Periodically-Poled Lithium Tantalate Ridge Waveguides for Efficient Nonlinear Frequency Conversion in the Near UV

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Abstract. Optical damage resistant ridge waveguides for blue and near UV wavelengths have been fabricated using high-temperature Zr and Zn diffusion doping and vapor transport equilibration (VTE) of congruent $LiTaO_3$ crystals. For both dopants high optical damage thresholds >10 MW/cm^2 for 532 nm light were demonstrated at room temperature, which can be increased by a factor ~3 when heating the samples to ~150°C. Ridge waveguides with low optical losses of ~0.4 dB/cm were fabricated using diamond-blade dicing. First-order periodic poling with grating periods of ~3 µm can be used for efficient nonlinear frequency conversion for both SHG (800 nm pump) or SPDC (400 nm pump) processes.

1 Introduction

$LiTaO_3$ is a preferred ferroelectric nonlinear crystal for optical frequency conversion by quasi-phase matching, offering principal advantages for usage at short wavelengths when compared to $LiNbO_3$. Very high nonlinear conversion efficiencies can be obtained for periodically-poled $LiTaO_3$ waveguides. However, because of light-induced photorefractive damage (PRD) appearing at high intensities and short wavelengths, waveguide applications of periodically-poled $LiTaO_3$ have so far been limited mostly to the visible or IR and low powers.

Here we present high-temperature surface diffusion doping of congruent $LiTaO_3$ (cLT) wafers with Zr and Zn in combination with vapor-phase transport equilibration (VTE), where the diffused ions also form a planar wave-guide. Secondary Neutral Mass Spectroscopy (SNMS) has been used to determine the diffusion parameters. After ridge waveguides definition using diamond-blade dicing, PRD threshold measurements at 405 nm and 532 nm have proven excellent damage resistance with power thresholds exceeding watt level. Also, samples were periodically poled with grating periods of 3.3 µm for SHG and SPDC of wavelengths 400 nm and 800 nm.

2 Sample Preparation and Methods

2.1. Diffusion doping

For in-diffusion we deposited (50 – 160) nm layers of ZrO_2 and Zn onto 0.5 mm z-cut cLT samples using e-beam evaporation. In-diffusion took place in a Pt crucible that contains a mixture of Li_2CO_3 and Ta_2O_5 powders of either congruent (c_{Li} = 48.4 mol%) or over-stoichiometric (c_{Li} ≈ 53 mol%, for VTE) composition, at temperatures of (1200 - 1400)°C for ZrO_2 and (1000 - 1200)°C for Zn, resulting in four different types of samples.

2.2 Ridge waveguide formation

To achieve lateral light confinement, ridges with widths ranges of (6 – 18) µm and 25 µm height were prepared using a precision wafer saw (Disco DAD322) with a 140 µm wide resin-bonded blade with grit 6000. Finally, smooth optical-grade end facets were prepared by cutting perpendicularly to the waveguides.

2.3 Optical and PRD characterization

The guided modes' effective indices of Zr:LT and Zn:LT planar waveguides at 532 nm were measured with a prism coupler (Metricon 2010/M) allowing for the reconstruction of refractive index profiles. Propagation losses were determined by transmission measurements for both 405 nm and 793 nm. The PRD thresholds were determined with the setup sketched in Fig. 1. We used two

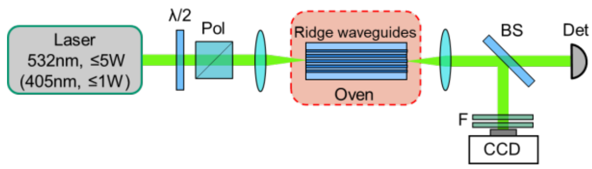

Fig. 1. *Optical setup used for PRD threshold measurement.*

cw laser sources at 405 nm and 532 nm wavelengths with maximum powers of 1 W and 5 W, respectively. The laser beam was coupled into the waveguides through the end facet, and the in-coupled power (max. ≈ 0.5 W at 405 nm and ≈ 3.2 W at 532 nm) was determined by accounting for in-coupling efficiency and Fresnel reflections.

3 Experimental Results

3.1. Diffusion-doped optical waveguides

An example of an SNMS measurement of Zr concentration profiles $C_{Zr}(z)$ is shown in Fig. 2. The experimental profiles were fitted with Gaussian functions,

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and the diffusion coefficients $D = D_0 \exp(-E_A/(k_B T)$ were calculated using the $1/e$ depths of the $C_{Zr}(z)$ depth profiles. From the fit, the values of $D_0 = (4.5 \pm 0.3)\cdot 10^4$ µm²/s and $E_A = (2.8 \pm 0.2)$ eV were determined.

Together with the refractive index profiles obtained by the prism coupler measurements the relation between index change and dopant concentration can be extracted following the method described in [2]. An example for the case of Zr doping is given in Fig. 3, demonstrating a typical slightly sublinear dependence.

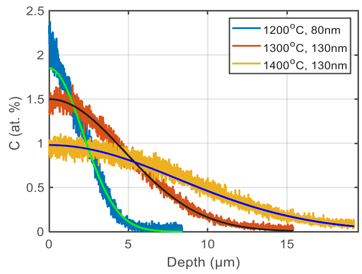

***Fig. 2**. SNMS measurement of Zr concentration profiles.*

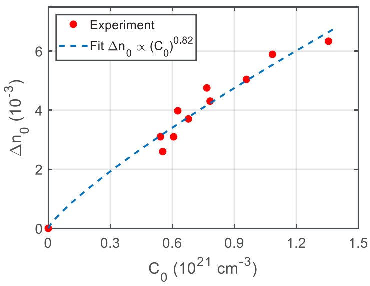

***Fig. 3**. Surface refractive index change Δn_0 vs. surface dopant concentration C_0 for the case of Zr:LT.*

Diffusion parameters and ridge width were chosen to obtain waveguides that are single mode for 800 nm (see Fig. 4). Propagation losses in these ridges were determined to be about (0.4 – 0.7) dB/cm for 405 nm and slightly lower at (0.3 – 0.5) dB/cm for 793 nm.

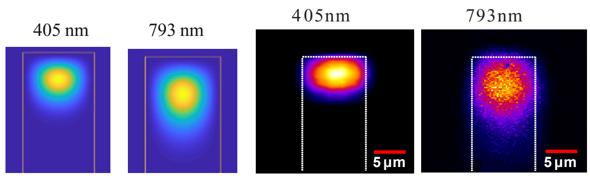

***Fig. 4**. Calculated (left) and measured (right) fundamental mode profiles of a ridge waveguide designed to be single-mode at 800 nm.*

While for Zn doping only TE modes (i.e. ordinary polarized) are guided, Zr doping allows for guiding TM modes (extraordinary polarized) only. With respect to the application of QPM, which applies the d_{33} coefficient, only Zr:LT and Zr:VTE:LT samples were used for poling.

3.2. Photorefractive damage thresholds

In the PRD measurements the onset of the optical damage caused distortion and temporal fluctuations of the mode intensity profiles at the output facet. The results are summarized in Table 1. For Zr- or Zn-doped VTE-treated ridge waveguides, the PRD threshold in the blue could not be reached, while for green light it is found to be above 2 W for both dopants. The two non-VTE-treated samples

***Table 1**. Experimentally determined PRD thresholds for the four different sample types.*

Sample	Pol.	PRD threshold 405nm, mW	PRD threshold 532nm, mW	I_{Peak} 532nm MW/cm²
Zr :VTE:LT	TM	> 500	≥ 2300	≥ 11.5
Zn :VTE:LT	TE	> 500	≥ 2000	≥ 10
Zr:LT	TM	160	280	1.4
Zn:LT	TE	220	650	3.4

showed by a factor of ~3 higher damage thresholds at 532 nm when heated to the temperature of 150°C.

3.3. Periodic poling

After any treatment of LT samples above the Curie temperature (cLT: 600°C, sLT: 700°C), homogeneous re-poling was required at field strengths exceeding the coercive field E_c (cLT: 21 kV/mm, VTE:LT: ≈ 0.2 V/mm). For periodic poling a lithographically-defined Cr grating on the +z facet with <50% Cr duty cycle was used together with real-time control of the flown charge for 50:50 ratio of flipped/un-flipped domains, see Fig. 5. Domains were visualized by etching the (former) +z facet for 1 h in 40% HF solution. An example is given in Fig. 6 on the right.

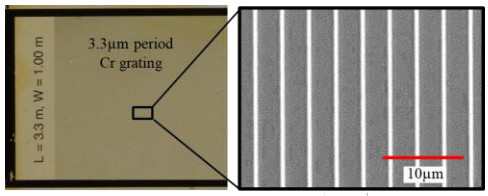

***Fig. 5**. Lithographically defined Cr pattern for periodic poling. Because of the small poling period a duty cycle of 20:80 is used.*

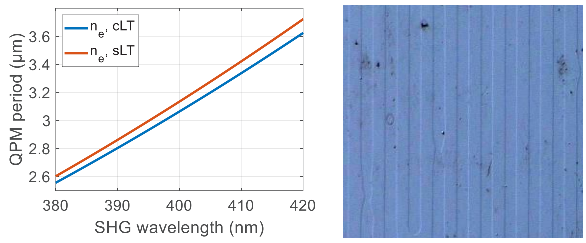

***Fig. 6**. Calculation of QPM periods Λ for SHG towards ~400nm and example of periodically poled (etched) LT sample with Λ = 3.3 µm.*

High resistance to PRD, along with the possibility of low-loss optical waveguide fabrication and periodic poling with small grating periods, makes Zr:LT and Zn:LT promising host materials for a number of applications in the visible and near UV. During the conference, we will thus report on the ongoing experiments of SHG towards 400 nm and spontaneous parametric down-conversion using a 405 nm pump laser.

References

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