Doctoral Thesis

Electro-optical microresonators in ion-sliced lithium niobate

Author(s):
Koechlin, Manuel

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Electro-optical microresonators in ion-sliced lithium niobate

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Manuel Koechlin
Dipl. Phys. ETH
born February 21, 1978
citizen of Basel (BS)

accepted on the recommendation of

Prof. Dr. B. Batlogg, examiner
Prof. Dr. P. Günter, co-examiner

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Abstract

Lithium niobate (LiNbO$_3$) is a highly stable ferroelectric crystal exhibiting superior physical properties, stemming from its non-centrosymmetric crystal structure. It also possesses a large transparency range from the violet to the infrared wavelength region wherefor it is a versatile material appreciated for various photonic applications. In nonlinear optics and optoelectronics its large electro-optic activity and nonlinear optical effects are in great demand especially for optical devices and modulators such as Mach-Zehnder interferometers. For decades, titanium indiffusion and proton exchange were the sole methods for the fabrication of planar waveguides in LiNbO$_3$, which imposes a severe limitation to the further development of very-large scale integrated (VLSI) photonic devices in this material. Microring resonators in particular are envisaged to be one of the main building blocks in future VLSI photonic devices, offering a bunch of new functionalities especially in the combination with nonlinear crystals such as LiNbO$_3$. In that field of research, which is still governed by the well established silicon-on-insulator platform, the recently developed ion-sliced LiNbO$_3$ thin films and fluorine-implanted LiNbO$_3$ crystals could play an important role. While the former exhibits a high index contrast $\Delta n = 0.65$, which suppresses bending losses in strongly curved optical waveguides with radii below 10 $\mu$m, the fluorine-implanted LiNbO$_3$ crystals allow structuring of single-mode optical waveguides with more relaxed fabrication requirements due to the moderate index contrast ($\Delta n = 0.17$), but still permit curvature radii of 40 $\mu$m. All in all, these new platforms are considered to tremendously increase the versatility of optical microcavities by combining small footprint with the excellent nonlinear properties of LiNbO$_3$. This work strives for an improvement of optical microrings in ion-sliced LiNbO$_3$, which were demonstrated the first time in our laboratory.

The fabrication of high-index contrast optical microresonators requires sophisticated lithography tools, allowing on the one hand fast and flexible prototyping, but also enabling patterning of structures with small dimensions and tolerances, which are needed for these resonators. In the framework of this thesis we therefore developed a laser lithography system based on acousto-optic deflection, enabling sub-micrometer precise exposure of photoresist with an optical resolution down-to 200 nm. The laser source, a solid state laser emitting at 375 nm, permits an efficient exposure of i-line sensitive photoresist such as SU-8. Due to its flexibility
and convenient handling, it is a suitable tool for fast prototyping of integrated photonics devices including microring resonators with diameters up to 200 µm. Well defined gaps in the 200-nm range between two structures are achieved by using a two-step lithography process. Moreover, large areas can be exposed allowing the patterning of diverse electrode configurations for electro-optical tuning. This highly capable device, which we describe in a separate chapter, builds the foundation of all other subsequently presented publications. In an appended chapter it is shown, that the laser-lithography setup could be further improved by the integration of a compact femto-second laser emitting at 390-nm wavelength, which enables two-photon absorption lithography with considerably increased resolution. The feasibility of exposing SU-8 with a two-photon absorption process at various wavelengths between 390 and 780 nm is demonstrated and the two-photon absorption coefficients $\beta$ at these wavelengths were determined experimentally.

Based on laser-lithographic structuring we present the first electro-optically active microring resonators in fluorine-implanted LiNbO$_3$. The implantation process deployed induces strongly confined planar waveguides for single-mode operation in the telecom wavelength range (around 1.55-µm wavelength) and a refractive index contrast $\Delta n = 0.17$ for TE-waves. In such crystals we have produced microring resonators with a radii of 80 µm. Their TE-wave transmission spectra, measured around 1.55-µm wavelength, exhibited resonances with free spectral ranges of 2.0 nm, finesse of 4 and modulation depths up to 14 dB.

However, due to the limited refractive index contrast high-Q microrings in fluorine-implanted LiNbO$_3$ are feasible only down to radii of approximately 40 µm. For smaller rings, which are envisaged for many applications, planar waveguides with higher index contrasts, such as ion-sliced LiNbO$_3$ thin films, are necessary. In these crystals, fabricated in our laboratory, we demonstrated planar structured racetrack resonators showing TE-wave transmission spectra with free spectral ranges of 7.0 nm at 1.55-µm wavelength. Due to the difficulties in fabricating sub-100-nm gaps between the ring and the port waveguide, resonances with modulation depths of only 3 dB could be measured.

In order to improve the performance of the microrings, we fabricated free-standing LiNbO$_3$ microrings from ion-sliced LiNbO$_3$ thin films, which can be coupled to waveguides from any material. Microrings were structured in such thin films, chemically detached from the polymer and subsequently transferred onto a new host substrate. Rings with 20-µm radii were combined with gallium nitride waveguides to vertically coupled hybrid microring resonators by using a micropositioning tool. Such microring resonators were characterized in a wavelength range around 1.55 µm with TE-polarized light. The resonances had modulation depths of up to 18 dB, finesse of 50 and free spectral ranges of around 1 THz, which corresponds to 8 nm at the measured wavelength.
Zusammenfassung

Lithiumniobat (LiNbO$_3$) ist ein strukturell stabiler, ferroelektrischer Kristall mit außergewöhnlichen nichtlinearen optischen Eigenschaften, welche von seiner nichtzentrosymmetrischen Kristallstruktur herrühren. Zusammen mit seiner Transparenz im Wellenlängenbereich zwischen violet und infrarot macht ihn das zu einem vielseitigen Material, welches in verschiedenen photonischen Anwendungen geschätzt wird. Im Bereich der nichtlinearen Optik und Optoelektronik sind die grossen elektro-optischen Effekte von LiNbO$_3$ sehr gefragt, insbesondere für integriert-optische Komponenten wie Mach-Zehnder Interferometer. Über Jahre waren Eindiffusion von Titan und Protonenaustausch die einzigen Möglichkeiten zur Herstellung von planaren Wellenleitern in LiNbO$_3$, was eine starke Einschränkung in der Entwicklung von hochintegrierten optischen Elementen in diesem Material darstellte. Insbesondere Mikroresonatoren sind dazu gedacht, die Hauptbauteile von zukünftigen hochintegrierten optischen Schaltungen zu sein, da sie, insbesondere in Kombination mit den Eigenschaften nichtlinearer Kristalle, ein Fülle von neuen Funktionen bieten. In diesem Forschungsbereich, welcher noch immer von der bewährten Silizium auf Isolator Plattform dominiert wird, könnten die kürzlich entwickelten ionengeschnittenen LiNbO$_3$ Dünnfilme und Fluor-implantierten LiNbO$_3$ Kristalle eine wichtige Rolle spielen. Während erstere einen hohen Brechungsindexunterschied $\Delta n = 0.65$ bieten, welcher Strahlungsverluste in stark gekrümmten Wellenleitern mit Radien bis unter 10 $\mu$m verhindert, sind Fluor-implantierte LiNbO$_3$ Kristalle aufgrund des moderaten Brechungsindexunterschiedes ($\Delta n = 0.17$) einfacher zu strukturieren, erlauben aber noch immer Radien von etwa 40 $\mu$m. Durch die Kombination kleiner Bauformen und der vortrefflichen nichtlinearen optischen Eigenschaften von LiNbO$_3$ könnten diese zwei Plattformen die Vielseitigkeit von optischen Mikrokavitäten in Zukunft erheblich vergrößern. In dieser Arbeit sind wir bestrebt, die Eigenschaften von optischen Mikroresonatoren in ionengeschnittenen LiNbO$_3$ Dünnfilmen zu verbessern, welche kürzlich erstmals in unseren Laboratorien gezeigt wurden.

Für die Herstellung von optischen Mikroresonatoren mit hohem Brechungsindexunterschied werden hoch entwickelte lithographische Methoden benötigt, die schnelles und flexibles Prototyping ermöglichen und zudem auch die Belichtung von hochauflösenden Strukturen erlauben, welche für solche Resonatoren nötig sind. Im Rahmen dieser Arbeit haben wir deshalb ein Laserlithographiesystem entwickelt, welches
ZUSAMMENFASSUNG


Um die Charakteristiken dieser Resonatoren zu verbessern, haben wir freiste-