Periodically Poled LNOI Photonic Wires

Hui Hu, Daniel Büchter, Raimund Ricken, and Wolfgang Sohler

Angewandte Physik, Department Physik
Universität Paderborn, Paderborn, Germany
hhu@mail.upb.de

Abstract: **The recent development of wafer-scale, single-crystalline lithium niobate (LN) thin films, crystal-bonded to a SiO_2 layer deposited on a Z-cut LN substrate ("LNOI"), was modified to get periodically poled LNOI of 9 µm grating constant. Using this material, photonic wires of cross-section down to ~ 1 × 0.7 µm^2 were developed. They allowed to demonstrate third order quasi phase matched second harmonic generation of λ = 1064 nm radiation. Unprecedented efficiency of nonlinear interactions in periodically poled LNOI photonic wires is predicted.**

Keywords-lithium niobate; periodic poling; photonic wires; second harmonic generation (SHG).

I. INTRODUCTION

Optical waveguides of high refractive index contrast – such as the well developed Silicon-On-Insulator (SOI) "photonic wires" - can have a very small cross section (even below 1 µm^2) and also bending radius (~10 µm), enabling the development of ultra-compact photonic integrated devices and circuits [1]. A corresponding technology for lithium niobate (LN) is still in its infancy, though LN offers – in contrast to SOI - excellent electro-optic, acousto-optic, and nonlinear optical properties. Moreover, it can be easily doped with rare-earth ions to get a laser active material [2]. Therefore, LN photonic wires will enable the development of a wide range of very compact, active integrated devices. In particular, periodically-poled LN photonic wires promise extremely efficient (quasi-) phase matched nonlinear interactions for wavelength conversion and all-optical signal processing.

Recently, the fabrication of wafer-scale, single-crystalline LN films has been reported enabling the development of LN photonic wires of excellent quality (see Fig. 1) [3]. They can have a cross section down to ~ 1 × 0.7 µm^2. In this contribution, the first periodically poled LN photonic wires of similar dimensions are reported. Moreover, third-order quasi phase matched (QPM) second harmonic generation (SHG) of λ = 1064 nm radiation has been successfully demonstrated.

II. LNOI (LITHIUM NIOBATE ON INSULATOR) FABRICATION

The special "smart cut" process, widely used for the fabrication of a thin single crystalline Silicon film on an amorphous SiO_2 layer on a Silicon substrate, better known as Silicon-On-Insulator (SOI) [4], was used for the fabrication of LN films on a SiO_2 cladding (LNOI). Such crystal bonded layer structures have been pioneered by the groups of Osgood [5] and Günter [6] on smaller substrates. At first, a Z-cut LN wafer of 3`` diameter is implanted by 250 keV or 350 keV He-ions, respectively, with a dose of 4×10^{16} ions/cm^2 forming an amorphous layer

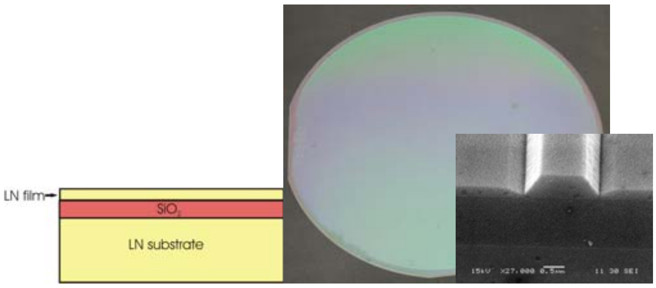

Fig. 1. Structure and photograph of a LNOI wafer of 3 inch diameter together with a SEM micrograph of a LNOI photonic wire on the right.

at about 760 nm or 1040 nm underneath the surface. Another Z-cut LN handle sample is coated by a SiO_2-layer of 1.8 µm thickness by plasma enhanced chemical vapor deposition (PECVD), and then annealed at 450 °C for 8 hours to drive off the gases trapped in the oxide layer. With a chemical mechanical polishing (CMP) process, the surface roughness is reduced from about 6 nm to 0.35 nm enabling direct wafer bonding. The bonded pair of samples is then annealed to improve the bonding strength; by a further increase of the temperature to 228 °C for 2 hrs the sample splits along the He implanted layer. Fig. 1 shows such a "LNOI" wafer of 3 inch diameter. Afterwards, it is annealed at 450 °C for 8 hours, before the LNOI surface is polished by another CMP-process. Fig. 1 also shows a photonic wire of 1 µm top width, fabricated by ion beam etching of a LNOI substrate [3].

The same technique was used to develop periodically poled LNOI samples. A PPLN crystal of 9 µm periodicity of the ferroelectric domain grating was "smart-cut" and crystal-bonded to the SiO_2 layer on top of the LN handle sample.

III. LNOI PHOTONIC WIRES

Starting with a periodically poled LNOI sample of 9 µm periodicity, several photonic wires of different width (1 – 7 µm) have been fabricated. Photoresist (OIR 907-17) stripes of 1.7 µm thickness and 1 - 7 µm width were defined by photolithography as etch mask. Subsequently, the sample was etched by Ar milling in an Oxford Plasmalab System100. Fig. 2 shows a scanning electron microscope (SEM) micrograph of a PPLN photonic wire of 1 µm top width and 710 nm thickness. On both sides of the ridge, etched trenches can be observed, resulting from additional etching by ions reflected by the angled walls of the ridge. As the domain structure was hardly visible in SEM micrographs, an optical micrograph is also presented taken with a differential interference contrast microscope. After some contrast enhancement, the domain grating is clearly visible not only in the remaining LN-film on both sides of the ridge, but also in the photonic wire itself. Finally, the end faces of the sample were carefully polished to enable efficient end-fire coupling of light; the length of the sample was about 3 mm.

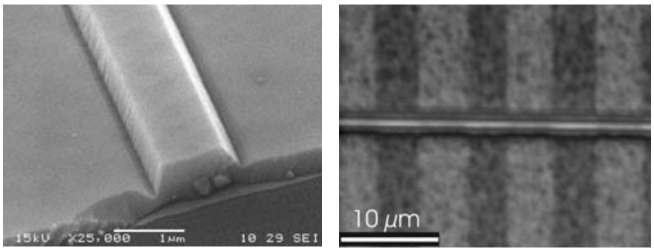

Fig. 2. SEM micrograph (left) and optical micrograph (right) of a periodically poled LNOI photonic wire of 1 µm top width and 710 nm thickness. The periodicity of the ferroelectric domain grating is 9 µm.

The waveguide mode dispersion is determined by the material dispersion of core and cladding and by the waveguide dimensions. It was calculated by the finite difference method for the fundamental qTM-modes; the results – together with some measured group indices – are displayed in Fig. 3 for a waveguide of 1 µm top width. As already known from SOI photonic wires, the strongly reduced cross-section dimensions significantly modify group and effective indices and their dispersion.

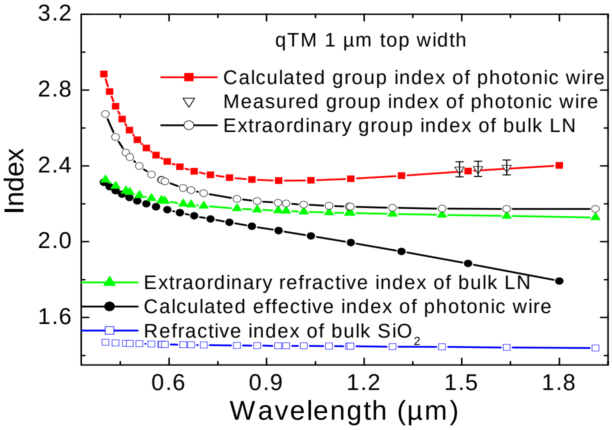

Fig. 3: Calculated effective and group indices for the fundamental modes of qTM polarization in a photonic wire of 1 µm top width and 730 nm thickness versus the wavelength. The measured group indices of photonic wires, the calculated group indices of bulk LN, and the refractive indices of bulk LN and SiO_2 are shown as well for comparison.

IV. SHG IN PP LNOI PHOTONIC WIRES

Due to the modified dispersion in the nonlinear LNOI photonic wires, also their phase matching properties for nonlinear interactions are correspondingly dependent on the waveguide dimensions. They were theoretically investigated for second harmonic generation (SHG) in our LNOI photonic wires taking also a periodically poled domain grating into account. The calculations showed that type I QPM SHG for a fundamental wave of 1064 nm wavelength should be possible in a wire of 1 µm top width and 730 nm thickness, but with a domain grating of 3 µm periodicity. As our PP-LNOI waveguides have a grating period of 9 µm, only a third order interaction could be expected, resulting in a strongly reduced efficiency. Fig. 4 shows the calculated normalized SHG-response (for 3 µm periodicity) for different lengths of the grating; the shorter the nonlinear interaction length, the broader the phase matching characteristic is. As only a section of ~ 100 µm length of the waveguide was successfully poled, uncritical phase matching was expected.

To test SHG in our PP-LNOI photonic wires, light of 1064 nm wavelength from a narrow-band laser diode of up to 40 mW output power was coupled to a waveguide by a 60× / 0.8 objective. On the output side a 100× / 0.9 objective magnified the near field distribution of the guided mode to form an image on the camera. The inset of Fig. 4 shows the observed modes of a photonic wire of 1 µm top width and 710 nm thickness at 1064 nm and 532 nm wavelength, respectively. Due to the broad phase matching characteristics, SHG could also be observed in waveguides of 2 - 7 width. As a tunable laser was not available, the SHG efficiency could not yet been tested as function of the fundamental wavelength.

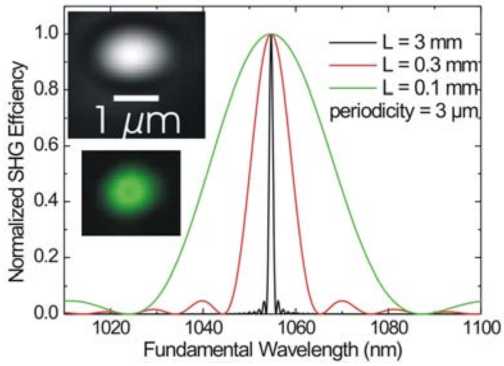

Fig. 4. Calculated quasi-phase-matching characteristics for SHG in periodically poled LNOI photonic wires of 1 µm top width and 730 nm thickness for different (interaction) lengths L and a domain periodicity Λ = 3 µm. Upper and lower insets: photographs of TM-polarized modes of the fundamental (λ = 1064 nm) and the SH mode (λ = 532 nm), respectively.

V. CONCLUSIONS

For the first time, a periodically poled LNOI photonic wire of 9 µm domain periodicity and cross-section dimensions of ~ 1 × 0.7 μm^2 was developed. Third order quasi phase matched SHG was successfully demonstrated. Due to their small mode size, periodically poled LNOI photonic wires have a great potential for the development of second order nonlinear devices of unprecedented efficiency.

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