young interferometers and Mach-Zehnder interferometers, as they can be easily fabricated as fiber-integrated or planar sensors [66–68].

Young interferometers

In an integrated Young interferometer the light path is split into two interferometer arms, as shown in Figure 1.4. One of the arms serves as a reference and the other arm includes a phase shifting structure sensitive to the measured quantity. The introduced asymmetry results in an optical path difference between the interferometer arms and shifts the interference pattern at the output if the measured quantity changes. This interference pattern can be captured by a photodiode array or a CCD-chip and used to calculate the relative phase of the propagating beams.

Figure 1.4 Schematic image of an integrated Young interferometer. The relative phase between two interferometer arms is detected at the output as an interference pattern.

Various Young interferometers were introduced for sensing applications. Most widespread are fiber-integrated elements and silicon oxide-based planar structures for biological sensing [69] and silicon nitride on silicon oxide waveguides for temperature sensing [70].

No fully polymer-based devices, however, exist to date. One of the few hybrid organic/inorganic systems reported in the literature was used for bio-sensing applications. It was based on commercially availableOrmocer[®] polymer waveguide materials patterned on a rigid silicon substrate [71].

Mach-Zehnder interferometers

Mach-Zehnder interferometers were one of the temperature sensor types investigated in this thesis. These structures are similar to Young interferometers; however, they recombine the modes propagating in the interferometer arms into a single waveguide.

Therefore, a modulation of the relative phase difference in the interferometer arms can be directly translated into an intensity change at the output.

The main advantages of these devices are their simple structure along with a simple read-out system. They only require a laser source for the input and a photodiode for the detection of the output intensity.

Such structures were reported mostly as fiber-integrated and silicon-based planar components in the past decades. The rather simple structure and high sensitivity to refractive index changes make them attractive for sensing applications. Mach-Zehnder-based strain [72], humidity [73], refractive index [74, 75], and temperature sensors [76] were reported recently.

Polymer-based devices are, however, rather rare. As in the case of Bragg sensors, mostly polymer waveguides on rigid inorganic substrates were reported in the literature. For example, Bruck et al. [74] reported a bio-molecule sensor consisting of a polyimide core deposited on a silicon oxide substrate layer. The high refractive index contrast between polyimide and silicon oxide allowed an enhancement of the refractive index sensitivity of the interferometers.

A Mach-Zehnder pressure sensor consisting of SU-8 waveguides on an oxidized silicon wafer was demonstrated as another hybrid system [77]. In this case the interferometers were deposited on top of a thin membrane and deformed on pressure change. The intensity change at the output of the interferometers was then used for the calculation of the applied pressure.

However, all of these devices incorporate a hybrid polymer/inorganic design and are fabricated on rigid semiconductor substrates.

1.6 Main results

The state-of-the-art review has shown that the concepts of fiber and waveguide Bragg gratings as well as interferometers for sensing applications were followed by various research groups over the years. The sensors developed here, however, are the first planar flexible fully-polymer realization of these sensing concepts. This thesis also realizes the transfer of such components into polymer patterning processes compatible with mass-production and roll-to-roll manufacturing. This transfer allows large-scale fabrication of the sensors and thus brings them closer to commercial applications.

To achieve these goals, specific changes in the design of waveguides and sensors were made to simplify the fabrication.

1.6.1 Polymer waveguides

Waveguides are the basic elements of planar optical systems. The inverted rib waveguide design shown in this thesis addresses two of the main challenges in the polymer waveguide fabrication. On the one hand, the lateral dimensions of the waveguides can be increased, simplifying the fabrication process. On the other hand, this design does not require residual-layer-free deposition of the core but rather depends on the precise control of the overall layer thickness, opening the possibility of printing or spray coating of the core layer on the patterned substrate.

Design concepts for single-mode and multi-mode waveguides were introduced in this thesis. According to these concepts, inverted rib waveguides on flexible 175 μm -thick PMMA substrates were fabricated by hot-embossing and spin-coating of the core layer. Although this approach required a master structure precisely fabricated under clean-room conditions, afterwards it was possible to use this master structure for the fabrication of multiple hot-embossing stamps. The stamps in turn allowed numerous replications of the designed structures in PMMA substrate foils, making the whole procedure compatible with mass-production. The developed microfabrication process for the master structures was optimized for design flexibility, precision of the structure dimensions, and low surface roughness to minimize stray losses of the fabricated waveguides.

After fabrication, propagation losses of the waveguides were measured by the cut-back method to be $2.2 \pm 0.3 \text{ dB cm}^{-1}$. This value is in the typical range for polymer waveguides [78, 79], confirming the feasibility of the chosen approach.

Based on the introduced waveguides, two temperature sensor types with different working principles and read-out concepts were designed, simulated, fabricated, and characterized experimentally.

1.6.2 Waveguide Bragg grating temperature sensors

Waveguide Bragg grating temperature sensors, shown in Figure 1.5, were realized in multi-mode and single-mode waveguides on thin flexible substrates. This thesis demonstrated the design and fabrication of the complete structures and presented experimental results, confirming the proper function of the sensors.

Nanostructured Bragg gratings were integrated into the top cladding layer of the waveguides in a separate manufacturing step, making the fabrication of the waveguides independent from the grating fabrication. This approach greatly simplified the overall manufacturing process at both the master structure generation and the hot-embossing stages.

Figure 1.5 A WBG-based temperature sensor developed and characterized in the scope of this thesis. The Bragg grating was fabricated in a thin polymer foil and attached to the top of a second foil containing polymer waveguides. Dotted lines indicate the waveguide direction and dashed lines the grating direction.

Optical characteristics of the used materials were measured at different temperatures, and the results of this characterization were implemented in a simulation model of the entire system. A series of extensive simulations was performed to explore and compare the performance of Bragg gratings in multi-mode and single-mode waveguides. The results showed a comparable sensitivity to temperature changes of $\approx -77 \text{ pm K}^{-1}$ for both sensor types. However, the single-mode sensors had a sharper and better predictable spectral response, which was easier detectable and interpretable than the one from the multi-mode sensors. Nevertheless, multi-mode sensors can be used to further release the size limitations of the waveguides if required.

The subsequent experimental evaluation showed a temperature-induced spectral shift of the Bragg wavelength of $-87 \pm 24 \text{ pm K}^{-1}$ and a temperature resolution of $\approx 0.55 \text{ K}$ for the single-mode sensor, confirming the theoretical results.

Asymmetric Mach-Zehnder interferometer-based temperature sensors

Asymmetric Mach-Zehnder interferometer (AMZI)-based temperature sensors shown in Figure 1.6 deliver an intensity signal at the output, allowing an easier read-out

Figure 1.6 Asymmetric Mach-Zehnder interferometer-based temperature sensors fabricated in a thin polymer foil. Dotted lines indicate the position of the sensing structures.

as no spectral analysis is required. In turn, they tighten the allowed manufacturing tolerance range, as slight size variations of the waveguide geometry shift the working point of the sensor from the ideal value.

Design of the integrated polymer Mach-Zehnder interferometers shown in this thesis made use of asymmetric waveguide widths in the interferometer arms to introduce a phase shift difference along the wave propagation path. This approach only required the structuring of the lower cladding layer. The core and top cladding were deposited from liquid materials as thin homogenous layers prior to UV-curing. This procedure greatly reduced the fabrication complexity.

The temperature-dependent properties of the sensor materials and previously measured waveguide losses were implemented into a simulation model for the AMZI temperature sensors. The simulations allowed the optimization of the sensor dimensions for the best sensitivity and linearity in the aimed temperature range.

Designed structures were fabricated via hot-embossing of the PMMA-substrates and spin-coating of the core and top cladding layers. Experimental evaluation of the fabricated structures showed a sensitivity of $0.98 \pm 0.33 \% K^{-1}$ and a temperature resolution of $\approx 0.66 K$, which closely matched the simulated value of $1.12 \% K^{-1}$.

2 Theory

As mentioned in Chapter 1, both temperature sensor types described in this thesis are waveguide-based. Therefore, the theory behind optical waveguides is necessary for the understanding of the working principles and sensing mechanisms of the introduced structures.

For this reason, this chapter begins with the theoretical analysis of optical waveguides and specially inverted rib waveguides. In the following sections working principle of waveguide Bragg gratings is addressed, and basic theory required for the understanding of the used simulation software is described. Subsection 2.2.5 considers the origins of the thermal sensitivity of polymer materials in general and of polymer-based Bragg devices in particular. Finally, Section 2.3 describes the working principle and the related theoretical background for Mach-Zehnder interferometers, including the asymmetric interferometer type used in this thesis.

2.1 Principles of optical waveguides

Dielectric waveguides are the basic elements in most integrated optical devices. They serve as interconnects guiding light waves between different parts of the system or directly contain light modulating elements and sensors.

2.1.1 Slab waveguides

A dielectric waveguide consists of a region with high refractive index surrounded by a region or medium with lower refractive index. The simplest case is a slab waveguide, shown in Figure 2.1, which is just a stack of three layers. In this case, a light-wave is confined in the middle, optically denser region with the refractive index n_g and thickness h by total internal reflection (TIR) at the material boundaries. An additional requirement for TIR is an incident angle of light θ_i larger than the critical angle θ_c [80], described by

$$\theta_i > \theta_c = \arcsin \left(\frac{n_{c,s}}{n_g} \right). \quad (2.1)$$

Figure 2.1 Side view of a slab waveguide. Refractive index of the core layer n_g is larger than the indices of the surrounding layers n_s and n_c , allowing the confinement of light inside the structure by total internal reflection at the boundaries. θ_1 and θ_2 represent the incident angles of two different modes.

The characteristic equation for a dielectric waveguide can be derived from the phase matching condition for the m -th mode [80]

$$\frac{4\pi h}{\lambda} \cos(\theta_i) - \Delta\phi_c - \Delta\phi_s = 2m\pi, \quad (2.2)$$

where λ represents the wavelength in the core material, while $\Delta\phi_c$ and $\Delta\phi_s$ represent the phase shifts occurring at the core-cladding and core-substrate interfaces during TIR respectively. They can be obtained from the Fresnel equations and inserted into Equation 2.2, leading to [80]

$$\frac{4\pi h}{\lambda} \cos(\theta_i) - 2 \arctan \left[\frac{\sqrt{\sin^2(\theta_i) - \left(\frac{n_c}{n_g}\right)^2}}{\cos(\theta_i)} \right] - 2 \arctan \left[\frac{\sqrt{\sin^2(\theta_i) - \left(\frac{n_s}{n_g}\right)^2}}{\cos(\theta_i)} \right] = 2m\pi \quad (2.3a)$$

for transverse electric (TE) polarization and

$$\frac{4\pi h}{\lambda} \cos(\theta_i) - 2 \arctan \left[\frac{\sqrt{\sin^2(\theta_i) - \left(\frac{n_c}{n_g}\right)^2}}{\left(\frac{n_c}{n_g}\right)^2 \cos(\theta_i)} \right] - 2 \arctan \left[\frac{\sqrt{\sin^2(\theta_i) - \left(\frac{n_s}{n_g}\right)^2}}{\left(\frac{n_s}{n_g}\right)^2 \cos(\theta_i)} \right] = 2m\pi \quad (2.3b)$$

for transverse magnetic (TM) polarization in the general case, where $n_c \neq n_s$.

Figure 2.2 Cross-section of an inverted rib waveguide divided into three homogenous regions. For the determination of the corresponding effective refractive indices $N_{\text{eff},1/2}$ the regions are approximated by a slab waveguide each. These effective refractive indices are required for the calculation of the single-mode waveguide dimensions.

2.1.2 Inverted rib waveguides and single-mode behavior

In contrast to the simple case of a slab waveguide, a more complex waveguide geometry was used in the scope of this thesis; namely a rib waveguide, better known from semiconductor technology, flipped upside down as shown in Figure 2.2. The light wave in such structures is confined due to the higher thickness and thus a higher effective refractive index of the middle region, compared to the outer region, $N_{\text{eff},1} > N_{\text{eff},2}$.

Multiple analytic approaches for modelling of rectangular waveguide geometries were proposed over the years. One of the most popular was introduced by Enrique Marcatili [81] and is known as the *Marcatili's method*. It ignores the electric field in the corners of a rectangular waveguide. The rib waveguide geometry is, however, too complex for an analytic investigation and generally requires a numerical simulation for precise results [82].

Therefore, a numerical calculation of the single-mode condition for rib waveguides by a mode-matching method was performed by Petermann [83]. It served as a basis for the semi-analytic criterion developed by Soref et al. [84]. The system was hereby divided horizontally into three regions as shown in Figure 2.2, and each of them was approximated by a slab waveguide of the respective thickness. The effective refractive index $N_{\text{eff},1/2} = n_g \sin(\theta_{i,1/2})$ of each region was calculated by solving Equations 2.3a and 2.3b numerically.

The maximal width of a single-mode waveguide is then given by

$$w_{\text{Soref}} < \frac{\pi}{k_0 \sqrt{N_{\text{eff},1}^2 - N_{\text{eff},2}^2}}, \quad (2.4)$$

with the vacuum wave vector k_0 . However, this approximation is only valid for large waveguide cross-sections ($H \geq 10 \mu\text{m}$).

The equation developed by Soref et al. [84] was then adapted by Müllner et al. [85] for smaller waveguide cross-sections of silicon on insulator (SOI) waveguides, namely

$$w < \xi + \frac{\pi}{H k_0 \sqrt{N_{\text{eff},1}^2 - N_{\text{eff},2}^2}}, \quad (2.5)$$

where $\xi_{TE} = 0.31 \pm 0.02$ for TE modes and $\xi_{TM}(H) = 0.28 \left(1 - e^{-\frac{H}{630}}\right) \pm 0.03$ for TM modes were determined from finite element method (FEM) simulations.

This equation was confirmed to be valid also for polymer waveguides [86] by a series of simulations with FIMMPROP by Photon Design® and used in the scope of this thesis.

2.2 Principles of Bragg gratings

This section describes the fundamental theory behind fiber and waveguide Bragg gratings required for the understanding of the introduced sensors and of the working principle of the simulation software used in Chapter 3. Therefore, the main focus here lies on uniform-period gratings with a step refractive index profile, ignoring such effects as apodization, fringe tilt and non-linear effects covered in the literature [87,88].

In the first part of this chapter the basic principle of waveguide gratings is discussed on a ray optics model for simplification. The origin of the well-known Bragg equation $\lambda_{\text{Bragg}} = 2N_{\text{eff}} \cdot \Lambda$ is derived and extended for the cases of coupling into cladding modes.

The following part addresses a more complex modeling of the Bragg grating effect by means of coupled-mode theory (CMT) and uses results of the CMT analysis to visualize the influence of the main grating design parameters on the spectral characteristics of Bragg gratings. The next subsection gives an overview of the transfer matrix method (TMM), a widely used technique for numerical solving of the differential equations obtained from CMT.

Finally, the origins of thermal sensitivity of polymer Bragg gratings are analyzed and compared to inorganic materials.

2.2.1 Basic principle

Generally waveguide Bragg gratings can be considered as one-dimensional diffraction gratings, diffracting light from the forward-propagating mode in the waveguide core into a backward-propagating mode meeting the corresponding Bragg condition. Thus, they can be regarded as reflection gratings. Another similar type of waveguide gratings are so called *long period gratings*, coupling light into modes propagating into the same direction as the original mode. Therefore, they are transmission gratings. Both grating types can be described by the grating equation [89]

$$n \sin(\theta_r) = n \sin(\theta_i) + m_g \frac{\lambda_0}{\Lambda}, \quad (2.6)$$

where an incident wave interacts with a grating of period Λ at an angle θ_i , resulting in the diffracted wave at an angle θ_r . The diffraction order of the grating is hereby described by m_g , whereas λ_0 represents the vacuum wavelength of the incident light and n is the refractive index of the surrounding medium.

Possible interactions between modes in a waveguide with a finite cladding and a grating-modulated core region are shown in Figure 2.3 (a)–(c). Bragg reflection is hereby covered by Figure 2.3 (a), where a forward-propagating mode with an incident angle θ_i is coupled into a core backward-propagating mode with the diffracted angle θ_r .

Considering the propagation constant of a mode

$$\beta = \frac{2\pi \cdot n_g}{\lambda_0} \sin(\theta) = \frac{2\pi}{\lambda_0} \cdot N_{\text{eff}}, \quad (2.7)$$

with $N_{\text{eff}} = n_g \sin(\theta)$ being the effective refractive index of the corresponding mode, Equation 2.6 can be expressed in terms of propagation constants. Additionally, assuming that the $m_g = -1$ order generally dominates in waveguide gratings Equation 2.6 becomes

$$\beta_r = \beta_i - \frac{2\pi}{\Lambda}. \quad (2.8)$$

For the coupling into a counter-propagating mode and thus $\beta_r < 0$ we obtain

$$\lambda_0 = (N_{\text{eff}(i)} + N_{\text{eff}(r)}) \cdot \Lambda, \quad (2.9)$$

which leads us to the well-known Bragg grating equation

$$\lambda_0 = \lambda_{\text{Bragg}} = 2N_{\text{eff}} \cdot \Lambda, \quad (2.10)$$

assuming the forward and backward propagating modes are identical.

Figure 2.3 Ray optic model for a waveguide grating coupling from the core forward-propagating mode into (a): the core backward-propagating mode (Bragg reflection); (b) the cladding forward-propagating mode and (c): the cladding backward-propagating mode.

Additionally, all waveguide Bragg sensors examined in this thesis have a finite cladding layer. Therefore, cases of cladding mode interactions sketched in Figure 2.3(b) and (c) also need a discussion, as they might have an effect on the transmission spectrum of the sensor.

In case of forward coupling as in Figure 2.3(b) and thus $\beta_r > 0$, the coupled wavelength can be described by $\lambda_0 = (N_{\text{eff}(i)} - N_{\text{eff}(r)}) \cdot \Lambda$. In this case a much larger grating period is required to achieve mode coupling in the same wavelength region as the Bragg reflection. Therefore, forward coupling can be ignored in the scope of this thesis.

Of more interest is the case visualized in Figure 2.3(c), covering the coupling into counter-propagating cladding modes. Here the effective refractive index of the cladding mode comes into play and is expected to be close to the effective refractive index of the core mode, leading to $\lambda_0 = (N_{\text{eff}(\text{core})} + N_{\text{eff}(\text{cladding})}) \cdot \Lambda$ and causing a mode interaction close to the Bragg wavelength.

Cladding modes generally have high losses and disappear after a short propagation length. Therefore, the wavelength range coupled into them is not present in the reflected signal, but leads to additional dips in the transmitted spectrum of the waveguide at wavelengths close to the Bragg reflection.

2.2.2 Coupled-mode theory

Although the previously described fundamental Equation 2.10 delivers the spectral position of the Bragg reflection in case of a single-mode waveguide, it neither addresses such factors as grating strength and the corresponding diffraction efficiency nor the exact spectral response of the structure. Therefore, a practical theoretical model of a waveguide Bragg grating is required.

The most common approach for analysis of waveguide Bragg gratings is the coupled-mode theory [90–93], which is considered to allow a straight-forward and precise modeling of uniform and non-uniform Bragg gratings. It assumes an ideal waveguide whose electric field $\vec{E}_t$ in transverse direction can be described by a superposition of p ideal modes with amplitudes A_j , traveling in the $+z$ -direction and B_j , traveling in the $-z$ -direction, namely

$$\vec{E}_t(x, y, z, t) = \sum_{j=0}^{p-1} [A_j(z) e^{i\beta_j z} + B_j(z) e^{-i\beta_j z}] \cdot \vec{e}_{jt}(x, y) e^{-i\omega t}. \quad (2.11)$$

The transverse mode field $\vec{e}_{jt}(x, y)$ hereby describes cladding modes, mentioned in the previous section [87].

In case of an ideal waveguide, modes do not exchange energy. On the contrary, if a corrugation and hence a dielectric perturbation is present (for instance introduced by a Bragg grating) this is no longer valid. As a result, mode amplitudes of the j -th mode change along the propagation direction as [87]

$$\frac{\partial A_j}{\partial z} = i \sum_{k=0}^{p-1} (\kappa_{kj}^t + \kappa_{kj}^l) A_k e^{i(\beta_k - \beta_j)z} + i \sum_{k=0}^{p-1} (\kappa_{kj}^t - \kappa_{kj}^l) B_k e^{[-i(\beta_k + \beta_j)z]} \quad (2.12a)$$

and

$$\frac{\partial B_j}{\partial z} = -i \sum_{k=0}^{p-1} (\kappa_{kj}^t - \kappa_{kj}^l) A_k e^{i(\beta_k + \beta_j)z} - i \sum_{k=0}^{p-1} (\kappa_{kj}^t + \kappa_{kj}^l) B_k e^{[-i(\beta_k - \beta_j)z]}. \quad (2.12b)$$

The coupling coefficients κ_{kj}^t in transverse and κ_{kj}^l in longitudinal direction describe the coupling between modes j and k . However, in case of waveguides the longitudinal coupling is much lower than the transverse coupling; therefore, κ_{kj}^l can be neglected [87]. κ_{kj}^t has the form

$$\left(\kappa_{kj}^t + \kappa_{kj}^l\right) \approx \left(\kappa_{kj}^t - \kappa_{kj}^l\right) \approx \kappa_{kj}^t = \frac{\omega}{2} \iint (\epsilon - \epsilon_0) \vec{e}_{kt} \cdot \vec{e}_{jt} \cdot dx \cdot dy, \quad (2.13)$$

where ϵ is the permittivity at a point (x, y, z) in space and ϵ_0 the permittivity of vacuum, while $\vec{e}_{kt}$ and $\vec{e}_{jt}$ represent the transverse mode fields [94].

Equations 2.12a and 2.12b can also be expressed in matrix form as

$$\frac{\partial}{\partial z} \begin{bmatrix} A_j \\ B_j \end{bmatrix} = \sum_{k=0}^{p-1} C(z) \begin{bmatrix} A_k \\ B_k \end{bmatrix} \quad (2.14)$$

with a matrix $C(z)$ consisting of the coupling coefficients $\kappa_{kj}^t = \kappa_{kj}$, namely

$$C(z) = \begin{bmatrix} i\kappa_{kj}e^{i(\beta_k - \beta_j)z} & i\kappa_{kj}e^{-i(\beta_k + \beta_j)z} \\ -i\kappa_{kj}e^{i(\beta_k + \beta_j)z} & -i\kappa_{kj}e^{-i(\beta_k - \beta_j)z} \end{bmatrix}. \quad (2.15)$$

Additional simplifications can be applied to this equation depending on the geometry and the number of supported modes of the particular waveguide. For general cases numerical methods need to be used to find a solution.

2.2.3 Bragg grating spectra

For the waveguide geometries presented in this thesis, solving the CMT equations requires a numerical calculation. Nonetheless, an analysis of a simplified model of a *single-mode step index circular cross-section waveguide* delivers a general overview of the Bragg grating performance and is, therefore, useful for the understanding of the basic features of a Bragg spectrum. The exact derivation of the used equations is widely discussed in the literature [87]. Thus, only results relevant for the understanding of the important spectral features are presented here.

Consider a uniform Bragg grating with a sinusoidal refractive index profile along the waveguide direction

$$\delta N_{\text{eff}}(z) = \overline{\delta N_{\text{eff}}(z)} \left[1 + \cos\left(\frac{2\pi}{\Lambda} z\right) \right], \quad (2.16)$$

where $\overline{\delta N_{\text{eff}}(z)}$ is the refractive index perturbation in the waveguide averaged over one grating period.

Using the CMT equations, the variation of the grating reflectivity can be calculated as [87]

$$r = \frac{\sinh^2 \left(L \sqrt{\kappa^2 - \hat{\sigma}^2} \right)}{\cosh^2 \left(L \sqrt{\kappa^2 - \hat{\sigma}^2} \right) - \frac{\hat{\sigma}^2}{\kappa^2}}, \quad (2.17)$$

with

$$\kappa = \frac{\pi}{\lambda_0} \overline{\delta N_{\text{eff}}(z)} \quad (2.18a)$$

and

$$\hat{\sigma} = \delta + \frac{2\pi}{\lambda_0} \overline{\delta N_{\text{eff}}(z)}, \quad (2.18b)$$

where L stands for the length of the grating and the detuning parameter

$$\delta = \beta - \frac{\pi}{\Lambda} = 2\pi N_{\text{eff}} \left(\frac{1}{\lambda} + \frac{1}{\lambda_{\text{Bragg}}} \right) \quad (2.19)$$

describes the difference between the propagating wavelength λ and the design wavelength $\lambda_{\text{Bragg}} \equiv 2N_{\text{eff}}\Lambda$ for an infinitesimally weak grating. The maximal reflectivity of the grating can then be described as [87]

$$r_{\text{max}} = \tanh^2(\kappa L) \quad (2.20)$$

and occurs at the wavelength

$$\lambda_{\text{max}} = \left(1 + \frac{\overline{\delta N_{\text{eff}}}}{N_{\text{eff}}} \right) \lambda_{\text{Bragg}}. \quad (2.21)$$

This calculation provides some important insights into the spectral response of a Bragg grating. Equation 2.20 demonstrates that the maximum reflectivity of a Bragg grating only depends on the strength of the refractive index modulation $\overline{\delta N_{\text{eff}}}$ and the grating length L . Thus, both quantities can be increased to enhance the maximal reflectivity of the grating, as demonstrated in Figure 2.4 (a) and (b).

However, at the same time variations of $\overline{\delta N_{\text{eff}}}$ and L have different effects on the bandwidth of the reflected spectrum. For convenience this bandwidth can be defined taking the distance between the first two minima $\Delta\lambda_{\text{min}}$ around the main reflection peak as [87]

$$\frac{\Delta\lambda_{\text{min}}}{\lambda} = \frac{\overline{\delta N_{\text{eff}}}}{N_{\text{eff}}} \sqrt{1 + \left(\frac{\lambda_{\text{Bragg}}}{\overline{\delta N_{\text{eff}}} L} \right)^2}. \quad (2.22)$$

Figure 2.4 (a): Spectral responses of a FBG for a fixed grating length L and different refractive index perturbation strengths δN_{eff} . (b): Spectral responses of a FBG for a fixed δN_{eff} and different grating lengths L . The maximal reflectivity of the grating is affected by both δN_{eff} and L . The corresponding bandwidth change of the signal is, however, dependent on the strength of the Bragg grating.

This relation allows the classification of Bragg gratings by the strength of the refractive index modulation. For $\delta N_{\text{eff}} \ll \lambda_{\text{Bragg}} \cdot L^{-1}$ Equation 2.22 can be reduced to

$$\frac{\Delta \lambda_{\min}}{\lambda} \approx \frac{\lambda_{\text{Bragg}}}{L N_{\text{eff}}}, \quad (2.23)$$

making the bandwidth independent of the refractive index modulation. Such gratings can be classified as weak Bragg gratings and are described by the $\kappa L = 0.8$ and $\kappa L = 2$ plots in Figure 2.4.

For the opposite case $\delta N_{\text{eff}} \gg \lambda_{\text{Bragg}} \cdot L^{-1}$, on the other hand, and thus

$$\frac{\Delta \lambda_{\min}}{\lambda} \approx \frac{\delta N_{\text{eff}}}{N_{\text{eff}}}, \quad (2.24)$$

the bandwidth of the Bragg grating becomes independent of the grating length. Light close to the Bragg wavelength is fully reflected before it penetrates the entire grating length, as depicted in Figure 2.4 for the strong grating $\kappa L = 8$.

For sensing applications a low bandwidth of the signal while still maintaining a high maximum reflectivity and, therefore, a weak Bragg grating is desired. The introduced calculations show that this goal can be achieved reducing the refractive index modulation while increasing the grating length.

Figure 2.5 For transfer matrix method the Bragg grating region is divided into M segments along the propagation direction, each with its individual phase shift ϕ , refractive index modulation Δn and period Λ . An individual transfer matrix of each segment is calculated, and the transfer matrix of the entire system is obtained as the product of the individual matrices.

2.2.4 Transfer matrix method

One of the numerical approaches to solve coupled-mode differential equations is the transfer matrix method (TMM), first presented by Yamada et al. [95]. It developed to one of the most used simulation techniques for fiber and waveguide Bragg gratings and waveguide couplers [96].

In this approach the grating region of length L is divided along z -direction into M small uniform subgratings $z_0, z_1 \dots z_b \dots z_M$ of length a each, as shown in Figure 2.5. They are assumed to have uniform coupling properties. Each segment generally has its own specific phase shift ϕ , refractive index modulation Δn and period Λ and thus its own transfer matrix T_b , which obeys Equation 2.14. Any grating profile, including chirped and apodized gratings, can be approximated by adjusting the properties of each section.

The number of TMM segments should be kept low for two reasons. On the one hand, a high number of segments increases the computational effort, canceling the benefits of the TMM. On the other hand, in this case each segment would only include a low number of grating periods. However, several periods are necessary for a complete coupling. Yet, the general approximate limitation of

$$M \ll \frac{L}{\Lambda} \quad (2.25)$$

is typically not reached for sensing applications, as $M \approx 100$ is normally sufficient for accurate modeling [97].

Although this technique drastically reduces the computational effort, refractive index variations on a scale shorter than one segment can not be accounted for. Nonetheless, the modeling of such rapid refractive index fluctuations is not necessary in the scope of this thesis.

A closer look at the position $z = a$ at the output of the first segment reveals

$$\begin{bmatrix} A_j(a) \\ B_j(a) \end{bmatrix} = T_1 \begin{bmatrix} A_j(0) \\ B_j(0) \end{bmatrix} = \begin{bmatrix} T_{11} & T_{12} \\ T_{21} & T_{22} \end{bmatrix}_1 \begin{bmatrix} A_j(0) \\ B_j(0) \end{bmatrix}. \quad (2.26)$$

The output of the first slice is used as the input value for the second slice of the grating

$$\begin{bmatrix} A_j(2a) \\ B_j(2a) \end{bmatrix} = \begin{bmatrix} T_{11} & T_{12} \\ T_{21} & T_{22} \end{bmatrix}_2 \begin{bmatrix} A_j(a) \\ B_j(a) \end{bmatrix} = \begin{bmatrix} T_{11} & T_{12} \\ T_{21} & T_{22} \end{bmatrix}_1 \begin{bmatrix} T_{11} & T_{12} \\ T_{21} & T_{22} \end{bmatrix}_2 \begin{bmatrix} A_j(0) \\ B_j(0) \end{bmatrix}, \quad (2.27)$$

and so on. Extending this approach, the general equation for the amplitudes of the forward and backward propagating modes at the end of the grating can be written as a function of the input amplitudes, namely

$$\begin{bmatrix} A_j(L) \\ B_j(L) \end{bmatrix} = \prod_{q=1}^M T_q \begin{bmatrix} A_j(0) \\ B_j(0) \end{bmatrix}, \quad (2.28)$$

with $\prod_{q=1}^M T_q = T$ being the combined transfer matrix of the system.

The elements of the transfer matrix at any position b , obtained from Equation 2.14, are pairwise complex conjugates of each other, so that

$$T_{11} = T_{22}^* = i\kappa_{kj} \cdot e^{i(\beta_k - \beta_j)b} \quad (2.29a)$$

$$T_{12} = T_{21}^* = i\kappa_{kj} \cdot e^{i(\beta_k + \beta_j)b}. \quad (2.29b)$$

The transfer matrix is therefore unitary and thus easily invertable. As a product of unitary matrices is also a unitary matrix, Equation 2.28 can be rewritten as

$$\begin{bmatrix} A_j(0) \\ B_j(0) \end{bmatrix} = \begin{bmatrix} T_{22} & -T_{12} \\ -T_{21} & T_{11} \end{bmatrix} \begin{bmatrix} A_j(L) \\ B_j(L) \end{bmatrix}. \quad (2.30)$$

The reflection and transmission coefficients for each mode, r_j and t_j respectively, can now be calculated under the assumption the magnitudes of the backward-propagating modes are zero after the grating, so $B_j(L) = 0$, leading to

$$\begin{bmatrix} A_j(0) \\ B_j(0) \end{bmatrix} = \begin{bmatrix} T_{22} & -T_{12} \\ -T_{21} & T_{11} \end{bmatrix} \begin{bmatrix} A_j(L) \\ 0 \end{bmatrix} \quad (2.31)$$

and

$$r_j(\lambda) = \frac{B_j(0)}{A_j(0)} = -\frac{T_{21}}{T_{22}}, \quad (2.32a)$$

$$t_j(\lambda) = \frac{A_j(L)}{A_j(0)} = -\frac{1}{T_{22}}. \quad (2.32b)$$

In order to further minimize the calculation effort, the section length for uniform gratings can be defined in fractions of the grating period. For non-uniform period gratings, sections can have a dynamic length adjusted along the grating to the changes of the period.

2.2.5 Thermal sensitivity of Bragg sensors

As shown in preceding sections, two quantities influence the position of the Bragg wavelength. These are changes in the grating period Λ and in the effective refractive index of the waveguide N_{eff} . Both quantities are temperature dependent and can be described through the thermo-optic coefficient (TOC) $\partial N_{\text{eff}}/\partial T$ and the thermal expansion coefficient (TEC) α_g of the waveguide. Equation 2.10 then evolves to

$$\Delta\lambda_B = \lambda_{B0} - 2 \left(N_{\text{eff}0} + \frac{\partial N_{\text{eff}}}{\partial T} \Delta T \right) (\Lambda_0 \cdot (1 + \alpha_g \Delta T)) \quad (2.33)$$

for a temperature change ΔT and normalized to λ_{B0} becomes

$$\frac{\Delta\lambda_B}{\lambda_{B0}} = \left(\alpha + \frac{1}{N_{\text{eff}0}} \frac{\partial N_{\text{eff}}}{\partial T} \right) \Delta T + \left(\alpha \cdot \frac{1}{N_{\text{eff}0}} \frac{\partial N_{\text{eff}}}{\partial T} \right) \Delta T^2. \quad (2.34)$$

The values of the Bragg wavelength, effective refractive index of the waveguide, and Bragg grating period before the temperature change are hereby denoted with λ_{B0} , $N_{\text{eff}0}$, and Λ_0 , respectively.

The quadratic term of Equation 2.34 introduces a non-linearity into the output signal of the Bragg sensor, but its prominence is strongly dependent on the thermal coefficient values of the used materials. As shown in Table 2.1, for fused silica fibers

Table 2.1 Optical and thermal properties of common optical materials.

Optical material	Refractive index at 658 nm	TEC 10^{-6} K^{-1} [48]	TOC 10^{-6} K^{-1} [48]
Polymethyl-methacrylate (PMMA)	1.488 [99]	36 ... 80	−105 ... −200
Polystyrene (PS)	1.585 [99]	60 ... 80	−120 ... −140
Polycarbonate (PC)	1.578 [99]	66 ... 70	−107 ... −143
Fused silica	1.456 [48]	0.55	6.7

the TOC $\partial n_g / \partial T (\text{SiO}_2) = 6.7 \times 10^{-6} \text{ K}^{-1}$ is considerably higher than the related TEC $\alpha_g (\text{SiO}_2) = 0.55 \times 10^{-6} \text{ K}^{-1}$. Therefore, the product of the two coefficients becomes almost six orders of magnitude lower than their sum, making the quadratic term of Equation 2.34 negligible. In this case $\Delta \lambda_B / \lambda_{B0}$ can be considered linear with respect to temperature changes. Consequently, λ_{B0} shifts towards longer wavelengths with increasing temperature, requiring a spectral resolution of 4 to 5 pm to resolve temperature change of one Kelvin at 658 nm.

Polymer materials, considered in this thesis, possess higher thermal expansion and thermo-optic coefficients than fused silica, allowing increased sensitivity of polymer waveguide Bragg gratings to temperature changes. However, Table 2.1 reveals that optical polymer materials show negative TOCs of the same order of magnitude as their positive TECs, making the quadratic term of Equation 2.34 more prominent and not generally negligible. Moreover, both thermal effects act against each other, requiring a very careful selection and characterization of the used materials. Therefore, polymer Bragg sensors show a significantly higher complexity of thermal behavior compared to silica fibers [98].

2.3 Principles of Mach-Zehnder interferometers (MZIs)

This chapter describes the basic theory behind Mach-Zehnder interferometers, including the origins of the temperature sensitivity. Furthermore, it discusses the drawbacks of conventional MZI-devices for planar mass-production in polymers and introduces the concept of asymmetric Mach-Zehnder interferometers (AMZIs) used in this dissertation.

Figure 2.6 A classic planar Mach-Zehnder interferometer design consists of a straight waveguide which is split into two arms and recombined by Y-junctions. The *reference arm* of the interferometer is covered with a homogenous cladding layer. A phase shift difference between the arms is achieved through a modification of the *sensing arm* by a phase shifting region. For temperature sensing, the core or the cladding in the phase shifting region can be replaced by a different material.

2.3.1 Basic description

In this thesis all-polymer planar Mach-Zehnder interferometers are used for temperature sensing. A classic planar Mach-Zehnder interferometer design is shown in Figure 2.6 and consists of a planar waveguide split into two and recombined by Y-shaped junctions. The *reference arm* is protected by a homogenous cladding layer, whereas the *sensing arm* is modified to achieve a difference in the phase shift with respect to the reference arm. This difference results in a shift of the output intensity when environmental conditions, in our case temperature of the entire MZI, change.

The phase shift difference can be induced by changing the effective refractive index N_s of the sensing arm. As discussed previously for WBGs, the effective refractive index of a waveguide depends on the material refractive indices of both the core and

the cladding as well as on the geometric dimensions of the waveguide. Consequently, any of these parameters can be modified to achieve the desired effect. However, in classic MZI designs the geometric dimensions are typically kept equal in both arms, and the necessary phase shift difference is achieved through a modification of the core or cladding material properties. For example, a core or a cladding layer material which differs from the one used in the rest of the structure can be deposited over the length of the phase shifting region L_P .

The output intensity I_T of such MZIs can be described in terms of intensities inside the sensing and reference arms, I_S and I_R respectively, and the initial relative phase of the arms ϕ_r as

$$I_T = \frac{I_S + I_R}{2} + \sqrt{I_S I_R} \cdot \cos(\phi_r). \quad (2.35)$$

As ϕ_r generally depends on the effective refractive indices N_S and N_R along the optical path P_S and P_R in the sensing and reference arm respectively, it can be described by

$$\phi_r = \frac{2\pi}{\lambda_0} \left(\int_{P_S} N_S(z) dz - \int_{P_R} N_R(z) dz \right). \quad (2.36)$$

Assuming a homogenous refractive index profile in each of the interferometer arms, except for the length of the phase shifting region L_P , Equation 2.36 can be simplified to

$$\phi_r = \frac{2\pi}{\lambda_0} (N_S - N_R) L_P + \phi_{\text{junction}}. \quad (2.37)$$

The additional phase shift ϕ_{junction} comes from the Y-junction regions in case they are asymmetric.

2.3.2 Temperature sensitivity of MZIs

Considering a temperature variation of the structure, the refractive indices of the interferometer arms and the geometric dimensions of the device change. Again, these effects are symmetric everywhere except in the phase shifting region L_P and in the asymmetric junction regions, leading to

$$\Delta\phi_r = \frac{2\pi}{\lambda_0} (\Delta N_S - \Delta N_R) \Delta L_P + \Delta\phi_{\text{junction}}, \quad (2.38)$$

or for a temperature change of ΔT

$$\begin{aligned} \Delta\phi_r(\Delta T) = \frac{2\pi}{\lambda_0} (N_S - N_R) \Delta L_P \Delta T + \frac{2\pi}{\lambda_0} \Delta (N_S - N_R) L_P \Delta T + \\ \frac{2\pi}{\lambda_0} \Delta (N_S - N_R) \Delta L_P \Delta T^2 + \Delta\phi_{\text{junction}}. \end{aligned} \quad (2.39)$$

Equation 2.39 shows that the origins of the thermal sensitivity of Mach-Zehnder interferometers are the same as described in Subsection 2.2.5 for Bragg sensors. Namely the change of the refractive index of the interferometer materials caused by the thermo-optic effect and the change of the sensor dimensions due to the thermal expansion of the structure.

As in case of Bragg sensors, the quadratic term of Equation 2.39 becomes small in inorganic materials due to their low thermal expansion coefficients and is typically omitted [100]. In case of polymer materials this assumption is no longer valid, making investigations of the MZI's temperature sensitivity by analytical methods challenging.

The basic Mach-Zehnder interferometer structure shown in Figure 2.6 has serious drawbacks in case of mass-producible planar structures. The definition of a structured core or upper cladding layer, needed for the fabrication of a phase shifting region, is not easily implementable outside of a clean-room environment due to small waveguide dimensions of several micrometers. However, there are alternative approaches for the realization of a comparable temperature sensitivity.

As previously discussed, the main goal of a phase shifting region is the generation of a non-symmetric phase shift in the interferometer arms on temperature changes. This effect can be achieved through a modification of the material properties of the sensing arm, as described before, or by the modification of the geometric dimensions of the sensing arm. Therefore, to design an MZI sensor suitable for the fabrication in polymers a temperature-dependent phase shift difference can be achieved by asymmetric arm width $w_1 \neq w_2$, as demonstrated in Figure 2.7. MZIs with an asymmetric arm width are referred as asymmetric MZIs (AMZIs) in the scope of this thesis. In this design the upper cladding layer serves only for protection and isolation from the outer medium and can be kept unstructured.

The phase shifting region of AMZIs is extended to the entire arm length L_S instead of L_P , so that Equation 2.38 becomes

$$\Delta\phi_r = \frac{2\pi}{\lambda_0} (\Delta N_S - \Delta N_R) \Delta L_S + \Delta\phi_{\text{junction}}. \quad (2.40)$$

This extension is generally desirable, as a longer phase shifting region leads to a higher temperature-dependent phase shift difference and, therefore, to a higher thermal sensitivity of the device. Additionally, in contrast to classic MZIs, the phase shifting region of an AMZI consists of the same material combination as the rest of the device. The reduced number of used materials helps to minimize the mechanical stress in the structure and thus avoids possible undesired stress-induced effects.

Figure 2.7 (a): Top view of an asymmetric Mach-Zehnder interferometer (AMZI). Due to the width difference in the interferometer arms ($w_1 \neq w_2$), a difference in the effective refractive indices of the arms is generated. The temperature-induced phase shift in the differently sized waveguides is also not equal, leading to a temperature-dependent intensity change of the output intensity I_T . (b): Cross-sectional view of the straight region of an AMZI.

Equation 2.39 is still valid for AMZIs. However, the relation between the effective refractive indices of the interferometer arms and the temperature of an AMZI is complex and requires a numerical simulation for a precise modeling of the structure.

An additional challenge for the mass-fabrication of polymer-based interferometers are the tight manufacturing tolerances. Equation 2.35 reveals that the output intensity follows a cosine function of the phase shift difference. The ideal working point for an AMZI-based sensor is located at the region of the cosine curve with the highest slope, and the ideal measurement range is limited to the nearly linear region around this point. However, fabrication errors and tolerances can induce deviations from the designed waveguide dimensions and from the expected refractive indices of the structure. These tolerances shift or scale the interference curve and might also lead to a large shift of the working point. Consequently, the magnitude and direction of the sensor signal step can differ from the expected values. The possible effects of this difference have to be addressed during the design and manufacturing phase of the final device.

3 Design

The previous chapter discussed the physical parameters that influence the operation of polymer temperature sensors developed in this thesis. It also demonstrated the complexity of the involved effects and showed that numerical simulations are necessary to optimize the sensor designs and obtain the best performance as well as consistent and predictable results.

The design of waveguides and sensors was, therefore, optimized and analyzed by extensive simulations and studies of the relevant design parameters. In the following sections the results of these simulations are introduced along with a summary of the final sensor designs.

3.1 Simulations

This section begins with the calculation of single-mode and multi-mode waveguide dimensions based on the procedure described in Subsection 2.1.2. The calculation took measured refractive indices of the used materials into account and was additionally confirmed by numerical simulations. Furthermore, Subsection 3.1.2 introduces design considerations for bent waveguides required for AMZI sensors.

Subsections 3.1.3–3.1.6 describe the design of WBG-based temperature sensors. After a description of the basic structure, the effect of manufacturing tolerances on the sensor performance is presented. After that, simulation results for single-mode and multi-mode Bragg temperature sensors are introduced and compared.

Finally, dimensions of AMZI temperature sensors were analyzed and optimized by means of numerical simulations to obtain a proper working point and enhance the sensitivity of AMZIs to temperature changes. The developed numerical model used the measured attenuation of the waveguides to determine the optimal device length.

3.1.1 Waveguides

Mass-fabrication of planar ridge waveguides introduces major challenges for the fabrication techniques as it requires residual-layer free deposition of the core material.

Figure 3.1 Cross-sectional view of an inverted rib waveguide. The effective refractive index of the core layer is locally increased due to the difference in core thickness between H in the middle and $H - d$ outside.

Moreover, the operation of the polymer sensors in the visible to near-infrared range results in typical waveguide sizes of several micrometers to maintain single-mode operation required for interferometric sensors. This size limitation introduces additional challenges for the waveguide fabrication and alignment of the light sources. Inverted rib waveguides represent an attractive alternative to ridge waveguides, as they solve these dimensional limitations in the lateral direction still maintaining single-mode operation. Additionally, they simplify the fabrication process, as no residual-layer free processing is required. The cross section of an inverted rib waveguide is shown in Figure 3.1.

For the inverted rib waveguides designed in this thesis, custom-made polymers developed at the *Laboratory for Materials Processing* at the University of Freiburg were used. The refractive indices and the thermo-optic coefficients of these materials were measured as described in Section 5.1. UGS60E, consisting of 38 weight-% Syntholux 291 EA (Synthopol) and 58 weight-% ethylene glycol dimethacrylate with a resulting refractive index of $n_{\text{UGS60E}}(\Delta T) = 1.527 - (2.564 \times 10^{-4}) \Delta T$, was used as the core layer for Bragg temperature sensors and as the cladding layer for AMZI temperature sensors.

The core layer for AMZI sensors consisted of the same material combination with the mixing ratio of 53 weight-% Syntholux 291 EA (Synthopol) and 43 weight-% ethylene glycol dimethacrylate, resulting in a refractive index of $n_{\text{UGS45E}}(\Delta T) = 1.537 - (2.014 \times 10^{-4}) \Delta T$. Diphenyl(2,4,6-trimethylbenzoyl) phosphine oxide with a concentration of 4 weight-% served as photo-initiator for all custom materials.

A commercial 175 μm -thick PMMA foil (PLEXIGLAS 99524 GT, Evonik Industries AG) with a measured refractive index of $n_{\text{PMMA}}(\Delta T) = 1.488 - (2.103 \times 10^{-4}) \Delta T$ served as substrate and Bragg grating material.

Figure 3.2 A semi-analytic model was used to calculate the values of w and d for the single-mode behavior of inverted rib waveguides. Selected points correspond to the $H = 3 \mu\text{m}$ curve and were additionally confirmed by numerical simulations. The region below each curve indicates single-mode behavior, while the upper region shows multi-mode behavior.

To determine the cross-sectional dimensions of inverted rib waveguides based on the given materials, the semi-analytic criterion for single-mode waveguide dimensions introduced by Müllner et al. [85] and explained in Subsection 2.1.2 was implemented in Wolfram Mathematica® (Wolfram Research) for a wavelength of 852 nm. With the help of this script, the width w and the rib depth d were determined for a given core layer thickness H . As shown in Figure 3.2, for a fixed core height H inverted rib waveguides confine a single mode if the combination of their rib width w and their rib depth d stays below the corresponding curve. For a core height of $H = 3 \mu\text{m}$ with a rib depth of $d = 850 \text{ nm}$, waveguide widths up to $w < 5 \mu\text{m}$ are possible. The source code of the script is supplied in Subsection A.4.2.

To verify these calculations, additional numerical simulations for the calculated dimensions were performed in FIMMWAVE by PhotonDesign®. Examples for $H = 3 \mu\text{m}$, $d = 850 \text{ nm}$ and two different widths are shown in Figure 3.2. For $w = 3.5 \mu\text{m}$ only the fundamental mode was confined inside of the central region, whereas higher order modes leaked outside of the waveguide. Increasing the width to $w = 6 \mu\text{m}$ resulted in the confinement of the first order mode in the waveguide core; the structure became multi-mode, as expected.

With the help of these calculations, dimensions for waveguides used in this thesis were set as shown in Table 3.1. The single-mode and the multi-mode waveguides share all dimensions except for the width of the rib w .

Table 3.1 Design parameters and dimensions of the single-mode and multi-mode waveguides used in this thesis.

Name	Symbol	Design value Bragg	Design value AMZI
Core height	H	3 μm	3 μm
Rib depth	d	0.85 μm	0.85 μm
Rib width (single-mode)	w_{sm}	3.5 μm	3.5 μm , 2.0 μm
Rib width (multi-mode)	w_{mm}	20 μm	—
Cladding refractive index	n_{c}	1.488	1.527
Core refractive index	n_{g}	1.527	1.537
Substrate refractive index	n_{s}	1.488	1.488

3.1.2 Design considerations for bent waveguides

The previous section discussed the design of single-mode waveguides in general. In case of AMZI structures additional requirements on the waveguide properties need to be formulated, the most important of which are related to the design of Y-splitter and Y-coupler structures. An even splitting ratio between the arms is important to maximize the contrast of the output signal, and the bending radii of the waveguides should be carefully designed to minimize the loss of light in the bending regions.

Especially the latter requirement needs a closer investigation. As shown in the literature, both transition losses at the entrance and exit of the bend and pure bending losses take place in a bent waveguide [101]. The bending losses are mostly governed by the length L_{bend} and the offset h_{bend} of the bending region, the cross-section of the waveguide, and the refractive indices of the layers.

Multiple suggestions for the design of S-bend waveguides suitable for Mach-Zehnder interferometers were proposed in the literature [102–105]. The S-bend geometry discussed in one of these studies [105] was investigated for the inverted rib waveguide geometry used in this thesis [86]. Two S-bend path functions

$$x_{\cos}(z) = \frac{h_{\text{bend}}}{2} \left[1 - \cos\left(\pi \frac{z}{L_{\text{bend}}}\right) \right] \quad (3.1a)$$

and

$$x_{\sin}(z) = h_{\text{bend}} \left[\frac{z}{L_{\text{bend}}} - \frac{1}{2\pi} \sin\left(2\pi \frac{z}{L_{\text{bend}}}\right) \right], \quad (3.1b)$$

shown in Figure 3.3 (a), were simulated in FIMMPROP to compare their performance. The results for an inverted rib waveguide with dimensions of $H = 500 \text{ nm}$, $w = 1 \mu\text{m}$

Figure 3.3 (a): Straight waveguides connected by S-bends introduced in Equations 3.1a and 3.1b. Length L_{bend} and offset h_{bend} of the bending region can be adjusted for optimal performance. (b): Transmission of the S-bend region as a function of the longitudinal offset L_{bend} for the lateral offsets $h_{\text{bend}} = 25 \mu\text{m}$ and $h_{\text{bend}} = 50 \mu\text{m}$.

and $d = 100 \text{ nm}$ at a wavelength of 658 nm are presented in Figure 3.3(b) as an example. The simulation showed lower overall bending losses for the cosine path function, which required a smaller longitudinal offset to reach optimal performance. Therefore, the corresponding bend geometry was chosen for all AMZIs presented in this thesis. Nevertheless, the length of the bend should be larger than $L_{\text{bend}} = 1 \text{ mm}$ for a transmission better than 90 %.

3.1.3 Bragg structures

As discussed in previous chapters, a waveguide Bragg grating is a periodic modulation of the effective refractive index inside the waveguide core. To simplify the manufacturing process, gratings used in this thesis were realized as a physical corrugation of the waveguide thickness, as demonstrated in Figure 3.4.

The performance of Bragg-based sensors is described by two main quantities. These are the *sensitivity* of the sensor given as a spectral shift of the signal over a temperature change, on the one hand, and the *bias point* or the spectral position of the signal at room temperature, on the other hand. The latter is especially important in a practical case as the spectral width of the light source should be broad enough to cover the entire operation range but also limited as far as possible to avoid unnecessary heating of the waveguide due to absorption losses. Additionally, a sufficient *reflectivity* for the Bragg wavelength is important to ensure a robust operation of the sensor.

Figure 3.4 Basic principle of a waveguide Bragg grating. A periodic modulation of the effective refractive index was realized as a physical corrugation of the waveguide core and optimized for the reflection of a narrow spectral region around the Bragg wavelength λ_{Bragg} .

The refractive index modulation necessary for Bragg reflection was realized by applying a physical grating on top of the previously introduced inverted rib waveguides as sketched in Figure 3.5. Thus, a periodic change of the effective refractive index in the waveguide core was achieved.

Two types of grating integration were examined by simulations. In the first case, shown in Figure 3.6 (a), the attached grating was filled with the same material as the core of the waveguide. In the second case, demonstrated in Figure 3.6 (b), the grating was filled with air, resulting in a higher refractive index contrast and thus in a higher effective refractive index modulation compared to case (a).

Figure 3.5 The examined waveguide Bragg grating temperature sensor consisted of a physical grating attached to an inverted rib waveguide. This way a periodic modulation of the effective refractive index in the core of the waveguide was generated.

Figure 3.6 (a): Core polymer filled Bragg-grating and (b): air-filled Bragg-grating. A higher effective refractive index modulation of the core is achieved in case (b) due to the higher refractive index contrast between the core and the air layers, compared to the core/cladding interface in case (a).

The sensors were designed to operate in the near infrared range (815 – 860 nm) with the standard wavelength of ≈ 845 nm at room temperature. This wavelength in combination with the previously introduced waveguide parameters corresponds to a grating period of ≈ 278 nm. Nanopatterned silicon stamps from LightSmyth™ Technologies Inc. were used as master structures for the polymer Bragg gratings. The exact manufacturing procedure is described in Section 4.3. The corresponding dimensions of the waveguides and gratings, including manufacturing tolerances, are summarized in Table 3.2.

Table 3.2 Design parameters of the Bragg temperature sensors. Grating depth GD and duty cycle DC showed no effect on the spectral position of the Bragg wavelength and the spectral range of the sensor and were excluded from the manufacturing tolerance study.

Name	Symbol	Design value	Origin of the tolerances
Waveguide:			
Core height	H	$3 \pm 0.5 \mu\text{m}$	Spin coating
Rib depth	d	$0.85 \pm 0.1 \mu\text{m}$	Deposition of silicon nitride
Rib widths	w_{sm}	$3.5 \pm 0.5 \mu\text{m}$	Photolithography and etching
	w_{mm}	$20 \pm 0.5 \mu\text{m}$	Photolithography and etching
Core index	n_g	1.527 ± 0.004	UV exposure and batch-to-batch
Substrate index/ Cladding index	$n_s = n_c$	1.488 ± 0.003	UV exposure
Grating:			
Grating depth	GD	$110 \pm 16.5 \text{ nm}$	Manufacturer specification
Duty cycle	DC	$50 \pm 7.5 \%$	Manufacturer specification
Grating period	Λ	$278 \pm 1.4 \text{ nm}$	Manufacturer specification

Table 3.3 Order of importance of design dimensions, summarized in Table 3.2, for the bias point of WBG-sensors (lower ranking corresponds to higher importance).

Ranking	Parameter
1	Core index
2	Grating period
3	Rib depth
4	Core height
5	Substrate index
6	Rib width
7 (negligible effect)	Grating depth
8 (negligible effect)	Duty cycle

3.1.4 Manufacturing tolerances

The influence of each design parameter on the sensitivity and the spectral position of the bias point of a Bragg temperature sensor was examined by a series of independent simulations using RSoft GratingMOD™ (Synopsis®) extended by a custom-made software package described in Section A.3. Each of the eight parameters listed in Table 3.2 was varied over the corresponding tolerance range and the whole sensor structure was simulated between 0 °C and 80 °C in 10 °C steps.

As explained in Subsection 2.2.5, in the ideal case the sensitivity of waveguide Bragg sensors to temperature changes only depends on the thermo-optic and thermal expansion coefficients of the used materials. Therefore, the effect of all simulated parameters had a negligible effect on the sensor sensitivity. The strongest effect was due to deviations of the core height H , but the maximal change in performance was below 250 fm K^{-1} which is more than two orders of magnitude below the total simulated sensitivity value of $\approx 77 \text{ pm K}^{-1}$. Thus it was confirmed that the sensitivity of the sensor is defined solely by the material properties of the used polymers.

The bias point, on the other hand, is sensitive to changes in the effective refractive index N_g of the core and to the variation of the grating period Λ . N_g is influenced by the geometry (H , d and w) and the refractive indices (n_g , n_s and n_c) of the waveguide. The order of importance of the single design parameters for the sensor bias point was determined by numerical simulations and is summarized in Table 3.3. Since the grating depth and the duty cycle of the grating showed neither an impact on the spectral position nor on the sensitivity of the sensor, they were excluded from further investigation to reduce the computational effort.

To investigate the possible deviations from the designed bias point due to manufacturing tolerances, a series of $2^6 = 64$ parameter sweeps in a temperature range

Figure 3.7 Worst case manufacturing tolerances for the six most critical design parameters. The resulting number of combinations is $2^6 = 64$. A maximal possible spread of the sensor bias point, defined by the maximum and minimum Bragg wavelength, is between 836.0 nm and 849.1 nm.

between 0 °C and 80 °C in 10 °C steps was performed to cover each possible combination of the worst-case parameters, shown in Table 3.2. The result of the simulation series is summarized in Figure 3.7, with the expected operating range of the sensor being between 836.0 nm and 849.1 nm. Furthermore, single plots in Figure 3.7 seemingly cluster in several groups. This effect occurred as only the highest and the lowest possible values for each design parameter were taken into consideration. Addition of intermediate tolerance values would fill the gaps between the plots but would also drastically increase the duration of the simulation series and was therefore omitted.

3.1.5 Single-mode Bragg temperature sensor

To evaluate the performance of the single-mode Bragg temperature sensor, a 3.5 μm wide waveguide described previously was used as a base structure for an RSoft GratingMOD™ (Synopsys®) simulation.

The complete structure was characterized with respect to its temperature sensitivity. Figure 3.8 shows a simulated typical spectral response of the designed Bragg sensor in a temperature range between 20 °C and 100 °C. The sensor showed a Bragg

Figure 3.8 (a): Simulated transmission of the Bragg sensor between 20 °C and 100 °C. (b): Bragg wavelength position extracted from graph (a) shows a linear relation with temperature over the complete range.

wavelength shift of -77 pm K^{-1} with a linear response behavior over the complete temperature range.

The negative slope of the curve in Figure 3.8 (b) indicates that the negative thermo-optic effect of polymer materials dominates the overall performance of the sensor; a dominating thermal expansion would lead to a positive slope of the curve.

3.1.6 Multi-mode Bragg temperature sensor

In case of a multi-mode Bragg sensor additional effects need to be considered for the prediction the output spectrum. As each propagating mode sees a different effective refractive index of the core, the spectral position of the Bragg wavelength varies for different modes. In addition, a broad-band light source results in an individual mode combination for each wavelength. Thus, the output spectrum of a multi-mode Bragg sensor is effectively a superposition of the Bragg spectra of each propagating mode.

To investigate the performance of such sensors by means of simulations, a 3D parameter sweep was performed. Due to the high computational effort of the simulation, the temperature range was reduced to 20–80 °C in steps of 10 °C. For each temperature step the physical properties (refractive indices and geometric dimensions) of the structure were calculated and implemented in a software model. In the wavelength range between 830 nm and 850 nm in steps of 1 pm the spectral responses of the first ten modes at each wavelength were simulated for each temperature.

The resulting spectral responses for the individual modes and wavelengths were superposed to a combined output spectrum at each temperature. As a prediction of the power distribution between modes is not possible in a practical case, a simplified assumption of an even power distribution between the modes was used. The resulting curves were evaluated to calculate the temperature-dependent spectral shift of the sensor.

The whole procedure was executed for both sensor integration types, shown in Figure 3.6. Figures 3.9 (a) and (b) show sample combined spectra of air-filled and core-filled multi-mode Bragg sensors at 20 °C along with the corresponding spectra at 60 °C. A fast Fourier transform (FFT) low-pass filter was applied to both graphs. This filtering removed the high frequency oscillations of the transmittance, as they exceed the spectral resolution of the spectrometer used in Section 5.4.

As expected, the air-filled sensor shows a higher overall reflectivity in the transmittance curve due to the higher refractive index contrast of the Bragg structure and thus a higher Bragg grating strength than in case of the core-filled sensor. The higher refractive index contrast of the grating also affects the bandwidth of the transmission dips, as discussed in Subsection 2.2.3. The higher bandwidth, in turn, leads to a stronger overlap of the single mode effects and to a more homogenous spectral response when compared to the core-filled sensor.

Nevertheless, apart from the grating strength the temperature sensitivity of both sensor types shown in Figure 3.10 is almost independent of the grating integration type. The difference in slopes of the curves of $[(-73.35) - (-76.97)] = 3.62 \text{ pm K}^{-1}$ can be neglected.

Figure 3.9 (a): Shift of the transmittance dips for a temperature step between 20 °C and 60 °C for the core-filled sensor. The sensor shows an inhomogeneous spectral profile due to multiple-mode effects.

(b): Shift of the transmittance dips in the same temperature range for the air-filled sensor. This sensor also shows an inhomogeneous spectral profile due to multiple-mode effects; however, due to the higher overall reflectivity and spectral bandwidth compared to the core-filled sensor, the peaks from single modes are not distinguishable.

A fast Fourier transform (FFT) low-pass filter was applied to both signals to reduce the high frequency oscillations of the transmittance.

Figure 3.10 Sensitivity of the two investigated sensor integration types described in Figure 3.6. The sensitivity is mostly a function of the sensor material properties (thermal expansion coefficient and thermo-optic coefficient) and is almost independent from the geometric design parameters. The difference in slopes of the curves of $[(-73.35) - (-76.97)] = 3.62 \text{ pm K}^{-1}$ can be neglected.

Figure 3.11 (a): Top view of an asymmetric Mach-Zehnder interferometer (AMZI). Due to the width difference in the interferometer arms ($w_1 \neq w_2$) the temperature-induced phase shift in the arms is also not equal, leading to a temperature-dependent change of the output intensity I_T . (b): Cross-sectional view of the straight region of an AMZI.

3.1.7 AMZI temperature sensors

As discussed in Section 2.3, in contrast to classic Mach-Zehnder interferometers AMZIs do not require a special phase shifting region. The interferometer arms directly generate a different temperature-induced phase shift due to their asymmetric design. In combination with inverted rib waveguides, this property leads to a simplification of the manufacturing process. A schematic of an AMZI structure is shown in Figure 3.11.

The measurement principle of such devices is based on a difference of the phase shift in the interferometer arms. The phase shift of each arm is related to the corresponding effective refractive index, which is for its part related to the physical dimensions of the waveguides and their material refractive indices. As in case of Bragg sensors, the refractive indices and the physical dimensions of the entire structure change with a temperature variation. Due to initial asymmetry of the interferometer arms, the corresponding temperature-induced phase shift in each arm is different, causing a change of the interference signal at the output.

Based on this fact, the dimensions of the AMZI structures were optimized for temperature measurements. As single-mode waveguides are required for interferometric applications, the basic single-mode waveguide design introduced in Subsection 3.1.1 with a rib width of $3.5 \mu\text{m}$ was used for the input and output parts of the structure as well as for the wide arm of the interferometer w_1 . The second arm shares all dimensions of the first arm except for the reduced width $w_2 = 2 \mu\text{m}$. The transition

from the 3.5 μm -wide input waveguide to the 2 μm -wide interferometer arm was realized by a linear taper along the cosine S-bend of the splitter. It is beneficial to set the asymmetry of the interferometer arms as high as possible; however, a further reduction of w_2 would introduce additional challenges for the fabrication process. The lateral offset of the interferometer arms was chosen to be $D_1 = D_2 = 10 \mu\text{m}$ in combination with the length of the Y-junction regions L_y of 2 mm to avoid bending losses.

As explained before, the signal of an AMZI is mainly influenced by the thermal expansion of the entire structure and by the thermo-optic effect. The latter is fixed by the material choice; the thermal expansion is, however, a percentage value of each geometric dimension. Thus, larger structures would have a larger absolute size modulation with changing temperature.

The largest dimension of the AMZI is the length L_S which, therefore, has the strongest absolute thermal expansion. Thus, L_S also has the strongest influence on the bias point of the sensor and needs to be optimized. Additionally, an increase of L_S generally leads to a higher phase shift difference in the interferometer arms and thus to a higher temperature resolution. However, at the same time a larger L_S also leads to higher propagation losses in the waveguides. Therefore, the optimal working point is reached when these two effects come into balance.

As in case of the Bragg sensors, the dimensions and material properties of the AMZI structure were calculated and implemented in a software model. To determine the optimal sensor bias point, sweeps in L_S from 0 to 50 mm for 0 °C and 60 °C were performed, covering the boundaries of the desired temperature range. A proper bias point for the sensor is achieved when the difference of these two signals, shown in Figure 3.12, is maximal. Therefore, the optimal length for the sensor is located at the global maximum of the curve at $L_S = 35.5 \text{ mm}$. However, for a real device this length is impractical as the measurement area becomes too large for many applications. Therefore, a local maximum at $L_S = 10.27 \text{ mm}$ was taken as a trade-off between the overall size and the performance of the sensor for further investigation.

A temperature sweep was performed for the previously optimized structure in the temperature range between 0 °C and 60 °C in 2.5 °C-steps. In general, it is not possible to keep the designed sensor linear in the complete desired temperature range and scan through a full period of the cosine intensity curve of the AMZI at the same time. Consequently, a common sensitivity definition for the simulated and measured results was required for the evaluation of the sensor performance. Therefore, the simulated output intensity curve was divided by the corresponding output intensity value at 25 °C and is shown in Figure 3.13, indicating a good linearity of the sensor in the designed measurement range.

Figure 3.12 Difference of two simulated L_S -sweeps for 60 °C and 0 °C at 852 nm normalized to the temperature difference. The global maximum at $L_S \approx 35.5$ mm corresponds to the bias point of the AMZI temperature sensor with the highest possible sensitivity. However, a local maximum at $L_S = 10.27$ mm was selected for further investigations to reduce the total length of the device.

Figure 3.13 Simulated output intensity for the designed AMZI temperature sensor in the range between 0 °C and 60 °C. The sensor shows a good linearity in the simulated range with a sensitivity of 1.12 % K^{-1} , referred to the intensity value at 25 °C as $I_T(25\text{ °C}) \cong 100\%$.

In this approach the output intensity I_T of the sensor at 25 °C was taken as the 100 % reference, and the intensity change per Kelvin was defined as a percentage of this value, resulting in a sensitivity of $S_{AMZI} = 1.12 \% K^{-1}$.

3.2 Final design summary

The final designs of the Bragg temperature sensors based on the previously introduced simulation results are summarized in Figure 3.14 and Table 3.4 and were selected for experimental evaluation.

Figure 3.14 Designed dimensions for the Bragg temperature sensors developed from the previously introduced simulation results.

Table 3.4 Geometric dimensions and refractive index values for the designed WBG-sensors.

Name	Symbol	Dimensions (Bragg)
Core height	H	3 μm
Rib depth	d	0.85 μm
Rib width (single-mode)	w_{sm}	3.5 μm
Rib width (multi-mode)	w_{mm}	20 μm
Cladding index	n_c	1.488
Core index	n_g	1.527
Substrate index	n_s	1.488

Figure 3.15 Designed dimensions for the AMZI temperature sensors developed from the previously introduced simulation results.

The expected sensitivities for the single-mode and multi-mode WBG-sensors are in a tight range between -76.97 pm K^{-1} and -73.35 pm K^{-1} . The range of operating wavelengths was determined by a tolerance study and is in the region between 836 nm and 850 nm. However, this theoretical evaluation did not include possible batch-to-batch variations in the physical properties and the overall quality of the used materials. As these materials were fabricated in small batches of 10 g, fluctuations in the material composition are expected to be large enough to have an additional influence on the sensor performance and the working point.

In the same manner, design values for AMZI temperature sensors were obtained from simulations and are presented in Figure 3.15 and Table 3.5.

Table 3.5 Geometric dimensions and refractive index values for the designed AMZI sensors.

Name	Symbol	Dimensions (AMZI)
Core height	H	$3 \mu\text{m}$
Rib depth	d	$0.85 \mu\text{m}$
Rib width of the arms	$w_{1/2}$	$3.5 \mu\text{m}, 2.0 \mu\text{m}$
Cladding index	n_c	1.527
Core index	n_g	1.537
Substrate index	n_s	1.488

The length of the straight part of the AMZI-structures was first optimized for a proper bias point of the sensor in the desired temperature range between 0 °C and 60 °C, taking into account the propagation losses of the waveguides. The following evaluation of the sensor performance showed a nearly linear sensor response to temperature changes and a temperature-induced shift of the output intensity of $S_{\text{AMZI}} = 1.12 \% \text{ K}^{-1}$, referred to the output intensity value at 25 °C.

4 Fabrication

The fabrication of the waveguides and sensors used in this thesis is based on hot-embossing. As a large number of waveguide substrates can be fabricated from a single stamp, this process is compatible with mass-production. However, a properly designed stamp with the corresponding master structure must be fabricated first.

This chapter describes the microfabrication process for such master structures and introduces the key data for their replication into polymer foils. This replication was performed by our colleagues at the *Laboratory for Process Technology* at the University of Freiburg for the waveguides and interferometer structures and at *Hannover's Center for Optic Technologies (HOT)* for the Bragg grating structures.

Additionally, all the steps necessary to build a working waveguide, interferometer, or Bragg sensor structure are described in the following sections. Finally, measurements results for the surface roughness of the yielded structures and the replication quality of the gratings are presented. The complete process chain is summarized in Figure 4.1.

An extended documentation of the described microfabrication process and the data sheets of the used materials are supplied in Section A.1 and Section A.2 respectively.

4.1 Fabrication of waveguide and AMZI master structures

After the design phase, the developed structures were transferred into a UV lithography mask for microfabrication. In contrast to straight horizontal and vertical lines typically used in silicon microchip designs, the structures used in this work partially consist of gradually curved patterns. Most CAD packages for lithographic mask design lack the proper tools to realize such waveguide structures. Also, electron-beam writing systems used to generate high resolution lithography masks require a proper approximation of curved structures by a set of coordinates for discrete steps on a Cartesian grid.

For the calculation of such paths, a Matlab (MathWorks®) script was developed to subdivide arbitrary mathematical path functions into a number of small segments, as shown in Figure 4.2, and generate the corresponding list of coordinate points.

Figure 4.1 Process chain for the fabrication of waveguides, interferometers and Bragg sensors. (a)–(b): Fabrication of master structures in a microfabrication process. (c)–(d): replication of the master structures into a polydimethylsiloxane (PDMS) hot-embossing stamp. (e): hot-embossing into PMMA-foil. A commercial silicon stamp was used to replicate Bragg grating structures. (f): spin-coating of the core layer. (g): attachment of the Bragg grating on the waveguide foil and UV-curing of the core polymer. In case of waveguides and interferometers the UV-curing was applied directly after step (f).

Figure 4.2 A Matlab script was developed for the conversion of curved structures into a list of polygon coordinates on a Cartesian grid. The result can be directly imported into commercial mask layout software and combined with the existing designs. The approximation step size is variable and a typical value of 200 nm was used in this thesis.

The result can be imported into commercial CAD mask layout packages and integrated into existing designs. A typical step size of 200 nm was chosen in this thesis as it by far exceeded the resolution of the used UV-lithography system. Nonetheless, the resolution can be changed to an arbitrary value if required. The source code of the script is shown in Subsection A.4.1.

The designed mask layouts were transferred to a quartz glass chromium mask by ML&C GmbH (Jena, Germany) and used in the subsequent lithography process.

The microfabrication processing started with a standard polished 4" silicon wafer. In the first step a plasma-enhanced chemical vapor deposition (PECVD) reactor (PECVD 310 PC by Surface Technology Systems) was used to deposit a homogenous silicon nitride layer on the top surface of the wafer. The thickness of this layer defines the rib depth d of the designed waveguides.

Subsequently, 1.5 ml of AZ[®]1518 positive resist (MicroChemicals GmbH) were dispensed onto a the wafer previously covered by a mono-layer of hexamethyldisilazane (HMDS) as an adhesion promoter. The following spin-coating step at 4000 rpm for 30 seconds resulted in a homogenous resist layer thickness of 1.9 μm .

After a soft bake step at 100 °C for 50 s, the wafer was exposed to UV light through the previously described chromium mask using the MA/BA6 Mask and Bond-Aligner

(SUSS MicroTec) with an exposure dose of 8 mJ cm^{-2} . After the exposure, the resist was developed in AZ 326MF[®] (MicroChemicals GmbH) inside a SIEMENS COROS OP15 spray developer.

The resulting patterned resist layer, sketched in Figure 4.1 (a), served as an etch mask in the subsequent reactive ion etching (RIE) process (Figure 4.1 (b)). The RIE reactor Multiplex RIE by Surface Technology Systems was used with a gas flow combination of 15 sccm CF_4 , 35 sccm CHF_3 and 50 sccm Ar. This gas composition resulted in an etch rate of $\approx 400 \text{ nm min}^{-1}$ for silicon nitride and $\approx 10 \text{ nm min}^{-1}$ for monocrystalline silicon. The high selectivity of 40:1 allowed the usage of the underlying silicon wafer surface as an etch stop, resulting in a precise and highly homogenous etch depth over the entire wafer.

After the etching step, the resist was removed in an acetone ultrasonic bath. The subsequent cleaning steps in isopropanol and deionized (DI) water finished the creation of master structures for the embossing process. Figure 4.3 shows one of the fabricated master structures, containing AMZIs and straight waveguides of different width for the WBG sensors.

Figure 4.3 Standard 4'' wafer covered with a structured silicon nitride layer. It was used as a master structure in the subsequent PDMS casting process. The result was a PDMS hot-embossing stamp for the waveguide and AMZI fabrication.

4.2 Substrate foil fabrication via hot-embossing

For the creation of a hot-embossing stamp, the processed master wafer was placed into a brass mold, as shown in Figure 4.4, and replicated into RT 601[®] polydimethylsiloxane (PDMS) resin (Wacker Chemie AG) in a casting process. After removing trapped air bubbles in a vacuum chamber, the liquid PDMS was poured into the prepared mold. The whole assembly was then mounted into a hot-embossing machine MB 25200VC (Schmidt Maschinentechnik, Bretten, Germany) and heated to 70 °C, holding the temperature for 30 minutes. After demolding, the resulting PDMS stamp was tempered in an oven for one hour at 180 °C to ensure the full polymerization of any remaining monomers (Figure 4.1 (c–d)).

During hot-embossing this PDMS soft stamp was used to pattern a PMMA foil PLEXIGLAS[®] 99524 (Evonik Industries AG) with a thickness of 175 µm and a glass transition temperature of 110 °C. The same hot-embossing machine as utilized for the stamp fabrication was used at a temperature of ≈ 170 °C with a stamping force of 12 kN. The processed foil was demolded after cooling down to the room temperature, resulting in a thin flexible waveguide substrate shown in Figure 4.5 (a). Figure 4.5 (b) shows an optical microscope image of two AMZI splitters on the fabricated foil, indicating the high quality of replication even for small structures with sharp edges.

Figure 4.4 Master wafer in a brass mold and a finished PDMS copy, used as a hot-embossing stamp in the following processing steps.

(a)

(b)

Figure 4.5 (a): A complete sensor foil after the hot-embossing process. The 175 μm thick PMMA substrate is highly flexible. The embossed groove structures were visible as thin lines if held in a suitable angle to the light source. They were further processed to become waveguides in the subsequent steps. (b): Optical micrograph of two AMZI splitters on a hot-embossed PMMA foil.

After demolding of the foils, the quality of the yielded structures was measured in a Zygo NewView 5000 white light interferometer. A sample scan through an AMZI structure is shown in Figure 4.6. The measured roughness of the foils was in the range of $R_a \approx 30$ nm and, thus, smaller than 1/10 of the operating wavelength of 852 nm. This R_a value is comparable with the roughness of the silicon master wafer.

Figure 4.6 White light interferometer scan of a hot-embossed PMMA foil through the straight part of an AMZI. (a): surface scan; (b): line scan depth profile. The measured roughness of the plain surface inside a waveguide groove was in the range of $R_a \approx 30$ nm.

4.3 Bragg grating fabrication via hot-embossing

For the replication of Bragg gratings, a commercially available silicon stamp SNS-C36-1212-110-S from LightSmythTM Technologies was used directly to hot-emboss another piece of 175 μm PMMA foil. The replication process was performed at 140 $^{\circ}\text{C}$ with an embossing force of 500 N and the replicated structure was demolded at 50 $^{\circ}\text{C}$.

Figures 4.7 (a) and (b) show the used master structure measured by atomic force microscopy (AFM) in comparison to an AFM scan of the replicated structures. The corresponding 3D-reconstructions of the profiles are shown in Figures 4.7 (c) and (d).

Figure 4.7 Atomic force micrographs of (a): the silicon master and (b): the replicated structure in PMMA-foil. The corresponding 3D profile reconstructions (c) and (d) show a good replication quality of the structure, but indicate rounding of the edges during the hot-embossing process.

Figure 4.8 Line scan through the AFM profile. The sharp edges at the bottom indicate that the used atomic force microscope tip was not sufficiently small to resolve the structures inside the grating grooves. Therefore, a region without a grating was scanned as a reference and set as zero height. The overall height of the structures is $\approx 94 \pm 4$ nm, which is close to the expected value of 110 nm reported by the manufacturer of the silicon master.

The overall transfer quality of the structures in PMMA was good with few small defects; although, as expected for a thermal process, rounding of the edges took place in the polymer material. The effect of this rounding on the sensors was examined by simulations and only influenced the spectral bandwidth of the Bragg sensors. However, the bandwidth variation was below 5 % and can therefore be neglected.

The period and height information of the structures was obtained from a line scan profile in Figure 4.8. The periods of both master and replica were measured to be 279 ± 3 nm, which corresponds to the 278 nm reported by the manufacturer of the silicon master. The sharp edges at the bottom part of the profile indicate that the AFM tip did not reach the bottom of the grating grooves. Therefore, a region without a grating was measured to obtain the zero height level. The measured height of the structures of $\approx 94 \pm 4$ nm is close to the expected value of 110 nm, reported by the manufacturer of the silicon master.

4.4 Core layer deposition

The hot-embossed substrate foil was homogeneously covered with the core polymer in a spin-coating step. The layer thickness was set to the designed value by adjusting the rotation speed. UGS45E, used as core material for AMZIs, had a viscosity of $0.08 \text{ Pa} \cdot \text{s}$ [106] leading to a rotation speed of 3200 rpm for a layer thickness of $3 \mu\text{m}$. For UGS60E, used as a core material for WBG sensors and as a cladding material for AMZIs, the corresponding viscosity value was $0.015 \text{ Pa} \cdot \text{s}$ [106], resulting in a rotation speed of 1600 rpm for a $3 \mu\text{m}$ -thick core layer and 1000 rpm for a $5 \mu\text{m}$ -thick cladding layer. The corresponding spin-coating curves are supplied in Section A.5.

In case of Bragg grating sensors, the grating foil was subsequently placed on top of the liquid spin-coated core layer and the entire assembly was clamped between two quartz glass plates.

Prior to curing, WBG and AMZI foils were placed in a nitrogen chamber for 5 minutes to remove oxygen molecules from the surface, as oxygen led to inhibition of the polymerization reaction [107]. Subsequently the core layer was cured under a 405 nm UV lamp in the same nitrogen chamber for another 5 minutes.

4.5 Facet preparation

After cutting of the wafer-sized foils into single samples, the end faces of the waveguiding structures were prepared for free space coupling of light.

Each foil sample was clamped between two 10 mm thick PMMA plates for mechanical stability and the whole sandwich was ground down on abrasive sheets with grit sizes of $22 \mu\text{m}$ and $8.4 \mu\text{m}$ for 60 s each on a rotating plate (Phoenix Beta, Buehler, Germany) at 150 rpm to achieve a plain surface. A subsequent polishing step by a series of MetaDiTM polishing suspensions (Buehler, Germany) with grit sizes of $3 \mu\text{m}$, $1 \mu\text{m}$, $0.2 \mu\text{m}$ and $0.05 \mu\text{m}$ was carried out on the same rotating plate for 300 s per step at 200 rpm. The MetaDiTM polishing lubricant (Buehler, Germany) was used for all polishing steps.

After polishing, the facets were examined by optical microscopy. Figure 4.9 (a) shows an optical image of the waveguide facet after polishing and Figure 4.9 (b) shows a scanning electron microscope (SEM) image of the same facet. The latter technique was not non-destructive, as it was necessary to selectively damage the PMMA substrate to distinguish between the layers. The selective destruction was done directly with the electron beam of the SEM. Both images show a good quality of the prepared facet without detectable roughness and scratches.

Figure 4.9 (a): Optical microscope image of the polished waveguide facet. (b): Scanning electron microscope image of the same waveguide facet made after a material-specific destruction of the substrate layer. The PMMA substrate on the bottom is destroyed by the electron beam of the SEM, a well known effect that enables the usage of PMMA as a resist for electron beam writing [108,109]. The waveguide material is unaffected by the electron beam, allowing to distinguish between the layers.

Finally, Figure 4.10 shows finished samples with AMZI and Bragg sensors prepared for experimental characterization.

Figure 4.10 Sensor foils after cutting and polishing of the facets. (a): AMZI sensor foil ready for measurement; (b): Bragg sensor foil ready for measurement. Dotted lines indicate the position of the waveguides and AMZI structures, and the dashed lines indicate the line direction of the Bragg grating.

5 Experimental results

Results of experimental measurements on the developed sensors along with a precise description of the entire measurement procedure are presented in this chapter. Optical and thermal parameters of the used materials are of high importance for the modeling and fabrication of the sensors. The evaluation, therefore, starts with the measurement of the refractive indices, the corresponding thermo-optic coefficients, and the thermal expansion coefficients of the used polymers.

Due to small waveguide cross-sections of several micrometers, a precise position control of the fabricated sensor foils is necessary for light coupling. Therefore, Section 5.2 contains a description of the developed optical set-up used for the incoupling of light into the samples, the detection of the output, and the temperature control of the sensor foils.

Measurement results for the multi-mode and single-mode Bragg temperature sensors are presented next and compared to the simulation results from Chapter 3. Additionally, the effect of grating chirp on the sensors is discussed using a simplified waveguide model.

Finally, the developed AMZI temperature sensors are experimentally evaluated. After confirming the insensitivity of the system to refractive index changes of the surrounding medium, results of temperature measurements with the fabricated AMZI sensors are presented and compared to simulations.

5.1 Optical and thermal properties of polymers

One of the key parameters for the design of integrated optical sensors is the refractive index of the used materials. As previously mentioned, refractive index is generally temperature-dependent, and this property was exploited for the design of the temperature sensors presented in this thesis. Therefore, the refractive indices of the used materials were measured together with the corresponding thermo-optic coefficients, and the results are presented in the first part of this section.

For the measurement of the material refractive indices, a digital multi-wavelength refractometer DSR- λ (Schmidt+Haensch, Germany) was used. It allowed refractive

Figure 5.1 UGS60E core layer sample pellets. The diameter of 8 mm corresponds to the chamber size of the used refractometer. The liquid core material was brought into the round shape in a PDMS-mold and covered with a microscope glass slide prior to UV curing to obtain a smooth optical surface for the subsequent measurement.

index measurements of liquid and solid materials in a spectral range between 404.7 nm and 706.5 nm at nine discrete wavelengths and in a temperature range between +10 °C and +70 °C.

Measurements on solid materials, however, required additional effort in sample preparation and handling. Therefore, round samples with a diameter of 8 mm, matching the size of the measurement chamber, were prepared for each measured material, as demonstrated in Figure 5.1. PMMA foil samples were cut into the proper size by a hole punching tool and therefore had a thickness of 175 μm , the same as the original foil. The custom-made core and cladding materials UGS45E and UGS60E as liquid co-monomers were molded in a PDMS-tool and covered by a microscope glass slide to achieve a smooth optical surface after UV-curing. These samples had a thickness of 4 mm for better handling.

Table 5.1 Optical and thermal properties of the used optical materials.

Optical material	Refractive index at 852 nm	TOC 10^{-6} K^{-1}	TEC 10^{-6} K^{-1}
UGS45E	1.537	201.4	77
UGS60E	1.527	256.4	77
PMMA	1.488	210.3	77 [48]

The obtained samples were mounted inside the measurement chamber on a sapphire prism using index-matching liquids (Cargille Refractive Index Liquid Series A) with refractive indices of 1.50 for the PMMA foil and 1.60 for the other materials.

Each sample was measured at nine wavelengths in a temperature range from $+10^\circ\text{C}$ to $+60^\circ\text{C}$ in 10°C steps. Hereby, ten measurements were taken at each temperature and the sample was rotated in the chamber for each measurement. This way possible measurement errors due to surface defects of the samples were minimized.

As the available wavelength range of the used refractometer ended at 706.5 nm, a fitting function based on the Sellmeier equation

$$n^2(\lambda) = 1 + \frac{B_1\lambda^2}{\lambda^2 - C_1} + \frac{B_2\lambda^2}{\lambda^2 - C_2} + \frac{B_3\lambda^2}{\lambda^2 - C_3} \quad (5.1)$$

was applied to the measured data to calculate the refractive index values at 852 nm. $n(\lambda)$ is hereby the wavelength-dependent refractive index, and $B_{1,2,3}$ and $C_{1,2,3}$ are Sellmeier-coefficients obtained by fitting.

The thermo-optic coefficient $\frac{\partial n}{\partial T}$ was then extracted from a linear fit to the data calculated for different temperatures. The resulting plots along with the corresponding thermo-optic coefficients are shown in Figure 5.2.

In addition to the thermo-optic coefficient of the used polymers, their thermal expansion coefficient is also important for the design of temperature sensors. Therefore, the TEC values for UGS45E and UGS60E were measured with a DIL 806 optical dilatometer (TA Instruments). The measurement resulted in a TEC value of $\approx 77 \times 10^{-6} \text{ K}^{-1}$ for both materials. The used machine, however, did not allow measurements on foil samples. Therefore, the same value of $77 \times 10^{-6} \text{ K}^{-1}$ was assumed for the used PMMA foils, as it was inside the typical value range for PMMA reported in the literature [48]. Table 5.1 contains a summary of the measured optical and thermal material values.

Although these measurements gave a starting point for sensor design, they were performed on bulk material pellets in contrast to the thin layers used for sensor

Figure 5.2 Refractive indices of the polymer materials used for sensor fabrication. The data was measured at nine discrete wavelengths and the values for 852 nm were obtained through a Sellmeier-function fit. Measurements at different temperatures allowed the determination of the corresponding thermo-optic coefficient for each material.

fabrication. The chain length of the characterized polymers as thin films can deviate from the bulk materials due to differing curing conditions. Additionally, multiple measurements on different material batches showed a high batch-to-batch variation of the material properties; for example, up to 25 % in case of the thermo-optic coefficient. Consequently, a certain deviation from the presented values can be expected for the experimentally evaluated structures.

5.2 Experimental set-up

Characterization of the fabricated foil samples yields two main challenges to be addressed by a proper characterization set-up. Due to small waveguide sizes of several micrometers, the alignment precision of the light source to the waveguide facet and the overall mechanical stability of the entire system during measurement must be ensured to maintain a stable signal. Additionally, a precise temperature control of the setup is required for temperature measurements.

Figure 5.3 Schematic image of the optical measurement set-up. The incoupling side was mounted on a six-axis precision positioning stage. The output was mounted on a three-axis stage. Both cameras were mechanically decoupled from the positioning system, reducing the transfer of vibrations.

The schematic in Figure 5.3 shows the developed optical set-up. Two custom-made digital microscopes, one on the input and one on the output side, were used to image the foil facets and allowed a precise adjustment of the light source simultaneously focused on the input facet of the waveguide. White light emitting diodes (LEDs) were used for additional back side illumination of the waveguides. Both cameras were mechanically decoupled from the positioning system to reduce the transfer of vibrations.

A precise adjustment of the input side to the waveguide facet was done by a six-axis NanoMax Stage (Thorlabs, Germany) through an Olympus Plan 40X/0.65 microscope objective. The output was captured by a 50X/0.55 Mitutoyo Plan Apo microscope objective, mounted on a three-axis 17ANC001/MD precision stage by Melles Griot.

The temperature closed-loop control was ensured by a Newport 3040 temperature controller attached to a Peltier-element and a standard Pt100 resistive platinum temperature sensor embedded into the sample-holder.

The set-up allowed a temperature control with a precision of $\pm 0.06^\circ\text{C}$ in the range between 20°C and 80°C without mechanical cooling elements. The latter is especially important, as moving parts would introduce vibrations into the system and compromise the mechanical stability of the set-up. The temperature range was sufficient for the performed measurements; however, it can be extended by applying a larger heat dissipation block to the bottom side of the Peltier-element if desired.

5.3 Measurement of waveguide losses

The evaluation of the waveguide propagation losses was done by the cut-back method. This technique allows a separation of the coupling losses from the propagation losses if the in-coupling conditions are kept constant between all measurements. The fulfillment of this requirement is generally challenging in case of free space coupling through the waveguide facet used in this thesis. Nonetheless, the cut-back method allowed a reduction of the coupling effects on the real propagation losses by keeping the input facet quality untouched.

For this approach, the power of the light source was kept constant over the entire measurement. The output power at the initial waveguide length P_{long} was measured first. Subsequently, the structure was shortened by a fixed length l_{cutback} and the output power of the shortened waveguide P_{short} was measured again. The procedure was then repeated for a second cut-back step.

The result was a value for the propagation losses in each cut-off piece, assuming the in-coupling facet of the waveguide stayed untouched.

Using this data, the propagation losses were calculated as [80]

$$10 \cdot \log\left(\frac{P_{\text{long}}}{P_{\text{short}}}\right) \cdot l_{\text{cutback}}^{-1}. \quad (5.2)$$

Waveguides with an inverted rib geometry, a width $w = 3.5 \mu\text{m}$, a rib depth $d = 600 \text{ nm}$ and an initial length of 45 mm were used for the experiment. The output power was captured by a linear CCD-camera Stingray F125B (Allied Vision), while the exposure time was kept constant for all measurements. The cut-back length in all steps was $l_{\text{cutback}} = 10 \text{ mm}$. Finally, the results from multiple loss measurements were averaged.

The calculated propagation losses for the fabricated waveguides were $2.2 \pm 0.3 \text{ dB/cm}$, which is a typical range for polymer waveguides [78, 79], indicating inverted rib waveguides to be a competitive concept for the simplification of the manufacturing process.

5.4 Temperature measurements with Bragg sensors

To characterize the temperature sensitivity of the Bragg sensors, the fabricated structures were fixed on a Peltier-controlled sample holder and a temperature range between 20°C and 60°C was swept in 2.0°C -steps for the multi-mode sensors and in 2.5°C -steps for the single-mode sensors. A waiting time of 10 minutes was determined to be sufficient for the Peltier controller to reach a stable state at the desired temperature.

Figure 5.4 (a): Spectra of the WBG sensor, the light source, and a reference waveguide from the same foil and with the same dimensions as the measured Bragg sensor. All measurements were done at 20 °C and normalized to one. This comparison verifies that the measured dips in the transmission spectrum are caused by the Bragg grating. (b): Spectral responses of the sensor at 20 °C and 30 °C divided by the spectrum of the reference waveguide. The median of the result was normalized to one.

Due to the thermal expansion of the sample holder and the associated movement of the sensor foil, the incoupling position was readjusted after each temperature change. After optimizing the incoupling into the sensor, a series of three spectral measurements with an optical spectrum analyzer AQ6317A (ANDO ELECTRIC CO., LTD) was recorded at each temperature. Additionally, a waveguide with the same dimensions as the sensor, however without a WBG was measured as a reference. The measured data from the WBG was divided by the reference spectrum and the median value of the result was normalized to one.

5.4.1 Multi-mode Bragg temperature sensor

Figure 5.4 (a) shows the measured spectral response of the multi-mode Bragg temperature sensor at 20 °C along with the output spectra of the light source and the reference waveguide without a WBG. As a 20 µm-wide multi-mode waveguide was used for the measurement, the spectral width of the transmission dips of ≈ 3.5 nm is rather large, which corresponds to the results from the simulations.

Additionally, multiple dips are visible in the transmission spectrum which are too far apart to originate from different waveguide modes. This phenomenon is well known for fiber Bragg gratings [110] and results from the coupling into backward-propagating cladding modes of the optical waveguide, as described in Chapter 2 and shown in Figure 2.3 (c).

Experiments showed that the distance between single spectral dips was not affected by the temperature in the evaluated range, rather the whole spectral feature shifted evenly with changing temperature. Therefore, the dip marked in the plot was taken for the calculation of the temperature response as the used light source had the highest power at this wavelength, resulting in a better signal to noise ratio.

The transmission plots shown in Figure 5.4 (b) for 20 °C and 30 °C as an example were obtained after processing the measured data as described in the beginning of this section. The strongest transmission dip showed a reflectivity of $\approx 43\%$.

The Bragg wavelengths for each temperature are demonstrated in Figure 5.5. The developed sensor showed a nearly linear behavior over the complete temperature range with a slope of $-306 \pm 142 \text{ pm K}^{-1}$ and the resulting temperature resolution of $\approx 0.93 \text{ K}$.

Figure 5.5 Temperature-induced Bragg wavelength shift of the developed sensor. The sensor behaves nearly linear over the measurement range. The slope of the applied linear fit of $-306 \pm 142 \text{ pm K}^{-1}$ represents the sensitivity of the sensor.

This sensitivity value is considerably higher than expected from simulations in Subsection 3.1.6. There are multiple effects that can be responsible for this discrepancy. For instance, the used materials were fabricated in small batches, and batch-to-batch variations of the material properties are expected to be high, which can result in a higher thermo-optic coefficient of the material than was assumed in the model.

Additionally, an increase in temperature sensitivity for stress-induced birefringent fibers has been reported in the literature [111], although the origin of this temperature sensitivity increase stays unexplored until now. Therefore, frozen stress in the fabricated structures, caused by the thermal processing of the foils, can possibly be responsible for the sensitivity increase. However, no investigations concerning possible frozen stress were performed on the fabricated sensors.

5.4.2 Single-mode Bragg temperature sensor

The measured transmission plots for the single-mode Bragg temperature sensor are shown in Figure 5.6 (a) for 20 °C and 60 °C as an example. The extracted spectral positions of the Bragg wavelength at each temperature are presented in Figure 5.6 (b).

The developed sensor showed a nearly linear behavior over the complete temperature range with a slope of $-87 \pm 24 \text{ pm K}^{-1}$. This value corresponds well with the simulated model presented in Chapter 3 and results in a temperature resolution of $\approx 0.55 \text{ K}$ with the current measurement system.

However, the Bragg wavelength of the sensor at 25 °C was at 829.8 nm in contrast to 844.2 nm expected from the simulation. This discrepancy can be caused by a slight deviation of the core refractive index of the waveguide or by a minor shift of the grating period. For example, a grating period difference of $\approx -3.5 \text{ nm}$ compared to the expected value would be sufficient for the observed deviation.

An additional effect may come from the presence of grating chirp and the resulting variation of the effective grating period along the waveguide. This effect will be discussed in the next subsection.

5.4.3 Bragg grating chirp

A closer inspection of the measured spectra in Figure 5.6 revealed a distorted transmission dip profile compared to the simulation results. The minimum of each dip was shifted to the blue side of the spectrum. Also, the overall reflectivity considerably differed from the results predicted by simulations. To further investigate these issues, the effect of a possible grating chirp on the sensor performance was inspected.

Figure 5.6 The same procedure as for the multi-mode Bragg sensors was used for the measurements on single-mode Bragg sensors.

(a): Spectral response of the sensor at 20 °C and 60 °C was divided by the output spectrum of a reference waveguide of the same geometry but without a WBG. The median of the result was normalized to one. An FFT-low-pass-filtered curve was placed over the measured data for better visualization.

(b): Temperature-induced Bragg wavelength shift of the developed sensor. The sensor showed a nearly linear behavior over the entire measurement range. The sensitivity of the sensor of $-87 \pm 24 \text{ pm K}^{-1}$ is represented by the slope of the applied linear fitting curve.

The applied simulation models assumed a perfectly uniform and periodic binary Bragg grating. In the real case, however, the effective grating period can vary along the waveguide causing distortions to the sensor signal. There are two possible sources of a grating chirp in the system. On the one hand, a physical variation of the grating period could occur due to manufacturing tolerances; on the other hand, the effective refractive index of the waveguide itself could vary along the propagation direction, for example due to lower and upper cladding not being parallel, as sketched in Figure 5.7 (a).

Subsection 2.2.2 showed that the mode coupling inside a WBG is dependent on the propagation constant β . A variation of β along the waveguide has an effect on the spectral output of the sensor similar to the effect of the grating chirp. Although a measurement of the exact refractive index variation along the waveguide direction is challenging, it is possible to evaluate a simplified model to get a qualitative feeling of the effect. To simplify these calculations a square root chirp profile,

Figure 5.7 (a): Schematic of the expected grating chirp origin. (b): The grating period was modulated by a square root function to approximate a possible parasitic chirp during manufacturing. Transfer matrix method was applied to simulate the response of this grating profile in a circular fiber. The average effective grating period change is 50 pm/mm.

intended to simulate a bending of the cladding layer during the lamination process, was introduced into a circular geometry waveguide model. Subsequently, the TMM calculation described in Subsection 2.2.4 was evaluated for the resulting Bragg grating. The amount of chirp was adjusted to achieve a close match between the simulated and the measured data at 60 °C, resulting in a profile shown in Figure 5.7 (b).

Figure 5.8 compares the measured data at 60 °C with the simulated results and confirms the presence of chirp in the fabricated system. A closer look at the chirp profile from Figure 5.7 (b) shows that the corresponding total period change of the grating is 500 nm, or 0.18 % of the initial period, over a grating length of 10 mm.

Finally, the applied chirp profile was removed from the simulation model while keeping all other parameters fixed. The resulting simulated spectra for the chirped and non-chirp gratings in Figure 5.9 demonstrate the effect of chirp on WBG-performance.

This comparison clearly indicates that even a slight amount of chirp in the system can have a dramatic effect on the reflectivity of waveguide Bragg sensors and needs to be precisely controlled during the manufacturing phase.

Additionally, the measured amount and the profile of the peak distortion was not uniform over the measured temperature range. This fact indicates a changing amount or profile of the chirp at different temperatures, which is possibly caused by variation of the layer stress in the sensor structure during temperature changes.

Figure 5.8 Comparison of the measured spectral response of the single-mode sensor at 60 °C with the simulated transmission spectrum of a circular waveguide with the grating chirp profile, described in Figure 5.7 (b). The amount of chirp in the simulation model was adjusted to achieve a good matching between the simulated and the measured data.

Figure 5.9 The previously simulated Bragg grating with an effective grating period change of 50 pm/mm was compared to the same grating with the chirp removed. The maximum reflectivity of the WBG changed from $\approx 15\%$ with chirp to $\approx 87\%$ without chirp, demonstrating the importance of the chirp control during the manufacturing phase.

Figure 5.10 A fluid chamber connected to a syringe pump and a waste container by silicone tubes. This fluid delivery system was placed on the AMZI sensor foil to confirm the insensitivity of the fabricated AMZI temperature sensors to refractive index changes of the environment.

5.5 Temperature measurements with AMZI-Sensors

AMZI sensors are potentially sensitive to refractive index changes of the environment if the core layer is not properly isolated. Therefore, prior to temperature characterization of the fabricated AMZI-structures the effectiveness of the applied upper cladding as a protective layer was evaluated experimentally.

5.5.1 Sensitivity to refractive index changes

AMZI-systems were successfully used for refractive index sensing in previous work [112]. In case of temperature sensing, on the contrary, a cross-sensitivity of the AMZI structures to refractive index changes of the surrounding medium was undesired. The effectiveness of the applied upper cladding layer for the isolation of the device from the surrounding medium was therefore examined first. Hereby, the experiment described by Xiao et al. [112] was carried out on the fabricated sensor foils.

AMZI sensors were covered by a fluid chamber as shown in Figure 5.10 and placed into the measurement set-up. Deionized (DI) water with a refractive index of 1.33 was used as a reference. Two DI-water/glucose solutions with 20 weight-% glucose

Figure 5.11 Temperature measurement with an AMZI sensor referred to the 25 °C intensity value ($I_T(25\text{ °C}) \cong 100\%$). The sensitivity of the AMZI represented by the slope of the linear fitting curve of $S_{\text{AMZI}} = 0.98 \pm 0.33\% \text{ K}^{-1}$ was close to the simulated value of $1.12\% \text{ K}^{-1}$, presented in Subsection 3.1.7.

and a refractive index of 1.357 and 40 weight-% glucose with a refractive index of 1.389 were used as analytes. All liquids were brought to room temperature prior to the measurement and pumped over the sample surface with a constant flow rate of 2 ml/min for 5 minutes each. DI-water was pumped first, followed by the 20 weight-% glucose solution and another DI-water step to flush the chamber. The sequence was then repeated with the 40 weight-% glucose solution.

The sensors did not show any reaction to the analyte changes, confirming the insensitivity of the AMZI temperature sensors to environmental refractive index fluctuations.

5.5.2 Temperature sensitivity

In the next step, the flow chamber was removed from the setup and the intensity output of the sensor was recorded in the temperature range between 20 °C and

60 °C in 5 °C steps. As in case of the Bragg sensors, a waiting time of 10 minutes was sufficient to reach a stable temperature level. After each temperature step the incoupling position was readjusted to compensate for the thermal movement of the foil.

For each temperature level, images of the output facet were captured by a linear 16-bit CCD-camera Stingray F125B (Allied Vision) at a sampling rate of 1 Hz over a period of 150 seconds. The relative output intensity for each temperature step was obtained by integration of the pixel levels from each corresponding image over the area of the output facet, followed by the averaging of the results between all images. The measurement was repeated for three times. The mean values of these measurements at each temperature were divided by the output intensity at 25 °C as described in Subsection 3.1.7. The sensitivity of the sensor is represented by the slope of the resulting curve shown in Figure 5.11.

The measured temperature sensitivity of $S_{\text{AMZI}} = 0.98 \pm 0.33 \% \text{ K}^{-1}$ with the resulting temperature resolution of $\approx 0.66 \text{ K}$ was close to the simulated value of $1.12 \% \text{ K}^{-1}$, presented in Subsection 3.1.7. The small deviation from the expected value can be explained by a minor shift of the sensor working point due to manufacturing tolerances. As expected, the exact determination of the working point was challenging, as only a small part of the interference curve was covered by the measurement range. Nonetheless, the performance of the AMZI temperature sensors was close to the performance of the Bragg temperature sensors. Therefore, AMZI sensors represent an attractive alternative to WBG sensors if an intensity read-out is desired.

5.6 Summary

Two temperature sensor concepts introduced in Chapter 3 were experimentally evaluated in this chapter. After the characterization of the used materials, propagation losses of the inverted rib waveguides were measured by the cut-back method. The resulting losses of $2.2 \pm 0.3 \text{ dB cm}^{-1}$ are in the same range as losses of the state-of-the-art waveguides reported in the literature. This measurement confirmed that the manufacturing process for the sensors was simplified without a degradation of the waveguide quality.

In the next step, a flexible temperature-controlled optical set-up was introduced. The set-up allowed an easy and precise waveguide coupling, assisted by a simultaneous imaging of the waveguide facets. Furthermore, it enabled a spectral and an intensity-based read-outs of the samples and was suited for both sensor concepts.

Temperature measurements with multi-mode and single-mode WBG-sensors showed a linear temperature-induced spectral shift. The sensitivity of the single-mode Bragg sensor of $S_{\text{Bragg}} = -87 \pm 24 \text{ pm K}^{-1}$ with the resulting temperature resolution of $\approx 0.55 \text{ K}$ was close to the value expected from simulations. However, the sensitivity of the multi-mode sensor was considerably higher than expected and requires further investigations on the reasons of this discrepancy. Finally, the effect of grating chirp on the performance of the sensors was discussed.

The developed AMZI sensors were proven to be insensitive to refractive index changes of the environment in the first step. Hence, the effectiveness of the applied upper cladding material for the isolation of the sensors from environmental interference was confirmed. The subsequent thermal characterization of the devices between 20°C and 60°C showed a sensitivity of $S_{\text{AMZI}} = 0.98 \pm 0.33 \% \text{ K}^{-1}$ referred to the room temperature of 25°C . The resulting temperature resolution of the sensors was $\approx 0.66 \text{ K}$.

The evaluated sensing concepts showed a similar temperature resolution. However, they differ in the corresponding read-out methods. The spectral read-out of the WBG-sensors allows the usage of broad-band light sources, such as LEDs and superluminescent diodes (SLEDs), which are easier to fabricate in polymer materials than laser sources. AMZI sensors, in turn, do not require a spectrometer and can be read out by a photodiode. As a part of a sensing network aimed in the future, both sensors can be easily interchanged or used simultaneously depending on the desired application.

6 Conclusion and Outlook

Conclusion This thesis described the development of two novel all-polymer planar temperature sensors. The realization of the devices on thin and flexible planar substrates enables the combination of multiple sensors into large spatially distributed sensor networks. The concept of optical sensor networks results in a versatile and highly-tunable measurement platform. In the future, this platform can be extended by addition of new sensor types for a simultaneous monitoring of multiple environmental parameters. Depending on the choice of each individual sensor combination, this concept can be easily adapted to new applications.

The manufacturing processes for the temperature sensors were optimized for roll-to-roll techniques and make the up-scaling of the fabrication to large-area substrates possible. In combination with the described sensor designs, these techniques show a high potential for low-cost manufacturing of optical devices. Additionally, the developed sensors differ in their measurement and read-out concepts and thus cover a broad-range of possible applications.

The first sensor concept was based on waveguide Bragg gratings. Such devices were for the first time demonstrated as a system entirely consisting of polymers on a thin flexible substrate and fabricated by mass-production techniques. The known state-of-the-art devices were realized either as discrete fiber elements or deposited on rigid glass and semiconductor substrates.

Bragg gratings allow the incoupling of the forward-propagating waveguide mode matching the grating condition into one or more backward-propagating modes. As a result, temperature changes are translated into a shift of the transmitted spectral features. Therefore, these sensors rely on a spectral read-out and are insensitive to possible fluctuations of the input light intensity. Additionally, this sensing concept allows the usage of broad-band light emitting diodes and thus simplifies the direct integration of light sources.

The Bragg sensors were designed by extensive simulations and fabricated in multi-mode and single-mode waveguides. The designs were based on a 175 μm -thick PMMA-foil structured by hot-embossing. The structured foil served as a substrate and a lower cladding layer for inverted rib waveguides. Bragg gratings were hot-embossed into a separate piece of PMMA foil which served as the upper-cladding

layer of the sensor. A customized UV-curable polymer was used as a core layer for the waveguides and as a glue for the combination of both parts of the sensor at the same time. Fabrication of the waveguide and grating structures in two separate steps greatly reduced the complexity of the replication techniques and allowed a targeted selective optimization of the process parameters for different feature sizes. The demonstrated single-mode sensor showed a spectral shift of $-87 \pm 24 \text{ pm K}^{-1}$ with a linear response over the temperature range between 20°C and 60°C and resolved temperature changes of 0.55 K .

Experimental evaluation confirmed the feasibility of both single-mode and multi-mode designs. The single-mode sensors hereby showed a narrower spectral bandwidth of the reflected light, potentially making them better suitable for high-precision temperature measurements. Multi-mode sensors, however, can be fabricated with larger structure dimensions, making them an attractive alternative for applications where a lower temperature resolution can be tolerated.

The second sensing concept was based on planar asymmetric Mach-Zehnder interferometers. As in the case of Bragg temperature sensors, conventional Mach-Zehnder interferometers were only realized as fiber elements or waveguides on rigid inorganic substrates up to now.

The realized devices transfer a phase shift difference in the interferometer arms into an interference intensity signal at the output. Therefore, they can be read-out by a photodiode or a CCD-chip. This concept, in contrast to Bragg sensors, does not require a spectral analysis and reduces the complexity of the read-out system.

The novel asymmetric design of the sensors successfully simplified the manufacturing process, as only one polymer layer needed to be structured. The temperature-induced phase shift difference in the interferometer arms was achieved through their different widths. The sensors consisted of inverted rib waveguides structured to split the propagating wave into two asymmetric arms by a Y-splitter and recombine the signal by a second Y-branch.

The described AMZI sensors were based on the same waveguide technology as Bragg sensors. Therefore both sensor concepts can be easily combined and integrated into a single network. The fabricated sensors showed a sensitivity of $0.98\% \text{ K}^{-1}$ and the corresponding temperature resolution of 0.66 K with a linear temperature curve inside the investigated range between 20°C and 60°C .

Both sensing concepts showed a similar temperature resolution. However, they use different read-out methods. As a part of larger sensing networks in the future, both sensors can be easily interchanged or used simultaneously depending on the aimed application.

Figure 6.1 Multiple AMZI sensors with different working points combined into a network. The simultaneous read-out of all sensor outputs would allow a reconstruction of a complete period of the cosine transfer curve. The result would deliver information about the exact working point of the sensor and would allow an absolute calibration of the structure by fitting the measurement results to the simulation data.

Outlook The effectiveness and the high potential of both sensor concepts was demonstrated in the scope of this thesis. A promising continuation of the project would be the direct integration of light sources and detectors into the developed sensor foils. The necessary light sources, photodiodes and foil spectrometers along with their integration technology are developed by our cooperation partners at the Technical University Braunschweig, Technical University Clausthal, and at Gisela and Erwin Sick Chair of Micro-optics at the University of Freiburg. The resulting structures will be fully integrated optronic sensors with a small footprint. This integration can be expected to eliminate potential mechanical disturbances from the optical set-up, simplify the read-out and further enhance the signal quality.

Furthermore, of particular interest for further investigation is the combination of multiple AMZIs with slightly different working points into a distributed network, as shown in Figure 6.1. A simultaneous read-out of the entire structure would make the sampling of a complete period of the cosine interference curve possible. In this case, the measured data could be fitted to the theoretical values, allowing an absolute calibration of the system. Additionally, it would further reduce the required precision of the manufacturing process.

The concept of asymmetric Mach-Zehnder interferometers can also be modified and extended for the measurement of additional parameters. For example, a humidity

Figure 6.2 AMZI structure with a hygroscopic material as an upper cladding. This modification of the AMZI concept can be developed to a humidity sensor.

sensor could be realized based on the AMZI platform through an integration of a hygroscopic material, or a hydrogel, into the cladding layer of the structure, as demonstrated in Figure 6.2. In this configuration, a change of the upper cladding refractive index due to water absorption by the hygroscopic material leads to a change of the interference signal at the output.

As discussed in Subsection 5.4.3, the signal quality of Bragg grating sensors can be further enhanced via reduction of the grating period chirp. This goal can be achieved by the implementation of an automatic assembly process for Bragg sensors. For example, a precise automatic alignment system, such as a lamination machine, can be used to ensure the optimum straightness and parallelism of the sensor layers.

Building a network of waveguide Bragg grating sensors is also of special interest for further research. An integration of multiple Bragg gratings with different periods into a single waveguide would enable temperature measurements at different locations with a single detector. In this case each single grating would have its signal at a different spectral position.

Finally, new polymer materials with improved thermal properties are the easiest way for the further sensitivity enhancement of both sensor types fabricated in this thesis. Therefore, a continuation of material research is highly desirable in the future.

A Appendix

A.1 Microfabrication process flow for master structures

Waveguide master structures AZ 1518 KLZ

Short description of the fabrication process

- Substrates: $6 \times 500 \mu\text{m}$ thick Si-wafers
- AZ1520-deposition and structuring
- Etching. Depth: $0.85 \mu\text{m}$

PROCESS:

1. Webfab: create KLZ ☐
2. Silicon nitride PECVD deposition. Targeted thickness $0.85 \mu\text{m}$. ≈ 73 minutes. ☐
3. HMDS priming: Oven, standard program ☐
4. Deposition of AZ1518: targeted resist thickness: $1.8 \mu\text{m}$. 2 ml dispensed statically, spread cycle: 500 rpm for 10 seconds, spin cycle: speed 4000 rpm for 30 seconds (Program 4) ☐
5. Soft bake 50 seconds @ 100°C ☐
6. Exposure: Low Vacuum contact, 2.8 seconds @ $9 \text{ mW}/\text{cm}^2$ ($6 - 8 \text{ mJ}/\text{cm}^2$), no I-Line filter ☐
7. Development: Spray developer, program P. ☐
8. Measure resist thickness with Profilometer (Tenkor T11) ☐
9. Etching: RIE, Process "OXIDE". Targeted depth: $0.85 \mu\text{m}$. Around 3 minutes? (Test) ☐

- 10. Measure etch depth with Profilometer (Tenkor T11) and etch again if necessary ☐
- 11. Strip resist with Standard Cleaning Nr. 1 (5 min Aceton+Ultrasonic, 5 min Isopropanol+Ultrasonic, DI-Water) ☐
- 12. Measure real etch depth with Profilometer (Tenkor T11) ☐
- 13. Antistiction layer: ICP, Around 120 seconds, thickness: 0.2 μm ☐
- 14. Cleanroom out ☐

A.2 Data sheets

A.2.1 PMMA-foil: Plexiglas 99524 GT

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PLEXIGLAS® Folien zur Lichtstreuung lassen sich sehr gut z.B. per Sieb- und Digitaldruck bedrucken. Außerdem können die Folien mit Hilfe von Bandstahlschnittwerkzeugen und säulengeführten Werkzeugen gestanzt werden. Beim Schneiden mit CO₂-Lasern ergeben sich optisch sehr saubere Schnittkanten.

PLEXIGLAS® Folien für den grafischen Siebdruck

Die Folien-Sorte PLEXIGLAS® Farblos 99524 ist am besten für das Folien-Hinterspritzverfahren geeignet. Damit lassen sich hochglänzende Oberflächen mit einer ausgezeichneten Tiefenwirkung erzielen. Die PLEXIGLAS® Folie Farblos 99524 wird bei optischen Anwendungen wie Lichtleitern eingesetzt. Eine hochpräzise optische Strukturierung lässt sich in die Folie prägen. Die Folie entspricht auch nach einer kratzfest-Beschichtung auf Acrylatbasis den höchsten optischen Anforderungen. Die Folien können außerdem mit einer matten Oberfläche geliefert werden.

Exposure time (h)	0	48	96	144	192	240	288	336	384
PVC-1									
PVC-1/HC 50 µm									
PVC-1/HC 30 µm									
PVC-2									
PVC-2/HC 50 µm									
PVC-2/HC 30 µm									

Beschleunigter UV-Test: Messung der Farbunterschiede von PVC; Super-UV-Tester SUV-W11, Bestrahlungsstärke: 83 mW/cm²; 300-400 nm, Schwarztafeltemperatur 63 °C, Luftfeuchtigkeit: 60 %
PVC-1, Basisformulierung
PVC-2, modifizierte Formulierung
HC = EUROPLEX® Folie HC 99710
Deckschicht auf PVC -1 / PVC-2 laminiert

Unser Produktprogramm

	Dickenbereich	Bemerkungen
Laminierfolien		
PLEXIGLAS® Folie 0F008	53 µm	PVC-Folienlaminierung
PLEXIGLAS® Folie 0F014	53 und 75 µm	Hochschlagzähe Einstellung, hochwertige optische Lamine, Tiefbedruckung
PLEXIGLAS® Folie 0F016	60 und 75 µm	hohe Oberflächenhärte, hochwertige optische Lamine, Tiefbedruckung
PLEXIGLAS® Folie 0F032	70 µm	seidenmatte Oberfläche, PVC-Folienlaminierung, Tiefbedruckung
PLEXIGLAS® Folie 99836	50 µm	optimierte Haftung für Melaminharz
EUROPLEX® Folie HC 99710	50 µm	eine Seite PMMA / eine Seite PVDF
EUROPLEX® Folie HC 99716	50 µm	eine Seite PMMA / eine Seite PVDF, optimierte Haftung für Melaminharz
Folien für grafische Anwendungen		
PLEXIGLAS® Folie 99524	175, 250, 375, 500, 750 und 1000 µm	hochglänzend, grafische Qualität
PLEXIGLAS® Folie 0F003	250 µm	eine Seite matt, eine Seite glänzend
Lichttechnische Weißfolien		
PLEXIGLAS® Folie Weiß 99547	250 µm	soft Light, Lichtstreuung
PLEXIGLAS® Folie Weiß 99532	500 und 1000 µm	soft Light, Lichtstreuung

Laminierfolien

Eigenschaft	Prüf- methode	Einheit	PLEXIGLAS® Folie 0F032 matt	PLEXIGLAS® Folie 0F008 glänzend	PLEXIGLAS® Folie 0F014 glänzend	PLEXIGLAS® Folie 0F016 glänzend	PLEXIGLAS® Folie 99836 glänzend
Mechanisch							
Streckspannung	ISO 527-3	MPa	35	45	47	43	52
Streckdehnung	ISO 527-3	%	6	5	6	6	5
Nominelle Bruchdehnung	ISO 527-3	%	> 50	> 50	> 50	25	12
Thermisch							
Vicat Erweichungstemp. ¹⁾	ISO 306	°C	78	86	86	96	–
Spezifische Wärme	/	kJ/kgK	1,5	1,5	1,5	1,5	1,5
Bewitterungsbeständigkeit							
Xenotest 1200 / 8000 h	/	/	Keine sicht- bare Ver- änderung	Keine sicht- bare Verän- derung	Keine sicht- bare Verän- derung	Keine sicht- bare Ver- änderung	Keine sicht- bare Ver- änderung
Optisch							
Transmissionsgrad D65	DIN 5036	%	90	92	92	92	92
UV- Transmission (280–380 nm)	DIN 5036	%	≤ 1	≤ 1	≤ 1,5	≤ 1,5	< 1
Trübung	ASTM D1003	%	/	≤ 1	≤ 1	≤ 1	≤ 1,5
Gelbwert	ASTM D1925	/	≤ 1,5	≤ 1,5	≤ 1,5	≤ 1,5	< 1
Brechungszahl	ISO 489	/	1,49	1,49	1,49	1,49	1,49
Glanz (60°)	DIN 67 530	/	22	–	–	–	–
Elektrisch							
spez. Durchgangswider- stand	IEC 250	Ohm cm	> 10 ¹³	> 10 ¹³	> 10 ¹³	> 10 ¹³	> 10 ¹³
Dielektrizitätszahl 100 Hz – 1 Mhz	IEC 250	/	0,04 – 0,03	0,04 – 0,03	0,04 – 0,03	0,04 – 0,03	0,04 – 0,03
Sonstige							
Oberflächenspannung	/	mN/m	50	50	50	50	50
Dichte ¹⁾	ISO 1183	g/cm ³	1,15	1,14	1,13	1,15	1,15

1) auf der Basis von Formmasse

PVDF coextrudierte Folien

Eigenschaft	Prüf- methode	Einheit	EUROPLEX® Folie HC 99710 glänzend	EUROPLEX® Folie HC 99716 glänzend
Mechanisch				
Streckspannung	ISO 527-3	MPa	45	45
Streckdehnung	ISO 527-3	%	–	–
Nominelle Bruchdehnung	ISO 527-3	%	> 50	> 50
Thermisch				
Vicat Erweichungstemp. ¹⁾	ISO 306	°C	–	–
Spezifische Wärme	/	kJ/kgK	–	–
Bewitterungsbeständigkeit				
Xenotest 1200 / 8000 h	/	/	Keine sichtbare Verän- derung	Keine sichtbare Verän- derung
Optisch				
Transmissionsgrad D65	DIN 5036	%	93	93
UV- Transmission (280– 380 nm)	DIN 5036	%	< 1	< 2
Trübung	ASTM D1003	%	2	2
Gelbwert	ASTM D1925	/	< 1	< 1
Brechungszahl	ISO 489	/	–	–
Glanz (60°)	DIN 67 530	/	–	–
Elektrisch				
spez. Durchgangswider- stand	IEC 250	Ohm cm	–	–
Dielektrizitätszahl 100 Hz – 1 Mhz	IEC 250	/	–	–
Sonstige				
Oberflächenspannung	/	mN/m	23	23
Dichte ¹⁾	ISO 1183	g/cm ³	1,2	1,2

1) auf der Basis von Formmasse

Grafische Folien und lichttechnische Weißfolien

Eigenschaft	Prüf- methode	Einheit	PLEXIGLAS® Folie 99524 glänzend	PLEXIGLAS® Folie 99547 Weiß	PLEXIGLAS® Folie 99532 Weiß opak
Mechanisch					
Streckspannung	ISO 527-3	MPa	54	55	51
Streckdehnung	ISO 527-3	%	5	4,5	4,5
Nominelle Bruchdehnung	ISO 527-3	%	35	–	–
Thermisch					
Vicat Erweichungstemp. ¹⁾	ISO 306	°C	100	100	98
Spezifische Wärme	/	kJ/kgK	1,5	1,5	1,5
Bewitterungsbeständigkeit					
Xenotest 1200 / 8000 h	/	/	–	–	–
Optisch					
Transmissionsgrad D65	DIN 5036	%	92	54,5 / 0,25 mm	57,5 / 0,5 mm
Trübung	ASTM D1003	%	< 1	–	–
Brechungszahl	ISO 489	/	1,49	–	–
Glanz (60°)	DIN 67 530	/	83	–	–
Elektrisch					
spez. Durchgangswider- stand	IEC 250	Ohm cm	> 10 ¹³	> 10 ¹³	> 10 ¹³
Dielektrizitätszahl 100 Hz – 1 Mhz	IEC 250	/	0,05– 0,03	0,05 – 0,03	0,04 – 0,03
Sonstige					
Oberflächenspannung	/	mN/m	50	50	50
Dichte ¹⁾	ISO 1183	g/cm ³	1,16	1,16	1,16

1) auf der Basis von Formmasse

A.2.2 Hot-embossing stamp material: Elastosil® RT 601

WACKER

SILICONES

ELASTOSIL®

ELASTOSIL® RT 601 A/B

RTV-2 SILICONE RUBBER

Product description

ELASTOSIL® RT 601 A/B is a pourable, addition-curing RTV-2 silicone rubber.

To eliminate any air introduced during dispensing or trapped under components or devices a vacuum encapsulation is recommended.

Special features

- two-part, 9 : 1 mixing ratio
- low viscosity
- medium cured hardness
- excellent tensile strength
- crystal clear vulcanizate

Curing:

Curing time of addition curing silicone rubber is highly dependent on temperature, size and heat sink properties of the component being potted.

The reactivity can be adjusted within wide limits by adding Catalyst EP or Inhibitor PT 88 to suit the processing requirements of the particular application. Catalyst EP increases the reactivity, i. e., pot life and curing time are reduced. Inhibitor PT 88 is a pot life extender and prolongs pot life and curing time. Further information is given in our leaflet "Catalyst EP/Inhibitor PT88".

Application

- all-round potting compound
- manufacture of molded articles by casting

We recommend running preliminary tests to optimize conditions for the particular application.

Processing

Caution:

Only components A and B with the same lot number may be processed together!

Comprehensive instructions are given in our leaflet "ELASTOSIL® - PROCESSING RTV-2 SILICONE RUBBERS".

Surface preparation:

All surfaces must be clean and free of contaminants that will inhibit the cure of ELASTOSIL® RT 601 A/B. Examples of inhibiting contaminants are sulfur containing materials, plasticizers, urethanes, amine containing materials and organometallic compounds - especially organotin compounds. If a substrate's ability to inhibit cure is unknown, a small scale test should be run to determine compatibility.

Temperature	Curing time, thickness 1 cm
23 °C	24 h
70 °C	20 min
100 °C	10 min

Mixing:

Component A of ELASTOSIL® RT 601 contains the platinum catalyst, component B the crosslinker. Even traces of the platinum catalyst may cause gelling of the component containing the crosslinker. Therefore tools (spatula, stirrers, etc.) used for handling the platinumcontaining component or the catalyzed compound must not come into contact with this component.

Storage

The 'Best use before end' date of each batch is shown on the product label.

Storage beyond the date specified on the label does not necessarily mean that the product is no longer usable. In this case however, the properties required for the intended use must be checked for quality assurance reasons.

The two components should be thoroughly mixed at a 9 : 1 ratio by weight or volume.

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require special handling precautions.

Safety notes

According to the latest findings, the addition-curing silicone rubber ELASTOSIL® RT 601 A/B contains neither toxic or corrosive substances which would

Comprehensive instructions are given in the corresponding Material Safety Data Sheets. They are available on request from WACKER subsidiaries or may be printed via WACKER web site <http://www.wacker.com>.

Product data

Typical general characteristics	Inspection Method	Value
Product data (uncured)		
Component A		
Color		colorless
Viscosity at 23 °C	ISO 3219	5000 mPa s
Density at 23 °C		1,03 g/cm³
Component B		
Color		colorless
Viscosity at 23 °C	ISO 3219	40 mPa s
Density at 23 °C		0,97 g/cm³
Product data (catalyzed A+B)		
Mix ratio (pbw)	A : B	9 : 1
Viscosity of mix at 23 °C	ISO 3219	3500 mPa s
Pot life at 23 °C, up to 20000 mPa s		90 min
Platinum-catalyst in component		A
Product data (cured)		
Color		colorless, transparent
Density at 23 °C	ISO 2781	1,02 g/cm³
Hardness Shore A	ISO 868	45
Tensile strength	DIN ISO 37	6,00 N/mm²
Elongation at break	ISO 37	100 %
Volume resistivity	IEC 60093	10 ¹⁵ Ω cm
Permittivity	IEC 60250	2,8

Cured for 30 min at 150 °C in a circulating air oven.

These figures are only intended as a guide and should not be used in preparing specifications.

The data presented in this medium are in accordance with the present state of our knowledge but do not absolve the user from carefully checking all supplies immediately on receipt. We reserve the right to alter product constants within the scope of technical progress or new developments. The recommendations made in this medium should be checked by preliminary trials because of conditions during processing over which we have no control, especially where other companies' raw materials are also being used. The information provided by us does not absolve the user from the obligation of investigating the possibility of infringement of third parties' rights and, if necessary, clarifying the position. Recommendations for use do not constitute a warranty, either express or implied, of the fitness or suitability of the product for a particular purpose.

The management system has been certified according to DIN EN ISO 9001 and DIN EN ISO 14001

WACKER® is a trademark of Wacker Chemie AG. ELASTOSIL® is a trademark of Wacker Chemie AG.

For technical, quality, or product safety questions, please contact:

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www.wacker.com

A.3 Flow charts of the simulation procedure

Waveguide Bragg grating sensors introduced in this thesis were simulated in the RSoft GratingMODTM software module, developed by Synopsis®. This program, however, lacks the tools necessary for the simulation of multi-mode grating structures and for multidimensional parameter sweeps, needed for tolerance studies. Therefore, the PythonTM application programming interface (API) of GratingMODTM was used to extend its capabilities by a custom-made program.

The developed software extension module allowed a convenient set-up and generation of RSoft model files through a graphical user interface automatic sweeps through a preset number of waveguide modes, automatic calculation of the multi-mode Bragg spectra and multidimensional sweeps of arbitrary model parameters. Furthermore, due to a high amount of data, generated by simulations, a managing mechanism for simulation models and raw data was developed along with a compatible result-viewer.

This section shows flow-charts of the algorithms, realizing the previously introduced tolerance study (Figure A.1) and the simulation of multi-mode spectral responses for waveguide Bragg gratings (Figure A.2).

Figure A.1 Simulation procedure of the tolerance study for the Bragg temperature sensors. $W = 64$ parameter combinations were simulated in the temperature range $T = 0 - 80^\circ\text{C}$. Mode profiles $\vec{e}$ were simulated along with the reflectivity r and the Bragg wavelength λ_{Bragg} .

Figure A.2 Simulation procedure for the spectral response of the Bragg temperature sensors. The spectral responses of the first 10 modes m were simulated in a wavelengths range λ . Mode profiles $\vec{e}$ were simulated along with the reflectivity r . The results of the individual modes were combined to a complete output spectrum. This procedure was repeated for each temperature step.

A.4 Source code

A.4.1 Matlab code for the generation of waveguide bends.

```
1 function [outcommand] = cosbendp(n,init_z,width,l,h,h2)
   % ---==
   % Yanfen Xiao, Stanislav Sherman – 2013/1/21
   % generate an L–Edit command to draw a cosine S–bend path.
   % ---
   % n is the number of points in the path,
   % init_z is the path begin,
   % l is the length of the path,
   % h is the lateral offset of the bend.
2   clf

4   outcommand = 'polygon -!',
5   outcommand2 = '',
6   cpts = zeros(n,2);
7   cpts2 = zeros(n,2);
8   z = linspace(init_z,l,n);
9   z2 = linspace(init_z,l,n);
10  p = 0;
11  maxpoints = 125; % maximum number of points per part/2

13  cpts(:,1) = z;
14  cpts(:,2) = h*(sin(pi*z./(2*l))).^2;

16  cpts2(:,1) = z2;
17  cpts2(:,2) = width + h2*(sin(pi*z2./(2*l))).^2;
   % Assemble a string to be copied into the L–edit's command window.
18  while p < n
19      for k = (p + 1):(p + maxpoints)
20          if k <= n
21              outcommand = [outcommand, ' ', num2str(cpts(k,1), '%.3f'), ' ', num2str(cpts(k,2),
22                  '%.3f')];
23          end
24          for k = (p + maxpoints):-1:(p + 1)
25              if k <= n
26                  outcommand2 = [outcommand2, ' ', num2str(cpts2(k,1), '%.3f'), ' ', num2str(cpts2(k,2),
27                      '%.3f')];
28              end
29          p = p + maxpoints - 1;
30          outcommand = [outcommand, ' ', outcommand2];
```

```

31     disp(outcommand)
32     outcommand = 'polygon -!';
33     outcommand2 = '';
34 end
35 % plot the generated cosine path
36 plot(cpts(:,1), cpts(:,2))
37 plot(cpts2(:,1), cpts2(:,2))
38 end

```

A.4.2 Wolfram Mathematica® code for the calculation of single-mode waveguide dimensions.

1 Calculation of single-mode dimensions for inverted rib waveguides.
 α is the fitting factor for TE and TM polarization.
 Theory source: Muellner et al. (2006).

```

3 In[23]:= Quit[]

5 In[153]:= nc = 1.488;
6           ng = 1.527;
7           ns = 1.488;
8           λ0 = 852;
9           λ = λ0/ng;
10          k0 = 2π/λ0;
11          H = 3000;
12          d =.;
13          dmin = 5;
14          dinc = 2;
15          dmax = 1000;
16          m = 0;
17          α = 0.32;

19 In[134]:= AsymTE[d_, θ_] := 2π(H-d)/λ Cos[θ] - mπ - ArcTan[
           Sqrt[Sin^2[θ] - (nc/ng)^2]/Cos[θ]]
           - ArcTan[ Sqrt[Sin^2[θ] - (ns/ng)^2]/Cos[θ]];

```

```
21 FindRoot[AsymTE[0,  $\theta$ ] == 0, { $\theta$ ,  $\frac{7\pi}{16}$ }]];
22 Theta1 = Evaluate[ $\theta$  /. %];
23 Neff1 = ng Sin[Theta1];
24 Table[FindRoot[AsymTE[dmin + dinc counter,  $\theta$ ] == 0, { $\theta$ ,  $\frac{7\pi}{16}$ }], {counter, dmax}];
25 Theta2 = Evaluate[ $\theta$  /. %];
26 Neff2 = ng Sin[Theta2];
27 width1 = Table[ $\left\{ \text{dmin} + \text{dinc counter}, 10^{-3} \left( \alpha H + \frac{\pi}{k_0 \sqrt{\text{Neff1}^2 - \text{Neff2}[[\text{counter}]]^2}} \right) \right\}$ ,
28 {counter, dmax}];
29 w1 = ListLinePlot[width1, Frame → True,
30 FrameLabel → {"Rib depth in nm", "Rib width in  $\mu\text{m}$ "},
31 PlotStyle → {Blue, Thickness[0.005]},
32 PlotRange → {{0, 2000}, {0, 20}}, PlotLegends → {"ng=1.51"},
33 BaseStyle → {FontFamily → "Arial", FontSize → 20}]
```

A.5 Spin-coating thickness curves

Figure A.3 Rotation-speed-dependent layer thicknesses for the spin-coating of UGS45E and UGS60E custom materials. The fitting function is based on a theoretical model for Newtonian liquids on a rotating disk [113].

Bibliography

- [1] Udd, Eric and Jr. William B. Spillman (editors): *Fiber Optic Sensors: An Introduction for Engineers and Scientists*. Wiley, New York, 2nd edition, 2011.
- [2] Deng, Da, Min Gyu Kim, Jim Yang Lee, and Jaephil Cho: *Green energy storage materials: Nanostructured TiO_2 and Sn-based anodes for lithium-ion batteries*. Energy and Environmental Science, 2:818–837, 2009.
- [3] Chen, Haisheng, Thang Ngoc Cong, Wei Yang, Chunqing Tan, Yongliang Li, and Yulong Ding: *Progress in electrical energy storage system: A critical review*. Progress in Natural Science, 19(3):291 – 312, 2009, ISSN 1002-0071.
- [4] Lu, Languang, Xuebing Han, Jianqiu Li, Jianfeng Hua, and Minggao Ouyang: *A review on the key issues for lithium-ion battery management in electric vehicles*. Journal of Power Sources, 226:272 – 288, 2013, ISSN 0378-7753.
- [5] Rezvanizani, Seyed Mohammad, Zongchang Liu, Yan Chen, and Jay Lee: *Review and recent advances in battery health monitoring and prognostics technologies for electric vehicle (EV) safety and mobility*. Journal of Power Sources, 256:110 – 124, 2014, ISSN 0378-7753.
- [6] Hill, K. O., Y. Fujii, D. C. Johnson, and B. S. Kawasaki: *Photosensitivity in optical fiber waveguides: Application to reflection filter fabrication*. Applied Physics Letters, 32(10):647–649, 1978.
- [7] Meltz, G., W. W. Morey, and W. H. Glenn: *Formation of Bragg gratings in optical fibers by a transverse holographic method*. Optics Letters, 14(15):823–825, Aug 1989.
- [8] Rao, Yun Jiang: *In-fibre Bragg grating sensors*. Measurement Science and Technology, 8(4):355, 1997.
- [9] Ouellette, François: *All-fiber filter for efficient dispersion compensation*. Optics Letters, 16(5):303–305, Mar 1991.

- [10] Williams, J. A. R., I. Bennion, K. Sugden, and N. J. Doran: *Fibre dispersion compensation using a chirped in-fibre Bragg grating*. Electronics Letters, 30(12):985–987, Jun 1994, ISSN 0013-5194.
- [11] Durkin, M., M. Ibsen, M. J. Cole, and R. I. Laming: *1 m long continuously-written fibre Bragg gratings for combined second- and third-order dispersion compensation*. Electronics Letters, 33(22):1891–1893, Oct 1997, ISSN 0013-5194.
- [12] Li, Hongpu, Yunlong Sheng, Yao Li, and Joshua E. Rothenberg: *Phased-only sampled fiber Bragg gratings for high-channel-count chromatic dispersion compensation*. Journal of Lightwave Technology, 21(9):2074, Sep 2003.
- [13] Ball, G. A. and W. H. Glenn: *Design of a single-mode linear-cavity erbium fiber laser utilizing Bragg reflectors*. Journal of Lightwave Technology, 10(10):1338–1343, Oct 1992, ISSN 0733-8724.
- [14] Ball, G. A. and W. W. Morey: *Compression-tuned single-frequency Bragg grating fiber laser*. Optics Letters, 19(23):1979–1981, Dec 1994.
- [15] Farries, M.C., C.M. Ragdale, and D.C.J. Reid: *Broadband chirped fibre Bragg filters for pump rejection and recycling in erbium doped fibre amplifiers*. Electronics Letters, 28:487–489(2), February 1992, ISSN 0013-5194.
- [16] Kersey, A. D., W. W. Morey, and T. A. Berkoff: *Fiber-optic Bragg grating strain sensor with drift-compensated high-resolution interferometric wavelength-shift detection*. Optics Letters, 18(1):72–74, Jan 1993.
- [17] Xu, M. G., L. Reekie, Y. T. Chow, and J. P. Dakin: *Optical in-fibre grating high pressure sensor*. Electronics Letters, 29(4):398–399, Feb 1993, ISSN 0013-5194.
- [18] Zhang, Ying, Dejun Feng, Zhiguo Liu, Zhuanyun Guo, Xiaoyi Dong, K. S. Chiang, and B. C. B. Chu: *High-sensitivity pressure sensor using a shielded polymer-coated fiber Bragg grating*. IEEE Photonics Technology Letters, 13(6):618–619, June 2001, ISSN 1041-1135.
- [19] Sheng, H. J., Ming Yue Fu, Tzu Chiang Chen, Wen Fung Liu, and Sheau Shong Bor: *A lateral pressure sensor using a fiber Bragg grating*. IEEE Photonics Technology Letters, 16(4):1146–1148, April 2004, ISSN 1041-1135.

- [20] Fomitchov, Pavel and Sridhar Krishnaswamy: *Response of a fiber Bragg grating ultrasonic sensor*. Optical Engineering, 42(4):956–963, 2003.
- [21] Betz, Daniel C, Graham Thursby, Brian Culshaw, and Wieslaw J Staszewski: *Acousto-ultrasonic sensing using fiber Bragg gratings*. Smart Materials and Structures, 12(1):122, 2003.
- [22] Fujisue, Takuma, Kentaro Nakamura, and Sadayuki Ueha: *Demodulation of acoustic signals in fiber Bragg grating ultrasonic sensors using arrayed waveguide gratings*. Japanese Journal of Applied Physics, 45(5S):4577, 2006.
- [23] Tjin, S. C., R. Suresh, and N. Q. Ngo: *Fiber Bragg grating based shear-force sensor: modeling and testing*. Journal of Lightwave Technology, 22(7):1728–1733, July 2004, ISSN 0733-8724.
- [24] Zhao, Yong, Yan Zhao, and Mingguo Zhao: *Novel force sensor based on a couple of fiber Bragg gratings*. Measurement, 38(1):30 – 33, 2005, ISSN 0263-2241.
- [25] Heo, Jin Seok, Jong Ha Chung, and Jung Ju Lee: *Tactile sensor arrays using fiber Bragg grating sensors*. Sensors and Actuators A: Physical, 126(2):312 – 327, 2006, ISSN 0924-4247.
- [26] Berkoff, T. A. and A. D. Kersey: *Experimental demonstration of a fiber Bragg grating accelerometer*. IEEE Photonics Technology Letters, 8(12):1677–1679, Dec 1996, ISSN 1041-1135.
- [27] Jiang, Yi: *Four-element fiber Bragg grating acceleration sensor array*. Optics and Lasers in Engineering, 46(9):695 – 703, 2008, ISSN 0143-8166.
- [28] Kersey, Alan D., Michael J. Marrone, and Kersey: *Fiber Bragg grating high-magnetic-field probe*. Proceedings of SPIE, 2360:53–56, 1994.
- [29] Dai, Jixiang, Minghong Yang, Xiaobing Li, Hongliang Liu, and Xinglin Tong: *Magnetic field sensor based on magnetic fluid clad etched fiber Bragg grating*. Optical Fiber Technology, 17(3):210 – 213, 2011, ISSN 1068-5200.
- [30] Rao, Yun Jiang, D. J. Webb, D. A. Jackson, Lin Zhang, and I. Bennion: *In-fiber Bragg-grating temperature sensor system for medical applications*. Journal of Lightwave Technology, 15(5):779–785, May 1997, ISSN 0733-8724.

- [31] Jung, Jaehoon, Hui Nam, Byoungcho Lee, Jae Oh Byun, and Nam Seong Kim: *Fiber Bragg grating temperature sensor with controllable sensitivity*. Applied Optics, 38(13):2752–2754, May 1999.
- [32] Liu, H.B, H.Y Liu, G.D Peng, and P.L Chu: *Strain and temperature sensor using a combination of polymer and silica fibre Bragg gratings*. Optics Communications, 219(1–6):139 – 142, 2003, ISSN 0030-4018.
- [33] Valis, T., D. Hogg, and R. M. Measures: *Fiber optic Fabry–Perot strain gauge*. IEEE Photonics Technology Letters, 2(3):227–228, March 1990, ISSN 1041-1135.
- [34] Shi, Q., Z. Wang, L. Jin, Y. Li, H. Zhang, F. Lu, G. Kai, and X. Dong: *A hollow-core photonic crystal fiber cavity based multiplexed Fabry–Perot interferometric strain sensor system*. IEEE Photonics Technology Letters, 20(15):1329–1331, Aug 2008, ISSN 1041-1135.
- [35] Zhu, Jiali, Ming Wang, Lu Chen, Xiaoqi Ni, and Haibin Ni: *An optical fiber Fabry–Perot pressure sensor using corrugated diaphragm and angle polished fiber*. Optical Fiber Technology, 34:42 – 46, 2017, ISSN 1068-5200.
- [36] Lu, Z., Y. Jiao, M. Quan, J. Tian, and Y. Yao: *Study on the response speed of Fabry–Perot interferometer gas pressure fiber sensor based on photonic crystal fiber and vernier effect*. In *2016 IEEE Optoelectronics Global Conference (OGC)*, pages 1–3, Sept 2016.
- [37] Fan, Xudong, Ian M. White, Siyka I. Shopova, Hongying Zhu, Jonathan D. Suter, and Yuze Sun: *Sensitive optical biosensors for unlabeled targets: A review*. Analytica Chimica Acta, 620(1–2):8 – 26, 2008, ISSN 0003-2670.
- [38] Nguyen, Linh Viet, Stephen C. Warren-Smith, Heike Ebendorff-Heidepriem, and Tanya M. Monro: *Interferometric high temperature sensor using suspended-core optical fibers*. Optics Express, 24(8):8967–8977, Apr 2016.
- [39] Ma, Y., N. Nguyen-Huu, J. Zhou, H. Maeda, Q. Wu, M. Eldlio, J. Pistora, and M. Cada: *Mach–Zehnder interferometer-based integrated terahertz temperature sensor*. IEEE Journal of Selected Topics in Quantum Electronics, PP(99):1–1, 2017, ISSN 1077-260X.
- [40] Kalli, K., H. L. Dobb, D. J. Webb, K. Carroll, M. Komodromos, C. Themistos, G. D. Peng, Q. Fang, and I. W. Boyd: *Electrically tunable Bragg*

- gratings in single-mode polymer optical fiber*. Optics Letters, 32(3):214–216, Feb 2007.
- [41] Yu, JianMing, XiaoMing Tao, and HwaYaw Tam: *Trans-4-stilbenemethanol-doped photosensitive polymer fibers and gratings*. Optics Letters, 29(2):156–158, Jan 2004.
- [42] Liu, H.Y., H.B. Liu, and G.D. Peng: *Tensile strain characterization of polymer optical fibre Bragg gratings*. Optics Communications, 251(1–3):37 – 43, 2005, ISSN 0030-4018.
- [43] Asseh, A., Sandgren H., Ahlfeldt B., Sahlgren, R. Stubbe, and G. Edwall: *Fiber optical Bragg grating refractometer*. Fiber and Integrated Optics, 17(1):51–62, 1998.
- [44] Pham, B. Thanh, Huy Bui, T. Huu Le, and H. Van Pham: *Characteristics of the fiber laser sensor system based on etched-Bragg grating sensing probe for determination of the low nitrate concentration in water*. Sensors, 17(1):7, 2017, ISSN 1424-8220.
- [45] Kashyap, Raman: *Fiber Bragg Gratings*. Academic Press, 1999.
- [46] Roths, J., G. Andrejevic, R. Kuttler, and M. Süßer: *Calibration of fiber Bragg cryogenic temperature sensors*. In *Optical Fiber Sensors*, page TuE81. Optical Society of America, 2006.
- [47] Villiers, Gerrit J. de, Johan Treurnicht, and Robert T. Dobson: *In-core high temperature measurement using fiber-Bragg gratings for nuclear reactors*. Applied Thermal Engineering, 38:143 – 150, 2012, ISSN 1359-4311.
- [48] Weber, M. J.: *Handbook of Optical Materials*. CRC Press, 2003.
- [49] Liu, H.Y., G.D. Peng, P.L. Chu, Y. Koike, and Y. Watanabe: *Photosensitivity in low-loss perfluoropolymer (CYTOP) fibre material*. Electronics Letters, 37:347–348(1), March 2001, ISSN 0013-5194.
- [50] Liu, H.Y., G.D. Peng, and P.L. Chu: *Thermal stability of gratings in PMMA and CYTOP polymer fibers*. Optics Communications, 204(1–6):151 – 156, 2002, ISSN 0030-4018.

- [51] Tomlinson, W. J., I. P. Kaminow, E. A. Chandross, R. L. Fork, and W. T. Silfvast: *Photoinduced refractive index increase in poly(methylmethacrylate) and its applications*. Applied Physics Letters, 16(12):486–489, 1970.
- [52] Shafee, E.El.: *Effect of photodegradation on the β -relaxation in poly(methylmethacrylate)*. Polymer Degradation and Stability, 53(1):57 – 61, 1996, ISSN 0141-3910.
- [53] Bowden, M. J., E. A. Chandross, and I. P. Kaminow: *Mechanism of the photoinduced refractive index increase in polymethyl methacrylate*. Applied Optics, 13(1):112–117, Jan 1974.
- [54] Kalli, K, H L Dobb, D J Webb, K Carroll, C Themistos, M Komodromos, G D Peng, Q Fang, and I W Boyd: *Development of an electrically tuneable Bragg grating filter in polymer optical fibre operating at 1.55 μ m*. Measurement Science and Technology, 18(10):3155, 2007.
- [55] Jiang, Changhong, Mark G. Kuzyk, Jow Lian Ding, William E. Johns, and David J. Welker: *Fabrication and mechanical behavior of dye-doped polymer optical fiber*. Journal of Applied Physics, 92(1):4–12, 2002.
- [56] Carroll, Karen E, Chi Zhang, David J. Webb, Kyriacos Kalli, Alexander Argyros, and Maryanne C. J. Large: *Thermal response of Bragg gratings in PMMA microstructured optical fibers*. Optics Express, 15(14):8844–8850, Jul 2007.
- [57] Xiong, Z., G. D. Peng, B. Wu, and P. L. Chu: *Highly tunable Bragg gratings in single-mode polymer optical fibers*. IEEE Photonics Technology Letters, 11(3):352–354, March 1999, ISSN 1041-1135.
- [58] Stefani, A., W. Yuan, C. Markos, and O. Bang: *Narrow bandwidth 850-nm fiber Bragg gratings in few-mode polymer optical fibers*. IEEE Photonics Technology Letters, 23(10):660–662, May 2011, ISSN 1041-1135.
- [59] Nam, Sung Hyun, Jae Wook Kang, and Jang Joo Kim: *Tunable polymer waveguide Bragg filter fabricated by direct patterning of UV-curable polymer*. Optics Communications, 266(1):332 – 335, 2006, ISSN 0030-4018.
- [60] Huang, Cheng Sheng and Wei Chih Wang: *SU8 inverted-rib waveguide Bragg grating filter*. Applied Optics, 52(22):5545–5551, Aug 2013.

- [61] Starodumov, A. N., L. A. Zenteno, D. Monzon, and E. De La Rosa: *Fiber Sagnac interferometer temperature sensor*. Applied Physics Letters, 70(1):19–21, 1997.
- [62] Rosa, E. De la, L. A. Zenteno, A. N. Starodumov, and D. Monzon: *All-fiber absolute temperature sensor using an unbalanced high-birefringence loop*. Optics Letters, 22(7):481–483, Apr 1997.
- [63] Choi, Hae Young, Kwan Seob Park, Seong Jun Park, Un Chul Paek, Byeong Ha Lee, and Eun Seo Choi: *Miniature fiber-optic high temperature sensor based on a hybrid structured Fabry–Perot interferometer*. Optics Letters, 33(21):2455–2457, Nov 2008.
- [64] Lee, C. E. and H. F. Taylor: *Fiber-optic Fabry–Perot temperature sensor using a low-coherence light source*. Journal of Lightwave Technology, 9(1):129–134, Jan 1991, ISSN 0733-8724.
- [65] Chen, Yichao and Henry F. Taylor: *Multiplexed fiber Fabry–Perot temperature sensor system using white-light interferometry*. Optics Letters, 27(11):903–905, Jun 2002.
- [66] Geng, Y., X. Li, X. Tan, Y. Deng, and Y. Yu: *High-sensitivity Mach–Zehnder interferometric temperature fiber sensor based on a waist-enlarged fusion bitaper*. IEEE Sensors Journal, 11(11):2891–2894, Nov 2011, ISSN 1530-437X.
- [67] Souza, K. De, G. P. Lees, P. C. Wait, and T. P. Newson: *Diode-pumped Landau–Placzek based distributed temperature sensor utilising an all-fibre Mach–Zehnder interferometer*. Electronics Letters, 32(23):2174–2175, Nov 1996, ISSN 0013-5194.
- [68] Wang, Y., Y. Li, C. Liao, D. N. Wang, M. Yang, and P. Lu: *High-temperature sensing using miniaturized fiber in-line Mach–Zehnder interferometer*. IEEE Photonics Technology Letters, 22(1):39–41, Jan 2010, ISSN 1041-1135.
- [69] Qi, Zhi mei, Shukai Zhao, Fang Chen, and Shanhong Xia: *Integrated Young interferometer sensor with a channel-planar composite waveguide sensing arm*. Optics Letters, 34(14):2213–2215, Jul 2009.
- [70] Dullo, F. T., M. Ingvaldsen, J. Jágerská, S. K. Jacobsen, and O. G. Hellesø: *Temperature sensitivity of a waveguide Young interferometer*. IEEE Photonics Technology Letters, 28(11):1205–1208, June 2016, ISSN 1041-1135.

- [71] Wang, M., J. Hiltunen, C. Liedert, L. Hakalahti, and R. Myllylä: *An integrated Young interferometer based on UV-imprinted polymer waveguides for label-free biosensing applications*. Journal of the European Optical Society - Rapid publications, 7(0), 2012, ISSN 1990-2573.
- [72] Dash, Jitendra Narayan and Rajan Jha: *Mach-Zehnder interferometer based on tapered PCF with an up-tapered joint for curvature, strain and temperature interrogation*. Journal of Optics, 18(10):105002, 2016, ISSN 2040-8986.
- [73] Liu, Nan, Manli Hu, Hao Sun, Tingting Gang, Zaihang Yang, Qiangzhou Rong, and Xueguang Qiao: *A fiber-optic refractometer for humidity measurements using an in-fiber Mach-Zehnder interferometer*. Optics Communications, 367:1–5, 2016, ISSN 0030-4018.
- [74] Bruck, R., E. Melnik, P. Muellner, R. Hainberger, and M. Lämmerhofer: *Integrated polymer-based Mach-Zehnder interferometer label-free streptavidin biosensor compatible with injection molding*. Biosensors and Bioelectronics, 26(9):3832–3837, 2011, ISSN 0956-5663.
- [75] Chalyan, Tatevik, Romain Guider, Laura Pasquardini, Manuela Zanetti, Floris Falke, Erik Schreuder, Rene G. Heideman, Cecilia Pederzoli, and Lorenzo Pavesi: *Asymmetric Mach-Zehnder interferometer based biosensors for aflatoxin M1 detection*. Biosensors, 6(1):1, 2016.
- [76] Li, Chao, Tigang Ning, Chan Zhang, Xiaodong Wen, Jing Li, and Chuanbiao Zhang: *Liquid level and temperature sensor based on an asymmetrical fiber Mach-Zehnder interferometer combined with a fiber Bragg grating*. Optics Communications, 372:196–200, 2016, ISSN 0030-4018.
- [77] Pelletier, N., B. Beche, N. Tahani, L. Camberlein, E. Gaviot, A. Goullet, J. P. Landesman, and J. Zyss: *Integrated Mach-Zehnder interferometer on SU-8 polymer for designing pressure sensors*. In *IEEE Sensors, 2005.*, pages 4 pp.–, Oct 2005.
- [78] Eaton, Shane M., Carmela De Marco, Rebeca Martinez-Vazquez, Roberta Ramponi, Stefano Turri, Giulio Cerullo, and Roberto Osellame: *Femtosecond laser microstructuring for polymeric lab-on-chips*. Journal of Biophotonics, 5(8-9):687–702, 2012, ISSN 1864-0648.

- [79] Sowa, Seiji, Wataru Watanabe, Takayuki Tamaki, Junji Nishii, and Kazuyoshi Itoh: *Symmetric waveguides in poly(methyl methacrylate) fabricated by femtosecond laser pulses*. Optics Express, 14(1):291–297, Jan 2006.
- [80] Zappe, Hans: *Fundamentals of micro-optics*. Cambridge University Press, Cambridge and New York, 2010, ISBN 978-0-521-89542-2.
- [81] Marcatili, E. A. J.: *Dielectric rectangular waveguide and directional coupler for integrated optics*. The Bell System Technical Journal, 48:2071–2102, 1969.
- [82] Okamoto, Katsunari: *Fundamentals of Optical Waveguides*. Elsevier, 2nd edition, 2006.
- [83] Petermann, Klaus: *Properties of optical rib-guides with large cross-section*. AEU-International Journal of Electronics and Communications, 30(3):139–140, 1976.
- [84] Soref, R. A., J. Schmidtchen, and K. Petermann: *Large single-mode rib waveguides in GeSi-Si and Si-on-SiO₂*. IEEE Journal of Quantum Electronics, 27(8):1971–1974, Aug 1991, ISSN 0018-9197.
- [85] Müllner, Paul and Rainer Hainberger: *Single-mode criterion for rib waveguides with small cross sections*. Proceedings of SPIE, 6115:1–8, 2006.
- [86] Xiao, Yanfen, Elke Pichler, Meike Hofmann, Konrad Bethmann, Michael Köhring, Ulrike Willer, and Hans Zappe: *Towards integrated resonant and interferometric sensors in polymer films*. Procedia Technology, 15:691 – 701, 2014, ISSN 2212-0173.
- [87] Erdogan, Turan: *Fiber grating spectra*. Journal of Lightwave Technology, 15(8):1277–1294, Aug 1997, ISSN 0733-8724.
- [88] Sterke, C. Martijn de, N. G. Raphael Broderick, Benjamin J. Eggleton, and M. J. Steel: *Nonlinear optics in fiber gratings*. Optical Fiber Technology, 2(3):253 – 268, 1996, ISSN 1068-5200.
- [89] Born, Max and Emil Wolf: *Principles of optics: electromagnetic theory of propagation, interference and diffraction of light*. Pergamon press, 6th edition, 1980.
- [90] Haus, H. A., W. P. Huang, S. Kawakami, and N. A. Whitaker: *Coupled-mode theory of optical waveguides*. Journal of Lightwave Technology, 5(1), jan 1987.

- [91] Yariv, A. and M. Nakamura: *Periodic structures for integrated optics*. IEEE Journal of Quantum Electronics, 13(4):233–253, April 1977, ISSN 0018-9197.
- [92] Lee, H. J., C. H. Henry, R. F. Kazarinov, and K. J. Orlowsky: *Low loss Bragg reflectors on $\text{SiO}_2\text{-Si}_3\text{N}_4\text{-SiO}_2$ rib waveguides*. Applied Optics, 26(13):2618–2620, Jul 1987.
- [93] Yamamoto, Y., T. Kamiya, and H. Yanai: *Improved coupled mode analysis of corrugated waveguides and lasers*. IEEE Journal of Quantum Electronics, 14(4):245–258, Apr 1978, ISSN 0018-9197.
- [94] Snyder, Allan W.: *Coupled-mode theory for optical fibers*. Journal of the Optical Society of America, 62(11):1267–1277, 1972.
- [95] Yamada, Makoto and Kyohei Sakuda: *Analysis of almost-periodic distributed feedback slab waveguides via a fundamental matrix approach*. Applied Optics, 26(16):3474–3478, Aug 1987.
- [96] Little, Brent E. and W. P. Huang.: *Coupled-mode theory for optical waveguides*. Progress In Electromagnetics Research, 10:217–270, 1995.
- [97] Prabhugoud, Mohanraj and Kara Peters: *Modified transfer matrix formulation for Bragg grating strain sensors*. Journal of Lightwave Technology, 22(10):2302, Oct 2004.
- [98] Sherman, Stanislav and Hans Zappe: *Printable Bragg gratings for polymer-based temperature sensors*. Procedia Technology, 15:702 – 709, 2014, ISSN 2212-0173.
- [99] Kasarova, Stefka Nikolova, Nina Georgieva Sultanova, Christo Dimitrov Ivanov, and Ivan Dechev Nikolov: *Analysis of the dispersion of optical plastic materials*. Optical Materials, 29(11):1481 – 1490, 2007, ISSN 0925-3467.
- [100] Liu, Yun, Wei Peng, Yuzhang Liang, Xinpu Zhang, Xinlei Zhou, and Lujun Pan: *Fiber-optic Mach-Zehnder interferometric sensor for high-sensitivity high temperature measurement*. Optics Communications, 300:194 – 198, 2013, ISSN 0030-4018.
- [101] Ladouceur, Francois and E. Labeye: *A new general approach to optical waveguide path design*. Journal of Lightwave Technology, 13(3):481–492, 1995, ISSN 0733-8724.

- [102] Baets, R. and Lagasse, P. E.: *Loss calculation and design of arbitrarily curved integrated-optic waveguides*. Journal of the Optical Society of America, 73(2):177–182, 1983.
- [103] Mustieles, F. J., E. Ballesteros, and P. Baquero: *Theoretical S-bend profile for optimization of optical waveguide radiation losses*. IEEE Photonics Technology Letters, 5(5):551–553, 1993, ISSN 1041-1135.
- [104] Marcuse, D.: *Bending losses of the asymmetric slab waveguide*. Bell System Technical Journal, 50(8):2551–2563, 1971, ISSN 1538-7305.
- [105] Kumar, Apurva and Sheel Aditya: *Performance of S-bends for integrated-optic waveguides*. Microwave and Optical Technology Letters, 19(4):289–292, 1998, ISSN 1098-2760.
- [106] Gleißner, Uwe, Bilal Khatri, Christof Megnin, Stanislav Sherman, Yanfen Xiao, Meike Hofmann, Axel Günther, Maik Rahlves, Bernhard Roth, Hans Zappe, and Thomas Hanemann: *Optically and rheologically tailored polymers for applications in integrated optics*. Sensors and Actuators A: Physical, 241:224 – 230, 2016, ISSN 0924-4247.
- [107] Studer, Katia, Christian Decker, Erich Beck, and Reinhold Schwalm: *Overcoming oxygen inhibition in UV-curing of acrylate coatings by carbon dioxide inerting, part I*. Progress in Organic Coatings, 48(1):92 – 100, 2003, ISSN 0300-9440.
- [108] Zailer, I., J. E. F. Frost, V. Chabasseur-Molyneux, C. J. B. Ford, and M. Pepper: *Crosslinked PMMA as a high-resolution negative resist for electron beam lithography and applications for physics of low-dimensional structures*. Semiconductor Science and Technology, 11(8):1235, 1996.
- [109] Vieu, C., F. Carcenac, A. Pépin, Y. Chen, M. Mejias, A. Lebib, L. Manin-Ferlazzo, L. Couraud, and H. Launois: *Electron beam lithography: resolution limits and applications*. Applied Surface Science, 164(1–4):111 – 117, 2000, ISSN 0169-4332.
- [110] Eggleton, B. J., P. S. Westbrook, C. A. White, C. Kerbage, R. S. Windeler, and G. L. Burdge: *Cladding-mode-resonances in air-silica microstructure optical fibers*. Journal of Lightwave Technology, 18(8):1084, Aug 2000.

- [111] Chehura, Edmon, Chen Chun Ye, Stephen E. Staines, Stephen W. James, and Ralph P. Tatam: *Characterization of the response of fibre Bragg gratings fabricated in stress and geometrically induced high birefringence fibres to temperature and transverse load*. Smart Materials and Structures, 13(4):888, 2004.
- [112] Xiao, Yanfen, Meike Hofmann, Ziyu Wang, Stanislav Sherman, and Hans Zappe: *Design of all-polymer asymmetric Mach–Zehnder interferometer sensors*. Applied Optics, 55(13):3566–3573, May 2016.
- [113] Emslie, Alfred G., Francis T. Bonner, and Leslie G. Peck: *Flow of a viscous liquid on a rotating disk*. Journal of Applied Physics, 29(5):858–862, 1958.

Author's bibliography

Journal articles

Publications written in the scope of this thesis:

1. Sherman, S. and H. Zappe: *Printable Bragg gratings for polymer-based temperature sensors*. Procedia Technology, 15:702-709, 2014.
2. Gleissner, U., S. Sherman, C. Megnin, H. Zappe and T. Hanemann: *Polymers with customizable optical and rheological properties for printable single-mode waveguides*. Procedia Engineering, 120:3-6, 2015.
3. Hofmann, M., Y. Xiao, S. Sherman, U. Gleissner, T. Schmidt and H. Zappe: *Asymmetric Mach-Zehnder interferometers without an interaction window in polymer foil for refractive index sensing*. Applied Optics 55(5):1124–1131, 2016.
4. Xiao, Y., M. Hofmann, Z. Wang, S. Sherman and H. Zappe: *Design of all-polymer asymmetric Mach-Zehnder interferometer sensors*. Applied Optics, 55(13):3566–3573, 2016.
5. Gleissner, U., B. Khatri, C. Megnin, S. Sherman, Y. Xiao, M. Hofmann, A. Günther, M. Rahlves, B. Roth, H. Zappe and T. Hanemann: *Optically and rheologically tailored polymers for applications in integrated optics*. Sensors and Actuators A: Physical, 241:224-230, 2016.

Publications from other projects:

1. Ruh, D., P. Reith, S. Sherman, M. Theodor, J. Ruhhammer, A. Seifert and H. Zappe: *Stretchable optoelectronic circuits embedded in a polymer network*. Advanced Materials, 26(11):1521-4095, 2014.
2. Ruh, D., S. Subramanian, S. Sherman, J. Ruhhammer, M. Theodor, L. Dirk, K. Foerster, C. Heilmann, F. Beyersdorf, H. Zappe and A. Seifert: *Photonic sensing of arterial distension*. Biomedical Optics Express, 7(9):3230-3246, 2016.

Conference contributions

Conference contributions written in the scope of this thesis:

1. Hofmann, M., Y. Xiao, S. Sherman, T. Schmidt, U. Gleissner, T. Wolfer, C. Müller, T. Hanemann, L. Ovmeyer and H. Zappe: *Printable multi-layer flexible foil system for integrated optical sensors*. Innovative Printed Smart Objects IPSO, (Gardanne, France), 2014.
2. Hofmann, M., Y. Xiao, S. Sherman, P. Bollgruen, T. Schmidt, U. Gleissner and H. Zappe: *Inkjet printed single mode waveguides on hot-embossed foils*. Optical Fabrication, Testing, and Metrology V, Proceedings of SPIE, 9628:1–6, 2015.
3. Xiao, Y., M. Hofmann, S. Sherman, Z. Wang, H. Zappe: *Technology for polymer-based integrated optical interferometric sensors fabricated by hot-embossing and printing*. Semicon China, (Shanghai, China), 2015.
4. Xiao, Y., M. Hofmann, Z. Wang, S. Sherman and H. Zappe: *Integrated all-polymer Mach-Zehnder interferometers without interaction window in asymmetric configuration*. Integrated Optics: Devices, Materials, and Technologies XX, Proceedings of SPIE, 9750, 9750–66, 2016.
5. Sherman, S., Y. Xiao, M. Hofmann, T. Schmidt, U. Gleissner and H. Zappe: *Optical temperature sensing on flexible polymer foils*. Micro-Optics (H. Thienpont, J. Mohr, H. Zappe, and H. Nakajima, eds.), Proceedings of SPIE, 9888, 98880I, 2016.
6. Xiao, Y., M. Hofmann, Z. Wang, S. Sherman, U. Gleissner, and H. Zappe: *Temperature characterization of integrated optical all-polymer Mach-Zehnder interferometers* Micro-Optics (H. Thienpont, J. Mohr, H. Zappe, and H. Nakajima, eds.), Proceedings of SPIE, 9888, 98880F, 2016.
7. Xiao, Y., A. Langenecker, M. Hofmann, S. Sherman, U. Gleissner, C. Mueller and H. Zappe: *Multimode interference structures as sensing elements integrated into Mach-Zehnder interferometers in polymer foils*. Proceedings of SPIE, Advanced Sensor Systems and Applications VII, 10025V:1-10, 2016.

Conference contributions from other projects:

1. Ruh, D., S. Sherman, M. Theodor, J. Ruhhammer, K. Foerster, C. Heilmann, F. Beyersdorf, H. Zappe and A. Seifert: *Determination of vessel wall dynamics*

by optical microsensors. 2012 Annual International Conference of the IEEE Engineering in Medicine and Biology Society, 2359-2362, 2012.

2. Ruh, D., S. Sherman, A. Seifert and H. Zappe: *Optoelectronics on flexible substrates for biomedical applications*. 2012 International Conference on Optical MEMS and Nanophotonics, 186-187, 2012.

Oral presentations

1. Sherman, S. and H. Zappe: *Printable Bragg gratings for polymer-based temperature sensors*. SysInt - 2nd International Conference on System-Integrated Intelligence, Bremen, Germany, 2–4 July 2014.
2. Sherman, S., Y. Xiao, M. Hofmann, T. Schmidt, U. Gleissner and H. Zappe: *Optical temperature sensing on flexible polymer foils*. SPIE Photonics Europe, Brussels, Belgium, 4–7 April 2016.

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