Electro-optically tunable microring resonators in fluorine-implanted lithium niobate

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ELECTRO-OPTICALLY TUNABLE MICRORING RESONATORS IN FLUORINE-IMPLANTED LITHIUM NIOBATE

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Microscopic cavities in the uncovered amorphised LiNbO$_3$ layer.
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Abstract

The field of optical microresonators has lately been a subject of intensive research as these devices promise to become a key element of future integrated photonics. Their use has been tested in a variety of applications such as filtering, combining and processing of optical signals, high-sensitivity biochemical sensing and nonlinear frequency conversion. A small footprint and planar geometry make microring resonators suitable for low-cost, high-density fabrication relying on current micro fabrication technologies. The research so far has been focused mainly on polymer and semiconductor materials. Polymers have the advantage of allowing great design flexibility and being easily processable, but they have low refractive index and are still plagued with photo- and chemical-stability problems. In semiconductors, the use of silicon on insulator is vigorously investigated, supported by vast expertise from microelectronics technologies. Lacking electro-optical activity, different approaches for active control of such devices are being pursued.

Inorganic ferroelectric oxide crystals possess properties that make them suitable for the optical microring resonators. They are inherently stable and exhibit large linear electro-optical and nonlinear optical effects. The former effect enables ultrafast resonance tuning while the latter can be used for efficient frequency conversion in the resonating ring. Among the ferroelectrics, lithium niobate is the most suitable material as it is widely available and already extensively used in a variety of bulk and guided wave applications. Practically useful ring resonators need a free spectral range of at least a few nm. Therefore, they need a high refractive index contrast in order to suppress the radiation losses, inevitable in small-radius microrings. Conventional techniques of waveguide fabrication in lithium niobate are not adequate for microring waveguides, because of a too-low index contrast ($\Delta n < 0.1$). In recent years it was discovered that the implantation with high-energy medium mass ions (swift-heavy ions) in lithium niobate can generate a buried optical barrier with an increased index contrast of $\Delta n = 0.17$ at $\lambda = 1.5 \mu$m. In this thesis, we have successfully imple-
mented the swift-heavy ion implantation technique in the design and fabrication of electro-optically controllable microring resonators in lithium niobate.

Our study begins with a theoretical discussion of the swift-heavy ion implantation and a summary of the most important physical relations in microring resonators. The mechanism causing crystal amorphisation is the lattice defect generation and eventual meltdown along the ion track, due to electronic excitation energy from the passing ion. We begin our device design by selecting fluorine as the implantation ion. Our study then focuses on optimisation of implantation parameters that give the optimal width and position of the amorphisation layer, yielding low-loss, strongly confining, single-mode optical waveguides, suitable for microring resonators. Finally, the microrings are structured on the implanted samples using the laser lithography and sputtering. The produced microresonators with ring radii $R = 80 \mu m$ exhibit a free spectral range of 2 nm, a finesse of 4 and an extinction ratio of 14 dB. With the application of a buffer layer and electrodes, we can control the transmission spectrum of these devices by the electro-optic effect. In case of a standard silicon dioxide buffer, the microrings show tunability of 3.3 pm/V. The introduction of a new material, high dielectric constant polyvinyl alcohol, enhances the electro-optical tunability to 10 pm/V. As we show, low-voltage optical amplitude modulation is possible with such devices.

The presented study shows that swift-heavy ion implantation can be a suitable method for the fabrication of optical microring resonators in lithium niobate. In further improving the devices, larger free spectral range, up to about 4 nm, is immediately possible by further shrinkage of the ring radii, and a higher finesse could be obtained by better structuring, particularly of the coupling region. Finally, for an even increased tunability we propose and evaluate the use of directly applied semitransparent electrodes.

In the Appendices, the results of the parallel projects are presented. In Appendix A we demonstrate the fabrication of planar waveguides in BiB$_2$O$_6$ and KNbO$_3$ by fluorine ion implantation. In both materials, the produced planar waveguides are optically isolated from the substrate by an optical barrier, generated by the nuclear stopping power at the end of the implanted ion’s track.
Additionally in BiB₃O₆, the implantation induces an increase of the refractive index in the region where electronic stopping power is dominant.

Appendix B describes a broadband fluorescence source consisting of a channel waveguide in Cr:LiSrAlF₆ material, optically pumped by a red laser diode at 660 nm. Cr:LiSrAlF₆ is a fluorescent crystal with a wide emission band in the near infrared and a wide absorption band in the visible wavelength range. As such, it is an alternative near-infrared source to Ti:sapphire laser, with a more convenient red laser diode optical pumping. The first-time demonstrated channel waveguides in Cr:LiSrAlF₆ are produced by low-temperature (100 K) helium ion implantation, followed by photolithographic surface structuring. The finalised devices emit fluorescence with a continuous-wave power of 13 μW and a wide emission bandwidth of 140 nm, which is among the largest in continuous-wave sources.
Zusammenfassung


trasts ($\Delta n < 0.1$), nicht geeignet für Mikroringwellenleiter. In den letzten Jahren wurde entdeckt, dass die Implantation von Lithiumniobat mit mittelschweren Ionen eine eingebettete optische Barriere mit einem erhöhten Indexkontrast von $\Delta n = 0.17$ bei $\lambda = 1.5 \mu m$ erzeugen kann. In dieser Doktorarbeit haben wir erfolgreich die Implantation mit mittelschweren Ionen für die Fabrication von elektrooptisch kontrollierbaren Mikroringresonatoren in Lithiumniobat verwendet.


Die vorliegende Studie zeigt, dass die Implantation mit mittelschweren Ionen eine adäquate Methode für die Herstellung von optischen Mikroringresonatoren in Lithiumniobat ist. Für eine weitere Verbesserung der Geräte ist ein grösserer freier Spektralbereich, bis zu ca. 4 nm, durch eine Verkleinerung der Ringradien, sofort möglich. Eine höhere Finesse kann durch eine bessere Strukturierung, insbesondere dem Kopplungsbereich, erreicht werden. Schliesslich,
für eine noch höhere Tunabilität evaluieren wir und schlagen wir die Anwendung der direkt applizierten halbtransparenten Elektroden vor.


Chapter 1

Introduction

1.1 Introduction to optical microring resonators

Optical microrings are optical cavities of micrometer size that can resonantly confine light. Exhibiting optical confinement in the same way as standard optical waveguides, a fundamental property of microring resonators is their specific spectral response; light can be stored in a microring only at certain discrete frequency values, specified by a constructive interference of the light circulating within the resonator. This frequency-dependent spectrum can be exploited for different applications [1, 2], such as on/off switching and add/drop-filtering in wavelength division multiplexed (WDM) telecommunication systems. Moreover, the resonant light enhancement in the cavity enables novel types of laser devices [3-5]. If the resonances are sufficiently narrow, the transmitted intensity can be very sensitive to externally induced perturbations of the microring effective index, which makes these devices potentially useful in sensing applications [6-8]. The use of nonlinear optical or electro-optical materials will further extend the range of microresonator applications. Non centro-symmetric materials exhibiting first order nonlinear effects could be employed for more efficient frequency conversion processes [9, 10].

Optical fibres and modulators form the backbone of the present-day long-distance and local area telecommunication networks. Their advantage over the classical electrical transmission lines lie in very high achievable modulation frequencies of 100 GHz and more, further extended with wavelength division multiplexing. As the optical data transmission is expected to be employed at ever lower levels, ranging from rack-to-rack to chip-to-chip and intra-chip
communication, the size of the related optical devices must accordingly shrink. A typical present-day optical modulator, the Mach-Zehnder interferometer, has a size of a few cm, unacceptably large for integrated photonic circuits. On the other hand, a microring resonator can span only a couple of tens of micrometer in diameter. The very small dimension of the microrings is their major advantage since it enables the integration of a large number of devices on high-density optical circuits foreseen for very large scale integrated (VLSI) photonics.

Making the cavity controllable by exploitation of some physical effects is of fundamental importance, since this allows dynamical tuning of the resonator spectral response. The utilized effects and materials are briefly enumerated in Chapters 4 and 5. Among them, electro-optical tuning allows a direct control and has an advantage of being extremely fast (about 1ps time response). In present-day technologies, lithium niobate is the most common substrate for the waveguide-based devices utilising electro-optical effects. It is therefore self-evident that the different possible routes of fabricating optical microrings out of lithium niobate pose a strong incentive for further research. In this respect, the subject of this work is the exploitation of the swift-heavy ion implantation for the fabrication of low-loss, strongly confining optical waveguides in lithium niobate out of which the electro-optically tunable microring resonators are finally fabricated.

1.2 Outline of this thesis

After we have positioned this work within the general context of the integrated optics research, we present in Chapter 2 two theoretical models that describe the physical situation in the target substrate upon the swift-heavy ion implantation. This type of implantation is our principal technique for the fabrication of planar waveguides in lithium niobate that form the base of our microring resonators. We conclude the theoretical part with a brief description of the basic optical properties of microresonators and lithium niobate crystal (Chapter 3). Having been equipped with the basic theoretical understanding, we present in Chapter 4 the actual design and fabrication of microring resonators in lithium niobate. As next, the fabrication of active, electro-optically tunable microresonators, employing a new polyvinyl alcohol cladding (Chapter 5) and a standard
silicone dioxide cladding (Chapter 6) is shown. We conclude with suggestions for possible future improvements of the device. The results of the parallel projects, namely the waveguide fabrication in BiB₃O₆ and KNbO₃ by fluorine ion implantation and the fabrication of a broadband fluorescence source in Cr:LiSrAlF₆, are presented in the Appendices.
Chapter 2

Ion implantation

Ion implantation is a universal technique for changing the composition of the surface layer in several materials and as such it is used for producing optical waveguides in many key optical materials [11]. Planar and channel waveguides in inorganic crystals KNbO$_3$ [12], Cr:LiSrAlF$_6$ [13], $\beta$-BaB$_2$O$_4$ [14, 15], Sn$_2$P$_2$S$_6$ [16] as well as in organic crystal DAST [17], all produced by light-ion implantation, have been a subject of continuing research in our laboratory. Implantation with heavier ions has gained attention recently, as it can produce strongly confined optical waveguides at lower implantation fluences [18]. We have used this method for producing optical waveguides in LiNbO$_3$.

In passing through matter, the kinetic energy of the impinging ion is coupled into the target material by the following processes: (1a) inelastic scattering from bound electrons of the target, which leads to ionisation of the target atoms, (1b) elastic scattering from bound electrons, (2a) inelastic collisions with target nuclei, resulting in excitations or nuclear reactions, and (2b) elastic collisions with more or less screened nuclei where part of the ion energy is transmitted to kinetic energy of the nuclei, leading eventually to their displacement. The rate of energy transfer for each process depends on the kinetic energy, nuclear charge and mass of the incoming ion, as well as on the target material.

2.1 Light ion implantation

For light ions such as H$^+$ and He$^+$ and energy range of about 1 to 4 MeV the two main occurring ion-target interaction processes are electronic ionisation
(1a) and elastic nuclear collisions (2b). While the former process is dominant at high velocity (ion energy > 10 keV) and generally accounts for more than 99% of the ion energy loss, it generally thermalises during the bombardment and therefore does not alter the substrate significantly. On the other hand, nuclear collisions peak at the end of the ion track, inducing there partial amorphisation that leads to a local decrease of the refractive index and hence to a buried optical barrier. Figure 2.1 shows the electronic- ($S_e$) and nuclear- ($S_n$) energy loss of 2.4 MeV He$^+$ ions implanted into Cr:LiSrAlF$_6$ crystal, calculated with SRIM-2003 simulation software (Stopping and Range of Ions in Matter [19]). Even though that the maximal nuclear energy loss is about 30 times smaller than the electronic energy loss, nuclear damage predominantly defines the refractive index profile. This can be seen by comparing the calculated $S_e$ and $S_n$ curves with experimentally determined refractive index profile in implanted Cr:LiSrAlF$_6$ (see Figure B.3 in Appendix B).

![Figure 2.1: Energy loss of 2.4 MeV He$^+$ ions in Cr:LiSrAlF$_6$ due to electronic ionisation (left scale) and nuclear collisions (right scale). Calculated with SRIM-2003 software.](image)

One of the main advantages of light ion implantation is its flexibility. In general, the barrier position in a particular material is set by the energy of the implanting ions, while implantation fluence (number of ions/cm$^2$) defines the barrier width and index contrast. This flexibility is of great importance in designing the waveguides according to specific needs of the intended application. We have
used He$^+$ implantation for the fabrication of optical waveguides in Cr:LiSrAlF$_6$ crystals, as presented in Appendix B.

### 2.2 Swift heavy ion implantation

For high-energy medium mass ions (swift heavy ions) incident on a crystalline material, the electronic ionisation can no longer thermalise without affecting the target material. Instead, the passage of an ion can create lattice defects or even local meltdown, which leads to amorphous tracks along the ion trajectory [20]. At fluences where an overlapping of individual tracks occurs, a homogeneous amorphous layer can be generated [18, 21]. This amorphous layer can expand upon further increasing the fluence [22]. Many theoretical models have been applied to explain the above-stated observations. Among them, we use here two models [23] that best match the experimental results.

The general theoretical framework of the involved physical processes is shown on Figure 2.2. The incident swift heavy ion losses its kinetic energy primarily due to inelastic scattering on bound electrons of the target atoms. The energy deposited by the passing ion, proportional to electronic energy loss (electronic stopping power) $S_e$ generates an excited electron cloud along the ion trajectory. Subsequently, this energy is transferred to the target ionic lattice, eventually leading to creation of defects. Two main processes occur during the thermalisation of the excited electron cloud: (a) energy transfer to the crystal lattice (phonon creation), (b) localization of the excitation energy as trapped excitons and finally recombination of these excitons. Exciton recombination leads to light emission (radiative recombination), atomic displacement or phonon creation (heating). The two latter non-radiative processes add to the permanent defect generation. Within this general scheme, one may consider two different alternative mechanisms that account for defect formation. One is the directly thermally induced (channel (a), i.e. thermal heating and subsequent quenching). This corresponds to a thermal spike model briefly explained in Section 2.2.1. The other mechanism is through exciton formation and non-radiative decay (channel (b)), explained in Section 2.2.2.
2.2.1 Thermally induced generation of defects – thermal spike model

The thermal spike model [24] gives qualitatively good agreement with the experiments, while it has the advantage of not requiring a detailed formulation of the electron and ion dynamics after irradiation that account for the heat transport processes. During the implantation the impinging ion transfers an energy $S_e(z)$ per unit length, $z$ being the depth coordinate, to the electron system of the substrate. A part of this energy, $\eta S_e$, is then rapidly passed onto the ionic lattice,
with an efficiency factor $\eta < 1$ independent of $S_e$. A high-temperature (of the phonon system) region is thus formed in the substrate in a cylinder around the ion trajectory. If the temperature in this region exceeds the melting point of the crystal, a melt is formed. Due to small diameter of the heated ion track cylinder, its cooling rate may reach $10^{13} - 10^{14}$ K/s resulting in amorphous structure when the melt rapidly solidifies. The thermal spike model approximates the temperature in the cooling spike with a Gaussian distribution:

$$T(z, r, t) = \frac{a_0^2 \Delta T(z, 0, 0)}{a^2(t)} \exp\left\{ -r^2 / a^2(t) \right\} + T_s,$$  \hspace{1cm} (2.1)

Where $a_0 = a(t=0)$ is the initial width of the Gaussian distribution and $T_s$ is the substrate temperature. The initial temperature rise $\Delta T(z, 0, 0)$ at the spike axis is obtained from the energy balance

$$\Delta T(z, 0, 0) = \frac{\eta S_e(z)}{\pi a_0^2 \rho C},$$  \hspace{1cm} (2.2)

with $\eta S_e(z)$ the energy deposited in thermal spike at the depth $z$ and $C$ and $\rho$ the mean specific heat and the density of the substrate, respectively. The time evolution of the profile width is obtained from solving the heat conduction equation

$$a^2(t) = a_0^2 + \frac{4K}{\rho C} t, \hspace{1cm} (2.3)$$

where $K$ is the thermal conductivity. The maximal temperature increase for any $t > 0$ at a given distance $r$ from the impact axis centre follows from the time evolution of the temperature Gaussian profile [24, 25]:

$$\Delta T_{\text{max}}(z, r, t) = \frac{\eta S_e(z)}{\pi a_0^2 \rho C} e^{-r^2 / a_0^2}, 0 < r < a_0, \hspace{1cm} (2.4)$$

$$\Delta T_{\text{max}}(z, r, t) = \frac{\eta S_e(z)}{\pi \rho C} \frac{1}{r^2}, r \geq a_0.$$  

The maximum temperature is reached at the track axis: $\Delta T_{\text{max}} = \Delta T(z, 0, 0)$. Putting $\Delta T_{\text{max}} = \Delta T_m = T_m - T_s$ in Equation 2.2, with $T_m$ as the melting temperature of
the crystal, the electronic stopping power $S_m$ needed to start the melting of the ion track can be estimated:

$$S_m = \frac{\pi a_0^2 \rho C \Delta T_m}{\eta}. \quad (2.5)$$

The parameters $\rho$, $C$ and $T_m$ are known material constants (see Table 3.1 in Section 3.3). $\eta$ and calculated $S_m = 4.2-12.5$ KeV/nm close to the experimentally determined values of around 5.2 KeV/nm [28]. By selecting $\Delta T_{\text{max}} = \Delta T_m$ in Equations 2.4, the radius of the melted region around the ion track can be calculated

$$R_m^2 = r^2 \left( \Delta T_m \right) = a_0^2 \ln \left( S_e / S_m \right) \text{ for } 0 \leq R_m^2 \leq a_0^2, \ (1 \leq S_e / S_m \leq e), \quad (2.6)$$

$$R_m^2 = \frac{a_0^2}{e} \left( \frac{S_e}{S_m} \right) \text{ for } R_m^2 > a_0^2, \ (e < S_e / S_m).$$

![Figure 2.3: Schematical representation of an amorphous track along the bombarding ion trajectory. Ratio of electronic stopping power to threshold stopping power $S_e(z)/S_m$ (upper graph). Radius of the melted region $R_m$, preamorphised region is also shown (lower graph).](image)

At any depth $z$ in the implanted substrate, the radius of the melted cylinder around the ion track is determined by the ratio between the electronic stopping
powers $S_c(z)$ and $S_m$ as schematically shown on Figure 2.3. During the irradiation, when a critical fluence corresponding to overlapping of amorphous tracks at the maximum of the electronic stopping power ($S_c(z_0) = S_{c,max}$) is achieved, a homogeneous amorphous layer is formed at $z_0$. Upon further increasing fluence, the model predicts a build up of the amorphous layer where $S_c \geq S_m$.

The experimentally observed generation and growth of the amorphous layer in the region with $S_c \leq S_m$ suggests that the amorphisation threshold decreases with increasing fluence. Even when the passage of a swift ion does not cause a local meltdown along the track, it always induces defects that, due to fast quenching, remain frozen in the substrate. Since the electronic damage from successive irradiations is cumulative [27], the defect concentration may become very high and generate a severely damaged, so-called preamorphised region in the substrate (see Figure 2.3). Consequently, the amorphisation threshold is decreased. The total number of defects per unit length $g_{def}(S_c)$, generated (at a given depth $z$) by a single ion impact, depends exponentially on $S_c(z)$. The average defect concentration $\bar{c}$ at depth $z$ is

$$\bar{c}(\phi, z) = g_{def} \left\{ S_c(z) \right\} \phi,$$

(2.7)

with $\phi$ being the fluence of the implantation. Finally, the threshold electronic stopping power in an already irradiated material is a function of the average defect concentration irradiation fluence

$$S_{th}(\phi, S_c) = S_{th}\left(\bar{c}(\phi, S_c(z))\right).$$

(2.8)

In absence of any previous irradiation $\bar{c}(\phi = 0, z) = 0$ and $S_{th}(0, S_c) = S_m$. A detailed theoretical derivation of $S_{th}(\phi, S_c)$ is presented [28]. By replacing $S_c$ by the stopping power curve $S_c(z)$ of the bombarding ion, simulated by SRIM-2003 simulation software, the thickness of the amorphisation layer after a fluence $\phi$ can be calculated by from $S_{th}[\phi, S_c(z)] = S_c(z)$.

2.2.2 Non-radiative exciton decay model

This model is based on the experimentally observed phenomena of lattice defect creation by nonradiative decay of localised excitons [29]. In LiNbO$_3$, as in many other materials, self-trapped excitons are created by the ionizing radia-
tion. In fact, a blue intrinsic luminescence band at 450 nm, observed also during our ion implantations, has been associated to electron-hole recombination at regular niobate groups [30]. The exciton decay model proposes that point defects are created via nonradiative decay of these self-trapped excitons. The theoretical scheme behind the model is presented here briefly, it is described in detail in [31].

During the thermalisation of the free electrons (see Figure 2.2) bound electron-hole pairs (excitons) are formed which become homogeneously localized (self-trapped) in the crystal lattice. An estimated total number of electron-hole pairs created by $S$, is $S/\varepsilon$, $\varepsilon$ being an effective ionization energy about 2–3 times the band-gap energy [29, 32]. Finally, excitons decay via either light emission or nonradiative recombination, generating phonons or lattice displacement. The latter can be enhanced by phonon energy from the thermal spike. A schematic exciton energy level diagram is illustrated in Figure 2.4.

![Figure 2.4: Schematic energy level diagram of a self-trapped exciton, from [31]. The energy $E$ of ground and excited electronic states as a function of configurational coordinate $Q$ are shown. If the electron overcomes the energy barrier $\varepsilon$, a lattice defect is created.](image)

It shows the adiabatic potential energy curves for the ground and excited electronic states as a function of an effective configurational coordinate of the target ion. The excited level leads to atom displacement and Frenkel pair formation if the excited electron overcomes an energy barrier $\varepsilon$ for nonradiative exci-
ton decay. The high temperature reached in the spike provides the kinetic energy needed to overcome this barrier, enhancing thereby the defect generation.

The growth rate of the volume density of defects \( u_D(r, z) \) in the track, generated by nonradiative exciton decay, obeys the rate equation

\[
\frac{du_D(r, z)}{dt} = -\frac{du_{\text{exc}}(r, z)}{dt} = v_0 u_{\text{exc}} \exp\{-e / kT\},
\]

where \( v_0 \) is a frequency factor and \( u_{\text{exc}} \) is the corresponding exciton density. The integration of Equation 2.9 is manageable only under several rough approximations. It is assumed that the thermal activation factor is determined by the maximum local temperature reached during the thermal spike \( T_{\text{max}}(r, S_e) = \Delta T_{\text{max}}(r, S_e) + T_S \), with \( \Delta T_{\text{max}} \) given by Equation 2.2. During track cooling, each point in the ion track (regardless of position) remains at that maximum temperature for the same time period \( \tau \), (in the order of \( 10^{-11} \) s), to stimulate the nonradiative relaxation of the excitons. This assumption is justified by the simulations of the thermal spike time evolution [33]. Afterwards the exciton relaxation proceeds via light emission, with radiative lifetimes on the order of \( 10^{-5} \) s. Taking into account these assumptions, the volume density of defects generated by one ion track is

\[
u_D(r, z) = \int_{0}^{\infty} v_0 u_{\text{exc}} e^{-e / kT} dt = v_0 u_{\text{exc}} e^{-e / kT_{\text{max}}(r, S_e)} \cdot \tau
\]

For simplicity, a constant radial exciton density in the ion track is assumed

\[
\begin{align*}
    u_{\text{exc}}(r, z) &= \frac{S_e(z)}{L\pi a_0^2} & \text{for } r \leq a_0, \\
    u_{\text{exc}}(r, z) &= 0 & \text{for } r > a_0.
\end{align*}
\]

Then, the total number of defects generated by a single ion impact and unit length can be numerically integrated:

\[
g_{\text{exc}}(S_e) = \int_{0}^{\infty} 2\pi r S_e \frac{v_0}{L\pi a_0^2} e^{-e / kT_{\text{max}}(r, S_e)} dr.
\]

25
The average concentration of defects due to implantation with fluence $\phi$ is

$$\bar{c}(\phi, z) = g_{\text{exc}} \left\{ S_e(z) \right\} \phi. \quad (2.13)$$

This averaged defect concentration can be finally inserted in Equation 2.8, which gives the final fluence-dependent threshold stopping power.

In both models, the calculation of the average defect concentration is relatively difficult. To a first approximation that sufficed for our experimental work, we estimated the thickness of the amorphous layer by equating $S_{\text{th,exp}}(\phi) = S_e(z)$ on both sides of the $S_e(z)$ curve, calculated with SRIM software. The $S_{\text{th,exp}}(\phi)$ was determined by measuring the thickness of the planar waveguides implanted with fluence $\phi$. The procedure is described in Sections 4.2.1 and 4.2.2.
Chapter 3

Introduction to electro-optic microring resonators

3.1 Basic principles of optical microring resonators

In this Chapter we briefly describe how ring-like resonators work and present a short summary of the most important physical quantities used for their description. A more detailed treatment of the topic can be found in Refs. 34-37. Detailed descriptions of the optical wave propagation in straight and bent waveguides and of the accompanying radiation losses are given in [38-40]. A basic ring resonator consists of a ring- and a bus- waveguide. The ring represents a closed loop waveguide with an optical feedback in which certain discrete wavelengths can resonate. The bus waveguide is placed in close proximity of the ring to couple light into it by means of evanescent coupling between the waves propagating in both waveguides. The model describing the ring resonator is schematically shown on Figure 3.1, where $E_i$ is the input electrical field of the propagating optical wave, $E_t$ the electrical field of the transmitted optical wave, $\kappa$ is the field coupling coefficient between the bus waveguide and the ring and $\tau$ is the field transmission coefficient across the coupling region. For lossless coupling, the relation $|\tau|^2 + |\kappa|^2 = 1$ is valid. In a microring resonator with a radius $R$, the round-trip phase contribution of the optical wave is $\Phi = (2\pi/\lambda)N_{\text{eff}}L$, where $L = 2\pi R$ is the circumference of the ring, $\lambda$ is the light wavelength and $N_{\text{eff}}$ is the effective index of the guided mode.
After one round trip the amplitude of the electric field in the resonator is reduced by $\sigma = e^{-\alpha L}$, where $\alpha$ is the power loss in the ring per unit length. The electric field of the transmitted optical wave is expressed with

$$\frac{E_t}{E_i} = \frac{\tau - \sigma e^{i\phi}}{1 - \tau \sigma e^{i\phi}}. \quad (3.1)$$

The ratio of the transmitted power through the device is then obtained as

$$T(\Phi) = \left| \frac{E_t}{E_i} \right|^2 = \frac{(\sigma - \tau)^2 + 4\sigma \tau \sin^2(\Phi/2)}{(1 - \sigma \tau)^2 + 4\sigma \tau \sin^2(\Phi/2)}. \quad (3.2)$$

With finesse of the resonator defined as $F = \pi \sqrt{\tau \sigma / (1 - \tau \sigma)}$, the device transmission can be written in a form analogous to the transmission of the Fabry-Perot resonators:

$$T(\Phi) = 1 - \frac{T_R}{1 + \left(4F^2 / \pi^2 \right) \sin^2(\Phi/2)}, \quad (3.3)$$

where $T_R = (1 - \sigma^2)(1 - \tau^2)(1 - \sigma \tau)^2$ is the maximal transmission reduction of a microring achievable under resonance conditions. Minima of the transmission correspond to a constructive interference in the ring resonator, i.e. when the resonance condition is fulfilled

$$\Phi = k_0 L N_{\text{eff}} = 2\pi n, \quad (3.4)$$
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where $m$ is an integer value. In this case the transmission is

$$T(2\pi m) = \left(\frac{\sigma - \tau}{1 - \sigma \tau}\right)^2. \quad (3.5)$$

At the resonance and the critical coupling condition $\tau = \sigma$ the transmission is zero. Physically, this condition corresponds to a perfect balancing between the power lost per round trip and the in-coupled power. For $\tau \neq \sigma$ the extinction decreases; the device functions as a phase filter for low round trip losses ($\sigma \to 1$) and does not show resonances for high losses ($\sigma \to 0$). In the latter case, the transmitted power is just attenuated to $\tau'$ of the input value.

**Figure 3.2:** Typical transmission curve of a microring resonator. The free spectral range (FSR) and the FWHM spectral width of the resonances are shown.

Like Fabry-Perot resonators, ring resonators are characterised by their free spectral range (FSR), spectral width ($\delta\lambda_{\text{FWHM}}$) of the resonance and finesse $F$ or quality factor $Q$.

The **free spectral range** is defined as the separation between two adjacent resonant wavelengths $\lambda_{\text{FSR}} = \lambda_m - \lambda_{m+1}$ (Figure 3.2). It can be calculated by differentiating the resonance condition $LN_{\text{eff}}/\lambda = m$ with respect to the wavelength, considering that the effective index depends on the wavelength (dispersion). Guided modes exhibit two types of dispersion. The refractive indices of the ma-
terials are wavelength dependent (material dispersion) and the guiding properties of the structure depend on the wavelength (modal dispersion).

\[
\frac{LN_{\text{eff}}(\lambda_{m+1})}{\lambda_{m+1}} - \frac{LN_{\text{eff}}(\lambda_{m})}{\lambda_{m}} = 1,
\]

\[-\Delta \lambda_{\text{FSR}} \left( \frac{d}{d\lambda} \frac{N_{\text{eff}}}{\lambda} \right) = \frac{1}{L},
\]

\[\Delta \lambda_{\text{FSR}} = \frac{\lambda^2}{L \left( N_{\text{eff}} - \lambda \frac{\partial N_{\text{eff}}}{\partial \lambda} \right)} = \frac{\lambda^2}{LN_{g}},
\]

where we define \( N_{g} = N_{\text{eff}} - \lambda \left( \frac{\partial N_{\text{eff}}}{\partial \lambda} \right) \) as the group effective index. \( N_{g} \) contains the material- and modal-dispersion. The latter may be especially relevant if the waveguide dimensions are close to the wavelength, as in single-mode devices.

The **spectral width** \( \delta \lambda_{\text{FWHM}} \) of the resonance is defined as the full-width at half-maximum of the resonance lineshape, (half-minimum of the dip, Figure 3.2), with the following equality in case of weak coupling \( \tau \approx 1 \) [35]:

\[\delta \lambda_{\text{FWHM}} = \frac{k^2 \lambda^2}{\pi LN_{\text{eff}}}.\]

The **finesse** \( F \) is defined as the ratio between the free spectral range and the spectral width of the resonance and is a measure of the sharpness of the resonance lines with respect to their spectral separation

\[F = \frac{\Delta \lambda_{\text{FSR}}}{\delta \lambda_{\text{FWHM}}}.\]

The **quality** of the resonator, expressed with the **Q-factor**, is defined as the ratio between the resonance wavelength and the resonance spectral width

\[Q = \frac{\lambda}{\delta \lambda_{\text{FWHM}}}, \text{ and, from Equation 3.7: } Q = \frac{\pi LN_{\text{eff}}}{\lambda k^2}\]

for weak coupling. The Q-factor is also defined as \( Q = (2\pi \tau_{p})/T \), in terms of photon cavity lifetime \( \tau_{p} \approx N_{\text{eff}}/(\alpha c) \) with respect to the optical period \( T = 1/\nu \).
3.2 Electro-optical effect in microring resonators

In electro-optically active microring resonators, the tuning of the transmission spectrum (and hence of the wavelength resonances) can be performed by the electro-optic effect. Applying an electric field on the microring waveguide material, its refractive indices change according to material electro-optic tensor $r_{ij}$. This change modifies the effective index $N_{\text{eff}}$ of the microring resonator. Consequently, the microring round-trip phase and the resonance condition change. The change of the effective index upon application of an electric field $\delta E = \delta V / d$ can be expressed with

$$
\delta N_{\text{eff}} = \frac{\partial N_{\text{eff}}}{\partial n} \delta n = -\frac{\partial N_{\text{eff}}}{\partial n} \frac{r_{nn} n^3}{2} \frac{\delta V}{d},
$$

where $r$ is the effective electro-optic coefficient, $n$ is the material refractive index and $d$ is the electrode separation, assuming that the field is homogeneous. The shift of the resonance wavelength due to a perturbation of the effective index can be obtained by setting the total differential of the resonance condition to zero

$$
\delta \left( \frac{2\pi N_{\text{eff}} (\lambda) L}{\lambda} \right) = 0,
$$

$$
\left( \frac{1}{\lambda} \frac{\partial N_{\text{eff}}}{\partial \lambda} - \frac{N_{\text{eff}}}{\lambda^2} \right) \delta \lambda + \frac{1}{\lambda} \delta N_{\text{eff}} = 0,
$$

$$
\delta \lambda = \frac{\lambda}{N_g} \delta N_{\text{eff}}.
$$

By combining Equations 3.10 and 3.11, we define the electro-optical tunability of a microring resonator, i.e. the resonance shift for applied voltage $V$:

$$
\frac{\delta \lambda}{\delta V} = -\frac{\lambda}{N_g} \frac{r_{nn} n^3}{2d} \frac{\partial N_{\text{eff}}}{\partial n}.
$$

We see that the tunability of the microring resonator does not depend on its length, since both the induced phase shift $\delta \Phi = k_0 L \delta N_{\text{eff}}$ and the phase $\Phi = k_0 L N_{\text{eff}}$ after one round trip are proportional to the length.
3.3 LiNbO$_3$ crystal

Lithium niobate (LiNbO$_3$) possesses excellent nonlinear, electro-optical and acousto-optical properties that make it a favourable material for realisation of integrated optic devices. LiNbO$_3$ is a ferroelectric oxide crystal with a trigonal crystal structure, belonging to the 3m crystallographic point group. It crystallises in colourless, stable, negative uniaxial crystals with a very large transparency range. Its large electro-optic, piezoelectric and nonlinear optical coefficients make it a material of choice for a myriad of optoelectronic applications. Large monocrystals of lithium niobate are easily grown by the Czochralski process, which makes it widely available in a form of single crystalline wafers. The properties relevant for this work are summarised in Table 3.1 [41, 42].

Equally important, recently it was discovered that the swift heavy ion implantations into the lithium niobate wafers yield low-loss, strongly confining waveguides with a refractive index contrast of $\Delta n \approx 0.17$ as a result of electronic irradiation damage. The occurrence of a wide, stable optical barrier beneath the surface, generated by electronic stopping power of impinging fluorine ions is not obvious in oxide ferroelectrics. For example, our experiments with fluorine ion implantations into the KNbO$_3$ crystals did not generate any observable optical barrier due to electronic stopping power.

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Refractive index at $\lambda = 1.55$ μm</td>
<td>$n_{eo} = [2.21, 2.14]$, $n$(amorph.) = 2.03</td>
</tr>
<tr>
<td>Transparency range</td>
<td>0.39 – 5 μm</td>
</tr>
<tr>
<td>Electro-optic coefficients</td>
<td>$r^{13} = 10 \text{ pm/V}$, $r^{33} = 32 \text{ pm/V}$</td>
</tr>
<tr>
<td>Dielectric constant</td>
<td>$\varepsilon_{11,33}^{T} = [85, 28]$</td>
</tr>
<tr>
<td>Density</td>
<td>$\rho = 4.65 \text{ g/cm}^3$</td>
</tr>
<tr>
<td>Melting temperature</td>
<td>$T_m = 1530 \text{ K}$</td>
</tr>
<tr>
<td>Specific heat</td>
<td>$C = 0.633 \text{ J/gK}$</td>
</tr>
<tr>
<td>Thermal conductivity</td>
<td>$K \approx 6 \text{ W/mK (at 300 K)}$</td>
</tr>
</tbody>
</table>

Table 3.1: Optical and other relevant physical properties of lithium niobate.
Chapter 4

Optical microring resonators in fluorine-implanted lithium niobate

Abstract: We report on the production and characterisation of optical microring resonators and optical channel waveguides by using fluorine-ion implantation and planar structuring in lithium niobate. We demonstrate the production of single-mode planar waveguides by low fluence fluorine-ion implantation ($\phi = 2.5 \cdot 10^{14}$ ions/cm$^2$) into lithium niobate wafers. The waveguides are strongly confined by the amorphous 2-$\mu$m wide optical barrier induced by the implantation process. A refractive index contrast of $\Delta n_r = 0.17$ at the telecom wavelength $\lambda = 1.5$ $\mu$m has been determined between the waveguide and the barrier. Planar structuring with ridge height of up to 1.2 $\mu$m has been achieved by laser lithography masking and Ar$^+$ sputtering. For TE waves, the channel waveguides exhibit propagation losses lower than 8 dB/cm. First ring resonators with 80-$\mu$m radius have been fabricated by planar structuring in fluorine-ion implanted lithium niobate. The measured resonance curves show an extinction ratio of 14 dB, a free spectral range of 2.0 nm and a finesse of 4.

$^1$This Chapter, except a part of Section 4.2.1 included here to describe the design process in more detail, has been published in Optics Express 16, 8769 (2008) [60].
4.1 Introduction

Optical microring resonators have attracted a growing interest as they can be used for ultrafast optical modulation, for add-drop filtering and for resonant enhancement of the circulating light [1]. Moreover, they are compact and can be embedded in high-density optical integrated circuits. Optical modulators, add-drop filters in wavelength division multiplexed systems and sensor elements have been demonstrated recently [43, 44]. Electrical control of microring’s resonant wavelength gives increased functionality in many of these applications. Different tuning methods have been demonstrated employing thermooptic, electro-optic, and carrier injection effect. Among them, electro-optic tuning [43, 45, 46] allows direct electrical control and ultrafast modulation. Lithium niobate (LiNbO₃) is a material of choice as it is readily available in large high-quality single-crystal wafers and possesses good electro-optical and nonlinear properties [42] and a large transparency range (0.39 – 5 µm). Furthermore, the material is already used in a series of photonic applications.

Low-loss planar and channel waveguides in LiNbO₃ can be fabricated using titanium-indiffusion and proton exchange techniques [47]. However, the resulting refractive index contrast between the waveguide and the substrate (typically |Δnₑ| < 0.1) is insufficient to suppress the bending losses in strongly curved waveguides. Due to this restriction, the radii of low-loss microring resonators fabricated solely with these techniques cannot be smaller than about 1 millimeter [5, 48]. A hybrid technique, combining titanium-indiffusion with ridge structures in order to enhance horizontal optical confinement, has just recently moved the low-radius limit to 100 µm [46, 49]. On the other hand, ion implantation [50] has recently regained new attention. A high dose He⁺ implantation can be used for the slicing of single-crystal LiNbO₃ thin films from bulk crystals [51]. Ion slicing combined with wafer bonding, that yields LiNbO₃ thin films embedded in a low-index cladding, has been significantly improved in our laboratory and electrically tunable microrings have also been demonstrated [45]. Depending on the choice of the substrate material the waveguides produced with this technique can have very high refractive index contrast with respect to the substrate (Δnₑ of up to 0.65). This allows much smaller microrings with radii down to ~10 µm showing no significant bending losses. Yet another
more recently studied technique for the production of planar waveguides in LiNbO$_3$ is the implantation with medium-mass ions (O, F, Mg) [52]. Fluorine implantation with ion energies of about 20 MeV yielded waveguides with a step-like index profile and largely preserved nonlinear optical properties [18]. The obtained wide optical barrier with ample index contrast provided a strong vertical light confinement as required for bent waveguides. The waveguides were several-µm thick and thus multimode at the telecom wavelength.

In this paper, we present the use of fluorine implantation for the production of effectively single-mode planar waveguides in LiNbO$_3$. Furthermore, we demonstrate the first low-loss microring resonators and optical channel waveguides in fluorine-implanted LiNbO$_3$, fabricated by lithographic masking and dry etching techniques.

4.2 Waveguide fabrication

In order to fabricate channel optical waveguides and microring resonators in LiNbO$_3$, we first characterised planar optical waveguides obtained by implantation with fluorine ions. We studied the refractive index, width and depth of the optical barrier as a function of the implantation energy and fluence. Based on these data we then determined the waveguide dimensions and implantation parameters for low-loss, effectively single-mode waveguides in LiNbO$_3$. Finally, we structured the channel waveguides and microrings using the lithography masking and dry etching technique. In the following, we describe waveguide design considerations and the fabrication steps.

4.2.1 Design considerations

Implantation of fluorine ions into LiNbO$_3$ causes material amorphisation beneath the crystal surface upon reaching the threshold fluence of approximately $10^{14}$ ions/cm$^2$ [18]. The resulting buried amorphous layer has lower refractive index and thus constitutes an optical barrier for the above-lying wave-guiding layer. Such waveguides are determined by three main parameters: the refractive index contrast between the wave-guiding layer and the optical barrier, the barrier position, and the barrier thickness.
Figure 4.1: Electronic stopping power ($S_e$) of 22-MeV fluorine ions implanted in LiNbO$_3$, calculated with SRIM-2003. The maximum of $S_e$ is at around 4.7 µm. From the measured waveguide thickness, the first approximation of the optical barrier thickness can be estimated by equating the corresponding $S_e$ on both sides of the curve, in this case $d_B \approx 2.7$ µm.

As mentioned in Chapter 2, the electronic excitation (electronic stopping) is the dominant effect of waveguide formation. We simulated the electronic stopping powers of fluorine ions hitting the LiNbO$_3$ substrate with the SRIM-2003 software (Stopping and Range of Ions in Matter [19]). Figure 4.1 shows the results of such a simulation for our preliminary experiments with 22 MeV ions. We chose this ion energy in order to generate several-µm thick waveguides, for easier characterisation and for comparison of our results with the published data [18]. The experimental determination of the thickness and the position of the amorphised layer upon the implantation was performed with the prism coupling measurements on several samples implanted at different implantation fluences. The measured values of the effective index squared $N_m^2$ as a function of $(m+1)^2$ for a fluence value of $5 \times 10^{14}$ cm$^{-2}$ are shown in Figure 4.2.
The resulting mode curve consists of two straight sections, which indicates an approximate step-like index profile. (Chapter 5.4 in Ref. 11) The steeper section follows the dependence

$$\frac{-N_m^2}{2} = -n_o^2 + (m + 1)^2 \left(\frac{\lambda}{2d}\right)^2,$$

from which the waveguide index $n_w$ and the waveguide thickness $d$ can be calculated. The index value at the kink of the mode curve shows the refractive index at the optical barrier. We observed that both ordinary $n_o$ and extraordinary $n_e$ refractive indices remain largely unperturbed in the wave-guiding region and fall sharply to a common value of 2.1±0.01 at $\lambda = 633$ nm in the amorphised barrier, which is in good agreement with previous studies [18] and matches the refractive index of the amorphous LiNbO$_3$ [53]. Assuming the same relative drop of the refractive indices at the infrared wavelengths, we estimated $n = 2.03±0.01$ in the amorphous layer at $\lambda = 1.5$ µm, yielding the index contrast of $\Delta n_o = 0.17$ and $\Delta n_e = 0.11$. The amorphisation spreads outwards in both directions with increasing ion fluence $\phi$, giving a barrier thickness $d_B$ of several micrometers (see Figure 4.3(a)). From the measured waveguide thickness, $d_B$ can
be roughly estimated by equating the corresponding \( S_e \) on both sides of the electronic stopping power curve (Figure 4.1). Actual barrier is usually slightly thicker [28, 31]. The origin of amorphisation coincides with the position of maximal electronic stopping power, \( d_{\phi} \), as simulated with

SRIM-2003 software. The simulated \( d_{el} \) as a function of the fluorine ion energy \( E \) is shown in Figure 4.3(b). The dependence of \( d_{el} \) on the ion energy \( E \) can be approximated by a second-degree polynomial \( d_{el} = a_0 + a_1 E + a_2 E^2 \), with \( a_0 = -1.08 \mu m \), \( a_1 = 0.165 \mu m/\text{MeV} \) and \( a_2 = 4.3 \cdot 10^{-3} \mu m/\text{MeV}^2 \). For the purposes of waveguide design, the waveguide thickness for given implantation parameters \( E \) and \( \phi \) can thus be estimated with the help of \( d_B \) and \( d_{\phi} \), as shown in Figure 4.3(b).

Propagation of optical modes in planar and channel waveguides on top of implanted Z-cut LiNbO\(_3\) was simulated with commercial software package OlympIOs [54]. We calculated the bending and tunnelling losses (combined together), electric field distribution and effective indices of TE modes at \( \lambda = 1.55 \mu m \). Absorption and scattering losses were not considered at this point (al-
Electro-optically tunable microring resonators in fluorine-implanted lithium niobate

though they represent the majority of the overall losses, see Section 4.2.3), as they could not be modelled adequately. With given refractive indices in the wave-guiding and barrier layer, the calculated maximum planar waveguide thickness for single-mode propagation is $1.05\pm0.05 \, \mu m$. However, waveguides with a thickness of up to $1.4 \, \mu m$ can still be used as single-mode for preliminary experiments since the second optical mode suffers roughly an order of magnitude higher tunnelling losses. For the case of channel waveguides, Figure 4.4 shows the calculated bending and tunnelling losses for the fundamental TE mode in a curved waveguide with a cross-section of $1.35\times3.2 \, \mu m^2$ (height×average width, as used in our experiments) as a function of the centre ring radius $R$. The bending losses decrease exponentially with increasing radius and are smaller than $2 \, dB/cm$ for waveguides with $R > 40 \, \mu m$. Along with the increasing losses the effective mode index decreases with respect to the one in straight waveguides. This hampers the evanescent optical coupling between the bus waveguide and the microring resonator. In our experiments we fabricated microrings with $R = 80 \, \mu m$ in order to preserve low bending losses ($\sim0.2 \, dB/cm$) and moderate optical coupling.

Figure 4.4: Calculated combined bending and tunnelling losses (left scale) and effective mode index $N_{\text{eff}}$ at ring’s outer rim (right scale) as a function of the waveguide bend radius. $N_{\text{eff}}$ of the straight waveguide with the same cross-section is 2.159. Calculation is for the first TE optical mode and wavelength 1.55 $\mu m$. Waveguide cross-section dimensions as in Figure 4.5.
A simulated electric field profile of the first TE optical mode for this case is shown in Figure 4.5. A drift of the mode towards the outer rim is clearly visible; however, the spread of the electric field into the implanted optical barrier is much smaller than the barrier thickness.

4.2.2 Planar waveguides

For the requested single-mode waveguide thickness of 1.1.4 µm, the implantation parameters \( E \) and \( \phi \) were chosen according to guidelines from Figure 4.3. Implantations with \( E \leq 14 \) MeV resulted in a brittle crystal surface, which prevented the subsequent fabrication of channel (ridge) optical waveguides. The implantation fluence was deliberately kept as small as possible in order to introduce minimal damage to the wave-guiding layer. On the other hand, tunneling losses at \( \lambda = 1.5 \) µm limited the minimal acceptable fluence to \( \phi = 2 \cdot 10^{14} \) ions/cm\(^2\).

Finally, implantations with \( E = 14.5 \) MeV and \( \phi = 2.5 \cdot 10^{14} \) ions/cm\(^2\) yielded waveguides with the lowest measured propagation losses, while retaining their thickness within requested constraints. The thickness of these planar waveguides, as measured with dark mode spectroscopy and assuming a step-
like index profile, was 1.35±0.06 µm. This is approximately 0.2 µm more than predicted above (see Figure 4.3(b)) because at small waveguide thicknesses the assumption of a step-like index profile gets less accurate. Although these waveguides support both TE₀ and TE₁ optical modes, they are effectively single-mode, since the second optical mode suffers roughly an order of magnitude higher tunnelling losses.

Implantations of fluorine ions F³⁺ into Z-cut LiNbO₃ wafers have been performed at room temperature. The samples were tilted at 8° relative to normal incidence to avoid channelling effects. The ion current density was kept at ~200 nA/cm² (which corresponds to a particle current of 4.2·10¹¹ ions/(s·cm²)), to minimise unwanted charging and heating. Nevertheless, the implantation times for the required fluences were only about 10 min. In addition to relatively thick optical barriers produced by the F³⁺-implantation, the short implantation time is of great advantage compared to implantations with light ions (He⁺) requiring one to two orders of magnitude higher implantation fluences and hence longer implantation times.

After the implantation, the waveguides exhibit high propagation losses, mainly due to irradiation-induced crystal defects. Thermal annealing efficiently improves the waveguide transmission [18]. The implanted samples were therefore annealed by heating them to T = 300°C in air for one hour (dwell time) and then slowly cooled down. This greatly reduced the propagation losses, from several tens dB/cm prior to annealing down to ~8 dB/cm afterwards, as measured at λ = 1.5 µm in our channel waveguides (see Section 4.3).

4.2.3 Channel waveguides and microrings

Channel (ridge-type) waveguides were fabricated from the annealed planar waveguides by means of photolithographic patterning and subsequent Ar⁺ sputtering. In the past, we have already successfully used this approach in Cr:LiSrAlF₆ [13], β-BaB₂O₄ [14] and other optical crystals. Photolithography was performed with an image-reversal photoresist (Clariant AZ5214). A laser beam lithography apparatus, home built in our laboratory, was used for the photoresist exposure. For the illumination we used a violet laser beam (λ = 430 nm) that was focused directly onto the photoresist film with a microscope objective (focal length f = 4 mm, numerical aperture NA = 0.75). The desired patterns were
written in the photoresist by lateral translation of the sample (for straight waveguides) or 2D acousto-optical deflection of the laser beam (for optical microrings). The main advantages of the laser lithography are its better resolution and flexibility as compared to the standard photolithographic technique utilizing UV lamps and mask aligners. If needed, different patterns can be written on each new sample, thus permitting an iterative approach towards optimised waveguide structures. Additionally, we are able to expose the photoresist with high lateral precision also in small samples, where spun edge bead prevents mask contacting.

The lateral evanescent wave coupling between a bus waveguide and a microring resonator requires a sub-micrometer wide gap. In order to accomplish this, we used a two-step laser lithography procedure. In the first step, straight bus waveguides were written and developed in the photoresist. In the second step, a new photoresist layer was spun on the sample surface. Microrings were then written in close proximity of the already-existing bus waveguides and subsequently developed. In this way, exposures (arising from Gaussian wings of the laser beam profile) from the ring and the bus waveguide were not accumulated in the same photoresist layer in the gap region. As a result, photoresist was not cross-linked in the gap. By careful positioning of the rings to the waveguides, coupling gaps as narrow as 200 nm could be obtained.

Figure 4.6: Scanning electron micrograph of a microring resonator and a bus waveguide, structured in LiNbO$_3$. (a) The whole ring and the bus waveguide. Ring radius is 80 µm, ridge height is 1.2 µm. (b) Enlarged coupling region, the gap size is ~0.2 µm.
The photoresist patterns were transferred to the planar waveguide surface by Ar⁺ sputtering (Oxford Plasmalab 80, RF power 200 W) and the ridge-type waveguides with a height of up to 1.2 µm were finally fabricated (Figure 4.6). LiNbO₃ is highly resistant to Ar⁺ sputtering. The measured sputtering rates were ~1.3 nm/min for both virgin and implanted crystals. Waveguide facets were finally polished using standard polishing techniques. The dimensions and surface quality of the structures were then investigated with a profilometer and a scanning electron microscope (SEM). The bus waveguide cross-section is trapezoidal with a sidewall slope angle of about 65° and slightly etched upper edges (Figure 4.7). The ring has steeper and smoother sidewalls, as can be qualitatively compared in Figure 4.6.

![Figure 4.7: SEM image of the fabricated ridge structure. The waveguide cross-section is trapezoidal with the base width 3.7 µm, top width 2.7 µm and ridge height 1.2 µm. The amorphised barrier layer beneath the ridge is visible.](image)

### 4.3 Optical characterisation of microrings

In order to optimise the performance of channel waveguides and microring resonator devices, their propagation losses at operational wavelengths should be as low as possible. An estimation of the propagation losses in straight channel waveguides (without adjacent microrings) was performed by measuring their light transmission around λ = 1.5 µm. The experimental setup for the measurement of losses and of the microresonator transmission spectrum is shown in Figure 4.8.
A pigtailed tuneable diode laser (Santec TSL-220, spectral range 1.53 - 1.61 μm, spectral linewidth 1 MHz) was used as the input beam source. The laser beam was end-fire coupled into the waveguides by a microscope objective with a 50 × magnification and NA = 0.8. The transmitted light was collected with a 100 × microscope objective and projected onto an InGaAs photodiode. On average, a total of 9% of the TE polarised and 2.1% of the TM polarised incident light was emitted from the exit facet of the 5.6-mm long waveguide. We determined the propagation losses of TE polarised light by measuring its wavelength-dependent transmission in the channel waveguides with polished facets that acted as low-finesse Fabry-Perot resonators. As described in [55], the upper limit of the propagation losses can be determined solely from the contrast $K$ between the maximum $I_{\text{max}}$ and the minimum $I_{\text{min}}$ of the measured transmitted power oscillations. Here $K$ is defined by $K = (I_{\text{max}} - I_{\text{min}}) / (I_{\text{max}} + I_{\text{min}})$ and is independent of the coupling efficiency. With the measured contrast $K = 0.10$ and assuming a facet Fresnel reflectivity of 14% we estimated the propagation losses to be $7.8 \pm 0.5$ dB/cm at $\lambda = 1.5$ μm. Comparing this value with the directly measured total transmission suggests that about one third of the laser power was effectively coupled into the first guided optical mode. According to our calculations (see Section 4.2.1), the tunnelling losses for the first guided mode are only 0.1 dB/cm. Obviously, absorption and scattering are the main sources of the total propagation loss.
The optical response at the through ports of the coupled ring resonators around $\lambda = 1.5 \, \mu m$ was probed by scanning the input wavelength over a range from 1.54 $\mu m$ to 1.58 $\mu m$. Resonances were not observed with TM polarised light, presumably due to smaller index contrast and higher propagation losses. With TE polarised light the characteristic responses of microresonators could be observed. The highest modulation depth was obtained with a microring slightly touching the bus waveguide (the length of the joined region was 6±1 $\mu m$). Figure 4.9 shows the measured transmission spectrum around $\lambda = 1.56 \, \mu m$. The measured free spectral range of the microresonator was $\Delta \lambda_{FSR} = 2.0 \pm 0.01 \, nm$. The spectral width of the resonances (full-width at half-minimum of the dip) was $\delta \lambda_{FWHM} = 0.5 \pm 0.05 \, nm$ and the modulation depth at the strongest resonances was 14 dB. The resonator finesse was $F = \Delta \lambda_{FSR} / \delta \lambda_{FWHM} = 4 \pm 0.4$ and the corresponding quality factor $Q = \lambda / \delta \lambda_{FWHM} = 3100 \pm 300$. The measured free spectral range agrees well with the calculated

$$\Delta \lambda_{FSR} = \frac{\lambda^2}{2 \pi R \cdot N_g} = 2.03 \, nm,$$

Equation 4.2

The calculated group effective index $N_g = N_{eff} - \lambda (\partial N_{eff} / \partial \lambda) = 2.3$ in Equation 4.2 includes both the material dispersion and the modal dispersion of the effective mode index $N_{eff}$. The modal dispersion becomes particularly relevant in single-mode waveguides. A detailed description of the calculation of the resonator’s free spectral range can be found in [34].
4.4 Discussion

In Table 4.1 we review some of the important properties of already demonstrated microring resonators in LiNbO$_3$ and compare them with our results. Our estimation of the maximum achievable free spectral range for a given fabrication technique (allowing 2 dB/cm bending losses) is included. As it can be seen, fluorine implantation enables fabrication of microrings with a $\Delta \lambda_{\text{FSR}}$ of 4 nm or even greater if bending losses higher than 2 dB/cm are acceptable.

<table>
<thead>
<tr>
<th>Fabrication technique</th>
<th>$\lambda$ [µm]</th>
<th>$\Delta n$</th>
<th>Curvature radius [µm]</th>
<th>Prop. losses [dB/cm]</th>
<th>$\Delta \lambda_{\text{FSR}}$ [nm]</th>
<th>Max. $\Delta \lambda_{\text{FSR}}$ [nm]</th>
<th>Ref.</th>
</tr>
</thead>
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<td>1500</td>
<td>1.4-4.2</td>
<td>0.027</td>
<td>~0.1</td>
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<td>Titanium indiffusion</td>
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<td>100</td>
<td>-</td>
<td>1.42</td>
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<tr>
<td>Fluorine implantation</td>
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<td>100</td>
<td>17</td>
<td>1.66</td>
<td>14</td>
<td>[45]</td>
</tr>
</tbody>
</table>

* estimated maximum free spectral range for calculated bending losses of 2 dB/cm

Table 4.1: Properties of demonstrated microring resonators in LiNbO$_3$.

For our envisaged application of these microring resonators as electro-optical light intensity modulators, we will implement tuning electrodes. Below we estimate the microring resonance wavelength tunability $\delta \lambda / \delta V$ for the optimized electrode configuration. The shift of the resonant wavelength can be derived by differentiating the resonance condition $\left(2\pi N_{\text{eff}}(\lambda) L/\lambda = 2\pi m\right)$ for a fixed integer value $m$:

$$\delta \left(\frac{N_{\text{eff}}(\lambda) L}{\lambda}\right) = 0, \text{ gives } \left(1 - \frac{N_{\text{eff}}}{\lambda} \frac{\partial N_{\text{eff}}}{\partial \lambda} - \frac{N_{\text{eff}}}{\lambda^2} \right) \delta \lambda + \frac{1}{\lambda} \delta N_{\text{eff}} = 0,$$

hence $\delta \lambda = \frac{\lambda}{N_g} \delta N_{\text{eff}}$.  \hspace{1cm} (4.3)

The resonance shift depends on the change of the effective index and is independent of the resonator’s perimeter $L = 2\pi R$. Because of the crystal’s natural birefringence and the ring’s axial symmetry, the $\delta N_{\text{eff}}$ for TE waves depends mostly on the vertical component of the applied electric field $E_z$ and can be
modelled to a good approximation by considering only electro-optical coefficient $r_{13}$. We simulated the electro-optically induced change of the effective index $\delta N_{\text{eff}} = (\partial N_{\text{eff}} / \partial V)\delta V$ with the OlympIOs software. The electric potential in the waveguide cross-section upon applying a voltage between the electrodes is shown in Figure 4.10. One of the electrodes must be on top of the ring waveguide, to provide the necessary $E_z$ component of the electric field. A 0.7-\(\mu\)m thick buffer layer of amorphous silicon dioxide (SiO$_2$) is used to prevent the absorption losses due to chromium electrode. The calculated effective index change is $\delta N_{\text{eff}} = (5\pm2)\times10^{-4}$ for a 100 V potential between the electrodes. The estimated tunability is therefore $\delta \lambda / \delta V = 3.4 \pm 1.4$ pm/V or, expressed in frequency, $\delta v / \delta V = 0.42 \pm 0.17$ GHz/V. The inaccuracy is due to the uncertain value of the dielectric constant of the amorphous LiNbO$_3$ in the optical barrier (values between the ones from SiO$_2$ and bulk LiNbO$_3$ were used).

![Figure 4.10: Simulated electric potential in the waveguide cross-section upon the application of a voltage $V = 100$ V between the electrodes. Equipotential contours separate a 5 V potential drop. About 55% of the potential drop occurs in the SiO$_2$ buffer layer.](image)

It is interesting to compare the electro-optical response of the presented microring resonator with an equivalent Mach-Zehnder (MZ) modulator. We compared the microring’s modulation sensitivity, expressed with an equivalent half-wave voltage $V_{\text{eq}}^{\pi}$, with the sensitivity of a MZ modulator [56]:
\[ V_{\pi}^{eq} = \frac{\pi}{2} \left( \frac{dT}{dV_{\text{max}}} \right)^{-1} = \frac{\pi}{2} \left( \frac{dT}{d\theta} \frac{d\theta}{dV_{\text{max}}} \right)^{-1} = \frac{V_{\pi}^0}{2|dT/d\theta|_{\text{max}}}, \]

where \( V_{\pi}^0 \) is the voltage that produces a \( \pi \) phase shift in one round trip in the resonator and is also the half-wave voltage of a one-arm driven MZ modulator with an interaction length equal to the microring’s perimeter \( (L_{\text{MZ}} = 2\pi R) \). The enhancement of the modulation intensity by the optical resonance in the microring is given by the factor of \( 2|dT/d\theta|_{\text{max}} \). The measured light transmission as a function of the phase shift \( \theta \) after one round trip is shown in Figure 4.11. The maximum slope on the left side of the resonance dip is \( |dT/d\theta|_{\text{max}} = 1.7 \pm 0.2 \). This gives the equivalent half-wave voltage \( V_{\pi}^{eq} = 0.29(1 \pm 0.04)V_{\pi}^0 \). The asymmetry in the transmission function can be attributed to the presence of higher spatial (horizontal) TE modes in the microring. These, due to phase mismatch, resonate at slightly different wavelengths and hence distort the transmission function.

![Figure 4.11](image-url)

Figure 4.11: (red) Measured light transmission as a function of the roundtrip phase \( \theta \). The line connecting the points is a guide to the eye. (blue) Transmission curve \( (T = \cos^2(\varphi/2)) \) of an equivalent Mach-Zehnder modulator, for phase \( \varphi = \theta - \pi \). Points of maximum transmission slopes \( |dT/d\theta|_{\text{max}} \) are marked with arrows.
4.5 Conclusions

We have demonstrated channel waveguides and microring resonators in fluorine-implanted lithium niobate. A low-fluence fluorine implantation \( (2.5\cdot10^{14} \text{ ions/cm}^2) \) into Z-cut LiNbO\(_3\) generates a 2-\(\mu\)m wide amorphous optical barrier beneath the crystal surface with a refractive index contrast of \( \Delta n_o = 0.17 \) at \( \lambda = 1.5 \text{ \(\mu\)m} \). This, combined with lithographic patterning and Ar\(^+\) sputtering, yields channel (ridge-type) optical waveguides in LiNbO\(_3\) with strong optical confinement. The fabricated channel waveguides have propagation losses lower than 8 dB/cm for TE waves.

Microring resonators with 80-\(\mu\)m radius that can operate as wavelength filters at 1.5 \(\mu\)m telecom wavelength have been realised. They have a transmission extinction ratio of 14 dB, a free spectral range \( \Delta\lambda_{\text{FSR}} = 2.0 \text{ nm} \), a finesse \( F = 4 \), a quality factor \( Q = 3100 \), and a phase sensitivity of \( |dT/d\theta|_{\text{max}} = 1.7 \). An estimation of the electro-optic response in these LiNbO\(_3\) microresonators shows that their resonance wavelength could be tuned by \( \delta\lambda/\delta V = 3.4 \text{ \(\mu\)m/V} \). We believe that the microresonators’ \( Q \) factor can be further increased by optimisation of the surface patterning process.

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Chapter 5

Optical microring resonators in fluorine-implanted lithium niobate for electro-optical switching and filtering

Abstract: We present a new approach for the fabrication of electro-optically tunable microring resonators in lithium niobate. Planar optical waveguides for vertical light confinement ($\Delta n_o = 0.17$ for TE modes) are produced by fluorine ion implantation. Optical microrings and coupling waveguides are then formed by laser lithography masking and Ar$^+$ plasma etching. Electrodes are optically isolated from the optical microrings by a high-dielectric constant ($\varepsilon \sim 70$ at 10 Hz) polyvinyl alcohol buffer layer to improve electro-optic tuning. The microrings with a radius of 80 $\mu$m exhibit optical resonances with a modulation depth of 11 dB, a free spectral range of 2 nm, and an electro-optical tunability of 10 pm/V.

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2 This Chapter has been submitted to IEEE Photon. Technol. Lett.
5.1 Introduction

Optical microring resonators combine attractive optical characteristics with compact size and thus promise to become important components in optical integrated circuits. In most applications, a control of microring resonant wavelength is required. Thermo-optic, electro-optic [43], plasma dispersion by injection [57] or photogeneration [58] of carriers are the most common physical effects that have been employed for wavelength tuning. Among them, electro-optic tuning allows a direct control and fast modulation of the optical transmission. The most commonly used oxide ferroelectric, lithium niobate (LiNbO$_3$) possesses a large transparency range (0.39-5 µm) and good electro- and non-linear-optical properties. It is widely available in large single-crystal wafers and as such an established material in many photonics applications. All these factors pose a strong incentive for the fabrication of efficient optical microrings in LiNbO$_3$ that could be used in high-density integrated optical circuits.

Channel waveguides fabricated in LiNbO$_3$ by standard techniques [47] of proton exchange or Ti indiffusion have small refractive index contrast between the waveguide and the substrate that is insufficient to suppress bending losses in strongly curved waveguides [40]. Microrings fabricated by these techniques are limited to radii greater than 1 mm [5, 48], which results in a too small free spectral range (FSR) that is not practical for many applications. Recently, 100-µm radius microrings fabricated by a combination of Ti indiffusion and ridge structuring for enhanced horizontal optical confinement have been presented [46, 49]. On the other hand, ion implantation has lately regained attention. Crystal ion slicing by He$^+$ implantation [59] enables the fabrication of waveguides with a very high refractive index contrast ($\Delta n = 0.6$), permitting microrings with radii down to 10 µm [45]. Fluorine ion implantation yields low-loss waveguides with a wide optical barrier and ample index contrast, as required for bent waveguides. Passive optical microrings in LiNbO$_3$ have been fabricated in our laboratory using this approach [60]. In electro-optically controlled microrings, waveguides are embedded in a buffer cladding that provides optical isolation from the metal electrodes. Due to the high dielectric constant $\varepsilon_{33} = 28$ of LiNbO$_3$, the cladding should have higher dielectric constant in order to maximize the voltage drop across the active LiNbO$_3$ layer. In Refs. 45
and 46 silicon dioxide \((\varepsilon = 3.8)\) was used for the buffer cladding, which resulted in a relatively low electro-optical tunability of the devices.

In this Letter, we report on the first demonstration on electro-optically tunable microring resonators in fluorine-implanted LiNbO\(_3\). The microrings are buffered with a high-dielectric polyvinyl alcohol [61] (PVA) cladding, leading to an order-of-magnitude increased electro-optical tunability at low modulation frequencies. In the following, we describe the fabrication and performance of these microring devices.

### 5.2 Design and fabrication of the device

Fluorine ion implantation combined with high-ridge planar structuring ensures sufficient optical confinement of TE waves to enable the realization of sub-100-\(\mu\)m radius microrings on z-cut LiNbO\(_3\) wafers. The corresponding design and fabrication procedure for passive microring resonators is given in more detail in Ref. 60. In short, planar waveguides are produced by room temperature implantation of fluorine ions \(\text{F}^{3+}\) into the z-cut LiNbO\(_3\) wafers. The ion current density is kept at 200 nA/cm\(^2\) to minimize unwanted charging and heating. Implantations with ion energy \(E = 14.5\) MeV and a fluence of \(2.5 \times 10^{14}\) ions/cm\(^2\) yield low-loss, single-mode waveguides with thickness of 1.35 \(\mu\)m, separated from the substrate by a 2-\(\mu\)m wide optical barrier. Both ordinary \(n_o\) and extraordinary \(n_e\) refractive indices remain largely unperturbed within the waveguide, and fall sharply to a common value of \(n = 2.03\) at \(\lambda = 1.5\) \(\mu\)m in the amorphised optical barrier, giving an index contrast of \(\Delta n_o = 0.17\) and \(\Delta n_e = 0.11\). According to our simulations with the OlympIOs integrated optics software [54], \(\Delta n_o\) enables low-bending-loss \((< 2\) dB/cm\) propagation of TE waves in the microrings with ring radius \(R > 40\) \(\mu\)m. After the implantation, the waveguides exhibit propagation losses of several tens dB/cm. The implanted samples are thereafter annealed by heating them to 300°C for one hour and then slowly cooled down. This effectively reduces their propagation losses down to \(~8\) dB/cm at \(\lambda = 1.5\) \(\mu\)m, with absorption and scattering accounting for most of the losses. The horizontal evanescent coupling between a bus- and a microring-waveguide requires a sub-\(\mu\)m wide gap. To achieve this, a two-step laser lithography process is used in which the masks for bus waveguides and micror-
ings are patterned in two successively spin-coated and illuminated image-reversal photoresist films (Clariant AZ5214). The photoresist pattern is transferred onto the planar waveguide surface by Ar⁺ sputtering, producing microrings with \( R = 80 \mu \text{m} \) center ring radius, 3.2 \( \mu \text{m} \) average width and 1.2 \( \mu \text{m} \) ridge height (see Figure 5.1). Both facets of the bus waveguides are finally polished for end-fire coupling.

The microring’s electro-optical tunability, i.e. the wavelength shift \( \delta \lambda \) of the transmission spectrum upon application of an electrode voltage \( \delta V \), is expressed with

\[
\delta \lambda = \left( \frac{\lambda}{N_g} \right) \cdot \delta N_{\text{eff}}
\]  

(5.1)

where the effective index change equals \( \delta N_{\text{eff}} = (\partial N_{\text{eff}}/\partial V) \cdot \delta V \) and the group effective index \( N_g = N_{\text{eff}} - \lambda \cdot (\partial N_{\text{eff}}/\partial \lambda) \) accounts for both material- and modal-dispersion of the effective mode index [34]. Because of the ring’s axial symmetry and the crystal orientation (optic axis orthogonal to the ring’s plane), the main contribution to \( \delta N_{\text{eff}} \) stems from the vertical component \( E_z \) of the electric field and can be modeled as

\[
\delta N_{\text{eff}} = \delta N_{\text{eff}}(\delta n_{o,e}) \quad \text{with} \quad \delta n_{o,e} = -\frac{1}{2} n^3_{o,e} \cdot r \cdot E_z
\]  

(5.2)

where \( r \) is the relevant electro-optical coefficient (\( r_{13} \) and \( r_{33} \) for TE and TM waves, respectively). The electrodes must thus be positioned in two vertically separated planes in order to induce the necessary electric field component \( E_z \). In our configuration with metal electrodes, the lower electrode was deposited in close proximity to the microring’s outer rim, and the upper electrode above the microring (see Figure 5.1).
The lower electrode, consisting of 10-nm Cr (for better adhesion) and 200-nm Al layers, was deposited by the standard lift-off technique. It was 15 µm wide and surrounded the microring with a separation of about 1 µm. To optically isolate the propagating light from the upper electrode a thin film of PVA was used as an intermediate buffer layer. This polymer has reportedly [61] high dielectric constant $\varepsilon_{\text{PVA}}$, which maximizes the electric field $E_z$ in the active LiNbO$_3$ layer. The PVA was spin-coated on the sample and heated to 65°C for 4 hours in order to harden the film. The thickness of the film was 600 nm on top of the ridge and 1.0 µm off the ridge. Since PVA is soluble in water, standard water-based developers could not be used for the lift-off deposition of the upper electrode. Therefore, the upper electrode (10 nm Cr and 100 nm Al) was deposited over the whole device. The waveguide cross-section, the simulated first TE optical mode intensity distribution and the electric potential therein upon applying a voltage on the electrodes are shown in Figure 5.1 (b). The 1.2 µm high ridge and $\Delta n_o = 0.17$ ensure strong optical confinement of the circulating light.
5.3 Experimental results

The optical characterization of the device included the measurement of the propagation losses of the channel waveguides, the measurement of the microring transmission spectrum, the electro-optical tunability and amplitude modulation. All measurements were performed with end-fire coupled laser light at \( \lambda = 1.5 \, \mu \text{m} \). Microring resonances were not observed with TM polarized light, presumably due to smaller index contrast and much higher propagation losses. Therefore, only the TE wave configuration was thoroughly investigated.

The propagation losses in the straight waveguides (without adjacent microrings) were estimated from the measurement of the Fabry-Perot resonances of the light reflected at the waveguide facets [55]. The loss estimation is independent on the coupling efficiency and is determined from the contrast \( K = (I_{\text{max}} - I_{\text{min}})/(I_{\text{max}} + I_{\text{min}}) \) between the maximum \( I_{\text{max}} \) and the minimum \( I_{\text{min}} \) of the measured transmitted power oscillations. With \( K = 0.10 \pm 0.006 \) and the waveguide length of 0.56 cm the estimated propagation losses were \( 7.8 \pm 0.5 \, \text{dB/cm} \). The calculated bending losses for the first TE mode in these microrings were small \( (0.2 \, \text{dB/cm}) \) in comparison with the measured propagation losses. A transmission spectrum of the device was obtained by scanning the input wavelength and simultaneously measuring the optical output at the microring resonator’s through port. A typical transmission spectrum is shown in Figure 5.2.

![Normalized Transmission](image)

**Figure 5.2:** Measured TE wave transmission spectrum of the fabricated microring resonators.
While resonances were observed in evanescently coupled microrings, the rings touching the bus waveguide in a 5-10 µm long section exhibited resonances with the highest modulation depth. The measured microresonator’s free spectral range is 2.03±0.02 nm, which agrees well with the calculated FSR = \( \frac{\lambda^2}{(2\pi R \cdot N_g)} \) = 2.03 nm. The resonances have a modulation depth of 11 dB and a FWHM spectral width of 0.5 nm.

To determine the electro-optically induced shift of the microring resonances, the transmission spectra were measured at different bias voltages applied on the electrodes. The results are shown in Figure 5.3. A voltage difference of 10 V shifts the resonance by 100 pm. The resulting electro-optical tunability is \( \frac{\delta \lambda}{\delta V} = 10 \text{ pm}/\text{V} \) or, in frequency terms, \( \frac{\delta \nu}{\delta V} = 1.24 \text{ GHz}/\text{V} \). The measured value is the highest reported in LiNbO\(_3\)-based microring resonators so far. The TE wave electro-optical tunability calculated from Eqs. 1 and 2, using \( r_{13}^T = 10 \text{ pm}/\text{V} \) from the bulk LiNbO\(_3\) and the measured dielectric constant \( \varepsilon_{\text{PVA}} = 69 \), is \( \frac{\delta \lambda}{\delta V} = 8 \text{ pm}/\text{V} \). We believe that the difference is mainly due to inaccurate value of the \( \varepsilon_{\text{PVA}} \) as well as due to discrepancy between the geometries of the model and the realized device. The high tunability also suggests that the electro-optical coefficients remain mainly preserved in LiNbO\(_3\) implanted with F\(^+\) fluences lower than about 2.5\( \times 10^{14} \) ions/cm\(^2\).

![Image](image_url)

Figure 5.3: Measured transmission spectra upon applying a bias voltage of -10 V, 0 V, and +10 V on the electrodes. Marked points represent: (1) maximum-slope point at \( T = 0.5 \), (2) maximum transmission and (3) minimum transmission upon applying a 10-Hz sinusoidal modulation voltage.
To demonstrate the electro optic modulation of the microring resonator, the laser wavelength was set on the maximum-slope point of the microring’s transmission resonance at $T = 0.5$, as marked in Figure 5.3. A sinusoidal voltage from a function generator applied on the electrodes resulted in a sinusoidal optical modulation at the device throughput as shown in Figure 5.4.

![Figure 5.4: Measured normalized transmission of the microring resonator as a function of modulation voltage. Lower graph shows the corresponding applied sinusoidal voltage, with a 10-Hz modulation and a peak-to-peak amplitude of 20 V.](image)

At an applied 20 V peak-to-peak amplitude and a frequency of 10 Hz, the difference between the maximum and minimum transmission was $2\Delta T = 0.62$. This corresponds to a wavelength shift of 200 pm in the transmission spectrum and conforms to the resonance shift upon applying a bias voltage of 20 V (Figure 5.3). The optical modulation decreased upon increasing the modulation frequency. At 100-Hz modulation the optical peak-to-peak transmission amplitude dropped to $2\Delta T = 0.48$, corresponding to a tunability of 7.7 pm/V. We attribute this amplitude drop to the frequency dependence of the dielectric constant of PVA that, according to room-temperature capacitance measurements in our spin-coated thin films, fell from $\varepsilon_{PVA} = 69$ down to $\varepsilon_{PVA} = 20$ at 10 Hz and 100 Hz, respectively, leading to a drop of the electric potential in the LiNbO$_3$ waveguides and causing a smaller refractive index change in the microring resonator. The electro-optical tunability of these LiNbO$_3$ microrings is one or-
order of magnitude larger than previously reported [45, 46]. However, the lower modulation depth hinders the use of these devices at much higher frequencies. To improve the tuning performance at higher frequencies we propose a use of semitransparent conductive electrodes, such as Al doped ZnO, which could be deposited directly on the microring waveguide.

5.4 Conclusion

In conclusion, electro-optically tunable microring resonators in fluorine-implanted LiNbO$_3$ have been demonstrated. Microring resonators with 80-$\mu$m radius were fabricated with fluorine ion implantation and planar structuring. A thin film of polyvinyl alcohol, a high dielectric constant material, was buffered between the waveguides and the upper electrode to maximize the applied electric field in the active layer and hence to increase the tunability. The optical and electro-optical properties of the compact device structures were studied in detail. For TE waves, optical resonances with a modulation depth of 11 dB, separated by a 2.0 nm free spectral range were observed. The microresonators exhibit the highest reported electro-optical tunability of 10 pm/V in LiNbO$_3$. The strong drop of the PVA dielectric constant at increased modulation frequencies decreases the modulation depth of the presented microrings. Application of semitransparent conductive electrodes is envisaged to increase the useful modulation frequency.

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Chapter 6

Influence of the cladding on the electro-optic tunability

6.1 Optical microrings with silicon dioxide cladding

In order to evaluate the influence of the cladding dielectric constant and of the device geometry on the electro-optical tunability, we performed additional simulations and experiments, in which the same microring devices were clad with silicon dioxide (SiO$_2$). We chose SiO$_2$ as this is a standard cladding material in integrated optics. Moreover, for all reported LiNbO$_3$-based optical microrings SiO$_2$ has been used as a cladding material [45, 46]. Hence, our experiments with SiO$_2$-clad microrings served as a reference for the PVA-based microrings and for a comparison with other published studies.

In the fabrication of SiO$_2$-based electro-optically tunable microresonators, we first removed the PVA cladding and the upper electrodes from the existing microrings by submerging the devices in a water ultrasound bath. The 800 nm thick SiO$_2$ buffer layer was then deposited onto the cleaned microring waveguides by the Plasma Enhanced Chemical Vapour Deposition (PECVD) process. The upper electrodes were structured on top of the SiO$_2$ cladding by patterning the photoresist mask with the laser lithography, evaporating 10 nm Chromium (for improved adhesion) and 200 nm Aluminium onto the sample and finally removing the photoresist mask. The upper electrode covered the microring waveguide and stretched for another 10 µm toward the ring centre, as shown in Figure 6.1.
The optical characterization of the SiO$_2$-covered microring resonators included the measurement of their transmission, their electro-optical tunability and amplitude modulation. All measurements were performed with TE polarised end-fire coupled laser light at $\lambda = 1.5$ $\mu$m. Figure 6.2 shows a photograph of the sample mounted in the testing setup during experiments.

The measured transmission spectra resemble the previous ones in all significant features: the free spectral range, the modulation depth and the spectral width of the resonances. The static electro-optic tunability was measured for bias
voltages between 0 V and 50 V, (Figure 6.3). The measured wavelength shifts give a tunability $\delta \lambda / \delta V = 3.7\pm0.3$ pm/V.

![Transmission spectra at selected bias voltages](image)

Figure 6.3: The measured transmission spectra at the selected bias voltages.

To measure the dynamic amplitude modulation the wavelength of the probe laser was set on $\lambda = 1603.05$ nm, the maximum-slope point of the transmission function, as marked on Figure 6.4 (a), and the electrodes were connected to a function generator giving a sinusoidal modulation voltage with a voltage peak-to-peak amplitude of 21.4 V at a frequency of 10 Hz. The measured microresonator optical response at the through port is shown on Figure 6.4 (b). The difference between the maximal and the minimal transmission was $2\Delta T = 0.22\pm0.2$, which corresponds to a $71\pm5$ pm wavelength shift, giving the electro-optical tunability of these devices as $\delta \lambda / \delta V = 3.3\pm0.3$ pm/V. The theoretically predicted tunability, calculated with the OlymPOS software, was 3.4 pm/V for the given microring waveguide geometry, which agrees remarkably well with the measured value. The measured electro-optical tunability is for a factor of 5 higher than the previously reported values in similar microring resonators [46].
6.2 Proposed steps for improving the microring performance

As described in Chapter 6, a PVA cladding enhances the electro-optical tunability for a factor of around 3, as compared to the SiO₂-based devices. Applying a high dielectric cladding is essential for increasing the tunability. Ultimately, applying semitransparent electrodes directly on the microring waveguides would avoid the loss of the electric potential outside of the active waveguide region, maximising thus the electro-optic tunability. We simulated the optical mode propagation in a waveguide with the same dimensions as in Figure 5.1, with Aluminium doped Zinc oxide (Al:ZnO) semitransparent electrode applied directly on top of the ring waveguide, with a similar geometry as the upper electrode in Figure 6.1. The calculated tunability for a 50 nm thick electrode with a low Aluminium doping was $\delta\lambda/\delta V = 9.2$ pm/V. This represents roughly a 15% increase over the simulations for the same microrings buffered with PVA.
Chapter 7

Conclusions

In this work, we have investigated one of the routes towards efficient, controllable optical microresonators, which are believed, among other applications, to form the backbone of the future very large scale integrated photonics. Our main contribution to the above stated aim was a successful implementation of several technologies and materials, which all combined yield microring resonators in lithium niobate with a high electro-optical tunability. For the fabrication of the planar waveguides, we have implemented fluorine ion implantation, a technique recently discovered to produce amorphisation in lithium niobate. The surface patterning was performed using laser photolithography and ion sputtering. The laser lithography provided us with extended flexibility in designing our waveguide- and electrode- structures. For optical isolation of the microring waveguides from the electrodes, we investigated the usage of a new material, a high dielectric constant polyvinyl alcohol and compared it to the standard silicon dioxide cladding.

Fluorine ion implantation in lithium niobate enables the fabrication of single mode planar optical waveguides, optically isolated from the substrate by a wide (several µm) optical barrier with a moderate index contrast of $\Delta n = 0.17$. Leaving the guiding layer almost unaffected, the method is also fast compared to other fabrication techniques, and well reproducible. Therefore, it would be worth to investigate further its potential for the lithium niobate-based integrated optics. The realised microring resonators with ring radii $R = 80 \mu\text{m}$ have a free spectral range of 2 nm, a finesse $F = 4$, a quality factor larger than 3000 and an extinction ratio of 14 dB. With a polyvinyl alcohol cladding, these microrings show an electro-optical tunability of 10 pm/V. This is a threefold in-
crease over using a standard silicon dioxide cladding. The improvement shows that for realising lithium niobate-based electro-optical devices, the waveguides must be clad with a high dielectric constant buffer or directly with semitransparent electrodes. We estimate that the performance of these devices can be further improved. The ample index contrast allows ring radii of around 40 µm, giving a free spectral range of 4 nm, without significantly higher radiation losses. In order to reduce propagation losses, the annealing and the surface structuring need to be further investigated. Such optimised devices would be real candidates for a variety of applications, particularly in the visible region, where silicon microresonators cannot be used.
Appendix A

Fluorine ion implantation into BiB$_3$O$_6$ and KNbO$_3$

In parallel to the main project, we performed preliminary investigations of the use of fluorine implantation for waveguide fabrication in other materials that were investigated in our research group, namely $\beta$-BaB$_2$BO$_4$, KNbO$_3$ and BiB$_3$O$_6$. The implantations were performed at room temperature, with current densities of 100-150 nA/cm$^2$, ion energies of 22-30 MeV and fluences of 0.5-5×10$^{14}$ ions/cm$^2$. The method proved not usable for $\beta$-BaB$_2$BO$_4$, as fluorine implantations induced cracks on the surface of all implanted samples. A possible reason could be the accumulation of charge on the surface, with the resulting high electric field splitting off the surface layer [62].

A.1 BiB$_3$O$_6$

Bismuth triborate BiB$_3$O$_6$ (BIBO) is a new nonlinear optical crystal [63] that offers major advantages over BBO. It has a substantially higher nonlinear optical coefficient ($d_{33} \sim 3$ pm/V), is not hygroscopic and offers a variety of phase matching schemes [64] due to its low crystal symmetry. Additionally, the facets of the cut samples can be easily polished and thus prepared for end fire optical coupling. Although planar optical waveguides in BIBO have been reported [65-67], the applied method of He$^+$ implantation seems to be difficult. In fact, sample surfaces regularly cracked upon He$^+$ implantation in our experiments [68]. This makes the search for alternatives to He$^+$ implantation highly interesting.
In our preliminary experiments on BIBO we performed several fluorine ion implantations with ion energy of 22 MeV and fluence of $5 \times 10^{14}$ ions/cm$^2$ into the $z$-cut crystals (implanted surface orthogonal to the refractive index $n_3$, as specified in [63]). The implanted samples were optically characterised with the dark-mode spectroscopy. On Figure A.1 (a), the measured relative intensity of the TM polarised light reflected from the coupling prism versus the prism angle is shown. The first 11 sharp dips indicate guided modes, with the following broader dips representing the substrate modes. Figure A.1 (b) shows the corresponding mode curves of the effective indices. The measured effective index of the first guided mode was $1.824 \pm 0.001$, which indicated about 1% increase of the refractive index in the waveguiding region as compared to the bulk value of $n_3 = 1.806$ [63], enabling non-leaky waveguide modes. The waveguide thickness, as estimated from the mode curves and Equation 4.1, was 8.4 $\mu$m. This matched with the edge of the nuclear damage peak, the centre of the peak being at 8.7 $\mu$m, as simulated with the SRIM software. For a rough estimation, the refractive index of the optical barrier equals the effective index of the last guided mode, which gave an index contrast of 2.7% between the waveguide and the optical barrier. With these experiments, we demonstrated that planar waveguides in BIBO could be produced by fluorine ion implantation. Further research is needed for an unambiguous assessment of the feasibility of this approach for the waveguide production in BIBO.
Potassium niobate (KNbO$_3$) is a ferroelectric crystal that has been heavily investigated in our laboratory [69, 70]. The implantations with 30 MeV fluorine ions at several different fluences into c-cut (c-axis orthogonal to the implantation surface) KNbO$_3$ samples induced a region of reduced refractive indices at the position of maximal nuclear damage. The index profiles of the implanted samples were inspected with dark-mode spectroscopy. Figure A.2 shows the measured mode curves for the three refractive indices in a sample implanted with a fluence of 3·10$^{14}$ ions/cm$^2$. From the effective indices of the first guided modes, we can infer that the refractive indices remained largely unaltered in the waveguiding region. The corresponding waveguide thickness, calculated with Equation 4.1, was 9.5 µm and coincided with the position of the edge of the nuclear damage peak, as simulated with the SRIM software. The index contrast of the optical barrier was in the range of 1% for all investigated implantation fluences (0.5-5·10$^{14}$ ions/cm$^2$). In conclusion, we demonstrated the optical waveguides in KNbO$_3$ generated by nuclear damage of fluorine implantation. However, the research has been discontinued due to small index contrast of the optical barrier.

Figure A.2: Mode curves for the effective indices of the implanted KNbO$_3$. 

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A.2 KNbO$_3$
Appendix B

Cr:LiSrAlF₆ channel waveguides as broadband fluorescence sources³

Abstract: We report on the production and fluorescence of active channel waveguides in Cr:LiSrAlF₆. We have produced ~ 10 µm wide and 5 µm high channel waveguides by He⁺ ion implantation, lithographic patterning and subsequent Ar⁺ ion sputtering. Diode-pumped waveguides emitted 13 µW of fluorescence light with a spectrum ranging from 760 nm to 900 nm at a pump power of 165 mW and a pump wavelength of 660 nm. The compact and cheap optical pump source is a main advantage of this fluorescence material. This makes Cr:LiSrAlF₆ channel waveguides a suitable candidate for a broadband fluorescence source in low-coherence interferometry and other applications in the near-infrared wavelength range.

³ This Chapter has been published in Applied Physics B 88, 205 (2007) [13]
B.1 Introduction

Cr:LiSrAlF$_6$ (Cr:LiSAF) is an interesting fluorescent material characterised by a wide emission bandwidth in a wavelength range of 750-930 nm, similar to that of Ti:sapphire, which makes it useful for tuneable laser action or ultra short pulse operation. Similarly as Ti:sapphire [71], this material may also be used as a broadband fluorescence source in optical low coherence interferometry and particularly in optical coherence tomography (OCT) [72]. However, the broadband light source based on Cr:LiSAF could be cheaper and more compact since its wide absorption band in the 640–680 nm range [73] permits direct optical pumping with commercially available red laser diodes. The material’s low peak emission cross section requires high pump power density for efficient fluorescence or cw lasing. On the other hand, high heat generation density leads to enhanced thermal quenching [74, 75], which is difficult to counteract in a bulk crystal, since the material thermal conductivity is rather low [76]. Both high optical pump power density and efficient heat removal can be provided by confining the light in a waveguide. In addition, the output light of channel waveguides can be more effectively coupled into a single mode fibre, as required for OCT applications. Recently, extensive research of broadband fluorescence sources in waveguide geometry has been carried out using Ti:sapphire. Active planar waveguides [77], active channel waveguides [78, 79] as well as waveguide lasers [80, 81] have been already presented. In the case of fluorides, research of waveguides in most common fluoride materials is reviewed in [82]. For Cr:LiSAF, only the fabrication of planar waveguides by ion implantation was reported [83]. In this paper, we report on the extensive work that has been recently carried out in our laboratory, with the goal to develop a compact Cr:LiSAF waveguide fluorescence source and ultimately a waveguide laser.

This paper is structured as follows. The fabrication of planar and channel waveguides is briefly described in Section B.2. A detailed optical characterisation of the obtained waveguides is covered in Section B.3. Subsection B.3.1 shows the results of the measurements of the propagation losses and induced refractive index change. The fluorescence emission spectral and spatial properties, the emitted fluorescence power and the optical amplification are presented.
and discussed in Section B.3.2. Conclusions and the outlook are drawn in Section B.4.

B.2 Waveguide fabrication

For producing Cr:LiSAF channel optical waveguides we used a three-step process based on light ion implantation, lithographic patterning and Ar⁺ sputtering. In the past, we have already demonstrated the suitability of this method for the waveguide fabrication in various inorganic [12, 16, 84] and organic [85] nonlinear optical crystals. In our experiments we used 5.5% doped optically polished Cr:LiSAF crystals. High doping was chosen in order to increase the output power and minimize the propagation losses by keeping the waveguides short. Implantations were performed with 2.4 MeV He⁺ ions, giving planar waveguides with a thickness of ~6.5 µm. Ion fluencies ranging from 2 to 15×10¹⁵ ions/cm² were used, with an average current density of 0.2 µA/cm². Implantations were carried out at 100 K, with the ion beam direction slightly off from the orthogonal to the crystal surface in order to avoid channelling effects. Both a-cut and c-cut crystals (c-crystal axis || and ⊥ to the implanted surface, respectively) were implanted.

In most of the a-cut crystals the surface became brittle upon the implantation. As shown in Figure B.1, striations [83], larger cracks, split-off islands and peeling-off of the surface layer developed with the growing implantation fluence. The thickness of the peeled-off layer did not always coincide with the implantation depth, but was in some cases ~2.5 times larger. No surface cracking was observed in the c-cut implanted crystals. Therefore, our research was focused on the development of waveguides in the c-cut crystals. Since the emission cross-section for the π- transition (E||c) is ~2.5 times higher than for the σ- transition (E⊥c), focus was put on the TM waveguide modes.
Channel waveguides were fabricated out of planar waveguides by photolithographic patterning and subsequent Ar⁺ sputtering. Since waveguide modes shift toward the optical barrier (see Subsection B.3.1), a rib height close to waveguide thickness is needed for complete lateral confinement of the propagating light. The achievable height of the smooth sputtered ribs was 4-5 µm, thus limiting the suitable planar waveguide thickness to ~ 5 µm. We thinned the already available implanted planar waveguides from 6.5 µm down to ~ 5 µm by Ar⁺ sputtering of the unmasked crystals. Essentially the same planar waveguides could also be fabricated directly by implanting the bulk crystals with ~ 1.9 MeV He⁺ ions. As a first step of the rib fabrication, a 5.3 µm thick
photoresist (PR) layer (Clariant AZ 4533) was spin-coated on top of the implanted crystal surface. PR stripes of 11 µm width were then formed by standard photolithography and hardened with a 30 min hardbake at 115°C. After that, the PR pattern was transferred down to the Cr:LiSAF planar waveguide by Ar⁺ sputtering (Oxford Plasmalab 80, RF power 300W) and the 5.0 µm high ribs were finally fabricated. The sputter rates of the Cr:LiSAF and the PR mask were 3.9 nm/min and 1.9 nm/min, respectively. The obtained structures were investigated with a profilometer and a scanning electron microscope (SEM). In Figure B.2 an SEM image of the fabricated rib waveguide with a polished end facet is shown. The He⁺ stopping region is clearly seen as a sharp groove, separating the rib from the bulk material.

Figure B.2: SEM image of the fabricated rib structure. The He⁺ stopping region is clearly recognizable as a sharp groove, separating the rib from the bulk. The waveguide cross section is trapezoidal with the width at the base $w \sim 11$ µm, width on top $d \sim 9$ µm and height $h \sim 5$ µm.

B.3 Optical characterisation

B.3.1 Refractive index profile and propagation losses

By TM dark mode spectroscopy using prism coupling, we could determine the refractive index profile $n_e$ in the surface region of the crystal. The calculation method is presented in more detail in [11]. Figure B.3 shows a reconstructed refractive index profile that best matches the measured data, together with the mode curve of the measured and calculated waveguide modes. The FWHM of the calculated barrier is $\sim 0.5$ µm, which is in agreement with the SRIM-2003
(Stopping and Range of Ions in Matter [19]) simulation. Comparison between the calculated index profile and the simulation of the implantation damage implies that the electronic energy loss (EEL) of He$^+$ ions shapes the nonuniform index profile in the wave-guiding layer. The EEL reaches its maximum at $\sim 3.5 \mu m$ and drops steeply afterwards. The nuclear energy loss (NEL) occurs only at the end of the ion track and gives shape to the low-index optical barrier. In-between, there is a window of minimal combined loss (EEL and NEL) that results in smaller index decrease at $\sim 5.5 \mu m$. Consequently, the centre of the waveguide modes shifts toward the barrier (see Figure B.5).

Figure B.3: Refractive index profile for an implantation using $5 \times 10^{15}$ ions/cm² of 2.4 MeV He$^+$ ions, measured at 633 nm. The data points represent the measured TM dark mode positions and the solid curve through them gives the theoretical mode positions corresponding to the shown fitted profile.

In order to optimize the performance of a potential waveguide laser or a broadband fluorescence source, the propagation losses at both the pump wavelength and especially the emission wavelength should be as low as possible. Measurements of the planar waveguide propagation losses at the near-infrared (NIR) emission wavelength of 830 nm (close to the max. of fluorescence, see below) were performed using the end-coupling configuration. A tuneable Cr:LiSAF laser (IR-Point, Rainbow Photonics) was employed as the source of the probe beam. The transmitted waveguide output was selected with the aperture and measured with a silicon power meter. Two cylindrical lenses were
used to focus the collimated beam in one plane and couple it into- and out of the planar waveguide. The lowest propagation losses of $9\pm1$ dB/cm (TM polarisation, assuming a coupling efficiency of 80%) were measured in the waveguides implanted with a fluence of $5\times10^{15}$ ions/cm$^2$. Relatively high losses are attributed to the absorption due to implantation-generated colour centres and to the tunnelling through the barrier. In order to reduce the losses due to absorption, the pulsed laser annealing (PLA) technique was suggested in [83]. However, the PLA performed similarly as in [83] did not reduce the losses. It is believed that the ultraviolet light penetrated the crystal far beyond the waveguiding layer and accordingly annealed the barrier as well. Alternatively, thermal annealing was performed for up to 10 hours at $\sim210^\circ$C. The measured losses decreased for $\sim5\%$, which is still within the experimental error of the loss measurement.

Channel waveguides fabricated by etching techniques usually suffer from additional losses with respect to the planar waveguides due to additional scattering on the waveguide sidewalls. The attenuation of the light propagating in the fabricated rib waveguides was measured by a similar end-coupling setup, in which the microscope objectives of magnification 10× were used to couple the light into- and out of the rib waveguides. The lowest value of the measured losses in a 2.0 mm long crystal for TM polarised light at $\lambda = 830$ nm was $10\pm2.5$ dB/cm, assuming a coupling efficiency of 80%. Because of strong tunnelling, the electric field of the light propagating in the waveguide extended significantly beyond the barrier. Comparison of the propagation losses in planar and channel waveguides suggests that surface scattering could have only a minor contribution (of $< 1$ dB/cm) to the overall propagation losses. Two major sources of losses were tunnelling through the optical barrier and absorption caused by the colour centres. According to the numerical simulation of the light propagating in the rib waveguide, the tunnelling and the absorption had similar contributions to the light attenuation in the waveguide.

B.3.2 Fluorescence emission characteristics

The spectral, spatial and power characteristics of the fluorescence light emitted by the optically pumped channel waveguides were investigated. A single transversal mode red laser diode (Opnext HL6526FM, max. 165 mW at 660 nm) was used as the optical pump source. The fluorescence emission from the exit
facet of the waveguide was imaged by a microscope objective onto the spectrometer, CCD camera and silicon power meter, respectively. A long-pass filter was used to remove the residual pump radiation.

Figure B.4: Measured spectrum of the fluorescence light emitted out of the waveguide (solid line) and the underlying bulk material (dashed line). The fluorescence spectrum of the waveguide remains predominantly unchanged.

Figure B.4 shows the measured spectra of the fluorescence light emitted from the waveguide and from the bulk crystal. The spectra differ only slightly, which suggests that the local environment of the active Cr$^{3+}$ ions remained mostly unaltered after the implantation. The spectrum width in the case of the waveguide was 75 nm FWHM, compared to 85 nm FWHM in the bulk material. The spectral distribution is narrower on the long wavelength side and the spectrum peak of the waveguide output is shifted for 7 nm to 803 nm. Both effects can be attributed to the comparatively higher tunnelling losses on the longer-wavelength side. The intensity profile of the fluorescence emitted from the waveguide is shown in Figure B.5. The measured intensity profile is symmetrical and strongly confined in the horizontal direction as a consequence of the 5 µm deep etching. The asymmetry in the vertical plane (⊥ to the implanted surface) is attributed to the nonuniform refractive index within waveguide and to the leakage of light through the optical barrier into the bulk material.
The output power of the fluorescence emission as a function of the input optical pump ($P_p$) power is shown in Figure B.6. The maximal measured fluorescence output power was around 13 µW at 165 mW input power. The crystal’s base surface was held at 6°C. According to our estimation, the temperature in the front part of the waveguide rose to 60-100°C for $P_p = 100$ mW. Therefore, we suppose that strong thermal quenching occurred and suppressed the emission at higher input powers. This would explain why the slope efficiency decreased from $\sim 15\times10^{-5}$ to $\sim 4\times10^{-5}$ with increasing input power. Polarisation ratio of the emitted fluorescence was $I_c : I_a = 2.4:1$, which is in agreement with the ratio of the corresponding emission cross-sections in a bulk crystal [73].
Actually in-coupled pump power is $\sim 0.7 \times$ input power. Dimensions of the waveguide: cross-section as in Figure B.2, length is 2.0 mm.

Additionally, the NIR probe beam was coupled simultaneously with the pump beam into the waveguide and the optical amplification of the NIR light was measured. The NIR power before first microscope objective was 2.1 mW, the out-coupled power was 0.82 mW, which gave propagation loss of 10.3 dB/cm for that particular waveguide. The rise of the NIR output with increasing optical pump is shown in Figure B.7. The out-going NIR increased nearly proportionally to the input optical pump until $P_p \sim 70$ mW, after which it remained constant, within the measurement error. We simulated NIR amplification along the waveguide with a simplified one-dimensional numerical model using the laser rate equations. The measurement data were in good agreement with the model for the product $n_i \times \tau_f$ being approximately 20-25 times smaller than the $n_{0i} \times \tau_{0f}$ of the bulk material, where, $n_i$ is the density and $\tau_f$ is the fluorescence lifetime of the active Cr$^{3+}$ ions in the waveguide, respectively. We believe that due to temperature increase within the waveguide the major contribution to the drop of $n_i \times \tau_f$ came from a smaller fluorescence lifetime due to thermal quenching, at least at higher optical pump powers.
B.4 Conclusion

Cr:LiSAF channel waveguides have been fabricated by He⁺ implantation and Ar⁺ sputtering. The waveguides supported NIR optical mode propagation with moderate propagation losses. The two major sources of propagation losses were found to be tunnelling through the optical barrier and absorption due to colour centres. Losses in the channel waveguides did not increase significantly with respect to the ones in planar waveguides due to the smooth rib surface of the channel waveguides. The fluorescence emitted from the optically pumped waveguides was spatially well confined and had a wide spectrum ranging from 760 nm to 900 nm. Therefore, we expect that such devices could be considered for the fluorescence source in the low-coherence interferometry where high longitudinal resolution is needed. The fluorescence output power in these proof-of-concept experiments was up to 13 µW at 165 mW of pump power. The output power could be further increased by optimising the optical barrier and by a more efficient annealing. Thermal quenching was the most probable cause that limited the output power. Attaching a clad waveguide directly to a heat sink could significantly diminish thermal quenching and allow a further increase of the emitted fluorescence output power.
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List of Publications

Journal Papers


Conference Publications

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