1. Introduction

In the last decade there has been an astounding growth in the data transmission capacity over optical fibers. The majority of this growth is based on the increasing popularity of the internet and its use for a myriad of different applications. These applications, like television or games, triggered the demand for high data rate access to the provided data or content. 100 Mbit/s connections are now available for private households and even over mobile channels data rates in excess of 10 Mbit/s are possible. In order to allow for such high transmission rates in the access networks efficient back bones are necessary. For this task optical communication systems have been proven superior to any other technology. The main advantage of optical transmission systems is the high carrier frequency of ~ 200 THz, which is several orders of magnitude higher than used in microwave based transmission systems (~ 10 GHz). This results in a larger usable bandwidth. Therefore all major telecommunication links are now based on optical technologies.

Several technological breakthroughs mark the development of optical communication systems during the last nearly 50 years [19]. The invention of the laser by Maiman in 1960 [20] was the starting point for the development of the semiconductor laser diodes, which are employed as transmitters in today's fiber optic networks. The use of optical fibers as transmission medium was proposed in 1966 [21] and in 1979 the low predicted losses of 0.2 dB/km at 1550 nm were achieved [22].

An amplification of the optical signals is necessary after approximately every 100 km even with these low loss levels. Until the end of the 1980s this was achieved by optoelectronic repeaters, where the optical signal is first converted into an electrical signal, amplified and then sent again using a laser diode. As this approach works on a per-channel basis such regenerators become quite expensive for transmission systems with several wavelength channels (WDM: wavelength division multiplex). With the invention of the erbium-doped fiber amplifier in 1987 [23] the direct amplification of optical signals without requiring its conversion into the electrical domain was made possible. Such optical amplifiers offer a broad amplification bandwidth (up to 100 nm) and the amplification is independent of the data rate and modulation format. Ultra long haul transmission systems in excess of 10000 km length have been realized with the help of such amplifiers.

There are still electrical components at the beginning and at the end of each optical transmission system. Their maximum modulation frequencies currently limit the data rate in the electrical domain to 40 Gbit/s. In order to go beyond these limits imposed in the electrical domain several multiplexing schemes are used. With the combination of optical time domain multiplexing (OTDM) and polarization multiplexing a transmission at 2.56 TBit/s within a single wavelength channel has been reported [24]. Even higher data rates over a single fiber have been achieved with a wavelength division multiplexing scheme. By using more than 250 wavelength channels, each modulated with 40 Gbit/s, a total transmission capacity of nearly 11 TBit/s has been demonstrated in laboratory experiments [25, 26].

Older fibers still have an absorption peak at 1.4 µm due to OH-contamination. New fabrication methods have eliminated this loss contribution and fibers with losses below 0.3 dB/km from 1300 to 1700 nm are now available [27]. This broad region with low losses results in a usable transmission window in excess of 50 THz. Optical amplification can be achieved in this full wavelength range by the combined use of rare earth doped fiber amplifiers and raman amplification [28].

At the moment the majority of the network management functionality is still realized in the electrical domain. One of the current challenges is to develop components for an all-optical network [29], where routing and switching is implemented in the optical domain. Only a few passive functions can be realized directly in optical fibers. The most notable examples for this are filters based on fiber Bragg gratings or long period gratings. Devices built out of bulk elements with interconnections realized by fibers are both expensive and unstable due to the possibility of misalignment. Therefore, as early as 1969, the concept of *integrated optics* in analogy to the *integrated electronics* was proposed [30]. By the monolithic or hybrid integration of active and passive components onto a common substrate the required functionalities can be realized on a small footprint.

Several material systems are used in the area of integrated optics, for instance silica-on-silicon, silicon on insulator, indium phosphide or polymers. The waveguiding structures are subsequently defined by photolithography and etching processes. In this way, complex planar lightwave circuits of a high quality can be fabricated [31].

The most widely used material for the core of both planar optical waveguides and fibers is germanium-doped silica. A variety of passive components have been realized with this material system. By incorporating active elements like Erbium, active components, e. g. amplifiers or lasers, have been fabricated using germanium-doped silica as host material. In addition to this it exhibits refractive index changes upon irradiation with green/blue or UV light [32, 33]. This photosensitivity is widely used today.

The main application area for UV-induced refractive index changes is the fabrication of fiber Bragg gratings. They are used for a variety of different applications, ranging from channel dropping filters, gain equalization elements, dispersion compensators up to sensors. The task is first to design a spatial grating structure suited for the application under consideration and finally to fabricate it.

The UV-induced refractive index changes can be large enough to form the core of an optical waveguide. Based on this finding the direct writing technique (DWT) was developed by Svalgaard et al. in 1994 [34]. Since then waveguide structures and even complete devices have been realized with this technique. Also different material systems have been probed in order to test their potential as host material for the DWT. The challenge is to find materials in which the desired functionalities can be fabricated with low losses. Another application area of UV-induced refractive index changes is the post processing of optical devices, where either the characteristics or the fabrication yield is improved. Compared to other trimming procedures no cleanroom processes are required nor is there any permanent power consumption during the life time of the device.

The main objective of this work was to investigate the use of UV-induced refractive index changes in the area of optical communication technology. This includes the structuring of planar optical waveguides and fabrication of Bragg gratings. The thesis is structured as follows:

Chapter 2 describes the basic theories about waveguides and Bragg gratings, which are needed for the understanding of this thesis.

Chapter 3 gives a brief overview about the origins of the UV-photosensitivity, which is exploited for the refractive index changes obtained in this thesis. Also explained are techniques for the enhancement of the photosensitivity.

In chapter 4 the measurement techniques for the UV-written waveguide structures and Bragg gratings are presented. The principles behind the methods used are explained and exemplary results are shown.

Chapter 5 forms the main part of this thesis. It is shown how UV-induced refractive index changes can be exploited for the patterning of waveguide structures. The direct writing technique is introduced and results obtained with different material systems are presented. In hydrogen-loaded germanium-doped silica layers straight waveguides, S-bends, directional couplers and multi-mode interference couplers were fabricated and characterized. In one of the tested material systems the UV-irradiation yielded a decrease of the refractive index. For this material system several experiments were performed in order to explain this behavior and the contribution of the different mechanisms involved will be discussed. The fabrication of waveguide structures by UV-induced refractive index changes is not limited to layered material systems. Results obtained with different multicomponent silicate glasses are reported and a specially developed writing technique for the realization of buried channel waveguides in bulk materials is presented. At the end of this chapter the use of UV-induced refractive index changes for the post processing of optical devices is shown.

Chapter 6 deals with the design and fabrication of Bragg gratings in optical waveguides. Three different approaches for the design of low-dispersion Bragg gratings are presented and the results obtained with them are compared. By using a holographic writing setup these designs are afterwards written in optical fibers and planar waveguides. The measured transmission and reflection properties are compared with the required specifications and possible origins for discrepancies are discussed.

The results obtained within the framework of this thesis are summarized in chapter 7. In addition an outlook regarding possible future work is given.

2. Waveguide and Bragg grating theory

In this chapter the necessary theoretical background for the understanding of the propagation of electromagnetic waves in single waveguides and coupled waveguide structures will be presented. From the refractive index distribution of waveguides it is possible to obtain the propagating mode fields. These mode fields make the calculation of coupling losses between different waveguides possible. The coupling of modes will be explained for the the special cases of directional couplers and Bragg gratings. For the latter the transfer matrix method will be presented as a fast method used for the calculation of reflection and transmission spectra for Bragg gratings with arbitrary coupling coefficients.

2.1. Optical waveguide theory

In homogeneous media ($\nabla\varepsilon = 0$) electromagnetic waves obey the wave equation

$$\left[\nabla^2 - \mu\varepsilon\frac{\partial^2}{\partial t^2}\right]\tilde{\mathbf{E}}(x, y, z, t) = 0 \tag{2.1}$$

which follows directly from Maxwell's equations. $\mu = \mu_r\mu_0$ and $\varepsilon = \varepsilon_r\varepsilon_0$ represent the permeability and dielectric constant of the material. For all the materials inside this thesis they are assumed to be scalar values (isotropic material). Furthermore no sources ($\nabla \cdot \tilde{\mathbf{E}} = 0$) are present.

For monochromatic waves the following ansatz $\tilde{\mathbf{E}}(x, y, z, t) = \mathbf{E}(x, y, z)e^{j\omega t}$ can be made in order to transform the wave equation into the Helmholtz equation.

$$\left[\nabla^2 - \omega^2\mu\varepsilon\right]\mathbf{E}(x, y, z) = 0 \tag{2.2}$$

Solutions of this equation which propagate along the longitudinal z direction as $\exp(-j\beta z)$ are called modes and β is the corresponding propagation constant.

For weakly guiding waveguides such as fibers or UV-written waveguides, the field is linearly polarized as $\mathbf{E} \simeq \hat{\mathbf{s}}\psi(x, y)$, where $\hat{\mathbf{s}}$ is a unit vector in the (x, y) plane transverse to the propagation direction of the waveguide. For a waveguide with a transverse refractive index profile $n(x, y)$, the scalar mode field $\psi(x, y)$ obeys the wave equation,

$$\frac{\partial^2 \psi}{\partial x^2} + \frac{\partial^2 \psi}{\partial y^2} + \left[k^2 n^2(x, y) - \beta^2\right] \psi = 0, \tag{2.3}$$

where $k = 2\pi/\lambda$, and λ is the wavelength.

The solutions $\psi(x, y)$ of eq. (2.3) depend on the transverse refractive index profile $n(x, y)$. For a circularly symmetric step-index fiber the solutions can be given in terms of Bessel functions J_m and K_m. In particular the fundamental mode is given by

$$\psi_{01}(x, y) = \begin{cases} \frac{J_0(U_{01} r/\rho)}{J_0(U_{01})} & 0 < r = \sqrt{x^2 + y^2} < \rho \\ \frac{K_0(W_{01} r/\rho)}{K_0(W_{01})} & \rho < r < \infty. \end{cases} \tag{2.4}$$

with $U_{01} = \rho\sqrt{k^2 n_1^2 - \beta_{01}^2}$ and $W_{01} = \rho\sqrt{\beta_{01}^2 - k^2 n_2^2}$.

For non-circular waveguides such as UV-written channel waveguides, the field of the fundamental mode can be well approximated by a two-dimensional Gaussian function,

$$\psi_{01}(x, y) = \exp\left\{-\left(\frac{x^2}{w_x^2} + \frac{y^2}{w_y^2}\right)\right\}. \tag{2.5}$$

A more detailed analysis of the modes of UV-written waveguides is given in [35]. For circular fibers the Gaussian approximation is also applicable and the mode spot sizes w_x and w_y are equal.

The knowledge of the mode fields ψ_1 and ψ_2 of two waveguides 1 and 2 allows for the estimation of the transition loss at the connection of the two waveguides. It follows from the field overlap integral

$$\eta = \frac{\left(\int\int \psi_1 \psi_2 \,\mathrm{d}x\,\mathrm{d}y\right)^2}{\int\int \psi_1^2 \,\mathrm{d}x\,\mathrm{d}y \int\int \psi_2^2 \,\mathrm{d}x\,\mathrm{d}y}. \tag{2.6}$$

The coupling efficiency η between a circular fiber with $w_x = w_y = w_0$ and a waveguide with spot sizes w_x and w_y follows from eq. (2.5) and (2.6) as

$$\eta = \frac{4 w_0^2 w_x w_y}{(w_0^2 + w_x^2)(w_0^2 + w_y^2)}. \tag{2.7}$$

This formula will be used later for the calculation of coupling losses between a fiber and the UV-written waveguides. These losses are obviously smaller the closer w_x and w_y are to w_0. Differences of the field radii up to 20 % (in both dimensions), however, only result in an insertion loss of 0.2 dB.

Knowledge of the fundamental mode field also enables the calculation of the form birefringence

$$B = \frac{\beta_x - \beta_y}{k} = n_{\mathrm{eff},x} - n_{\mathrm{eff},y}, \tag{2.8}$$

i. e. the difference of the propagation constants between the two orthogonally polarized states of the fundamental mode. Form birefringence occurs if the waveguide geometries along the x and y dimensions are different. In a circular fiber and all other waveguides with $w_x = w_y$, there is no form birefringence. Using a perturbation method and the Gaussian field approximation eq. (2.5), the form birefringence can be approximated by [36]

$$B = \frac{1}{2k^4 n_{\mathrm{cl}}^3} \left(\frac{1}{w_y^4} - \frac{1}{w_x^4} \right). \tag{2.9}$$

with n_{cl} as the refractive index of the waveguide cladding [36].

It should be noted that the total birefringence is composed of an amount of form birefringence and an amount caused by material anisotropy such as stress birefringence in systems of materials with different thermal expansion coefficients.

2.2. Coupled mode theory

For the case of unperturbed waveguides as discussed above no interaction between different propagating modes takes place. This situation is different if there is a periodic dielectric perturbation. In such cases a power exchange between different modes is possible. The amount of coupling depends on the difference between the propagation constants of the participating modes as well as on the strength of the coupling effect [37].

2.2.1. Directional couplers

The layout of a directional coupler is shown in Fig. 5.10. If the distance between the two parallel waveguides is small enough, optical energy can be transferred