# Optical Damage Resistant Near-stoichiometric $Ti:Mg:Er:LiNbO_3$ Strip Waveguides

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***Abstract*—We report optical damage resistant near-stoichiometric $Ti:Mg:Er:LiNbO_3$ single-mode strip waveguides fabricated on congruent $LiNbO_3$ by Er diffusion, Mg/Ti co-diffusion, and vapor-transport-equilibration process. The waveguide optical properties, compositions, crystalline phases and Mg, Er and Ti profiles were characterized, and stable signal enhancement has been measured with >200mW pump power.**

***Keywords-*** *$Ti:Mg:Er:LiNbO_3$ strip waveguide; Near-stoichiometry; Photorefractive effect; Optical amplifier.*

## I. INTRODUCTION

Over the past years, a family of Ti-diffused $Er:LiNbO_3$ (Er:LN) waveguide devices have been demonstrated [1-4]. However, the photorefractive effect not only affects the performances of these devices, but also limits both the pumping and operating wavelengths, and hence hinders further development of new devices. To suppress this effect, two methods have been proposed. One is by propagating along the optical axis *Z* [2]. A disadvantage of this scheme is that it sacrifices the larger electro-optic coefficient $r_{33}$. Another method is by using ZnO-diffused waveguide on an Er:LN codoped with >5 mol% MgO [3]. In this approach, heavy MgO doping causes difficulty in growing high quality Er/Mg-codoped single-crystal, and extremely low Er diffusivity and solubility in the case of local Er-doping. A near-stoichiometric (NS) LN doped with lesser amount of MgO (> 0.8 mol%) can also effectively suppress the photorefractive effect [5]. The realization of a NS Ti:Mg:Er:LN waveguide would open up some new applications, such as 980nm pumped green upconversion and mid-infrared (2.7µm) lasers, and various quasi-phase-matching devices based on periodically poled lithium niobate (PPLN) waveguides.

Recently, we have demonstrated NS Ti:LN strip waveguides fabricated using vapor transport equilibration (VTE) process [6,7]. The realization of NS Ti:Mg:Er:LN waveguide is a challenge. In this work, we report the first demonstration of NS Ti:Mg:Er:LN strip waveguides using VTE process.

## II. EXPERIMENT AND RESULTS

A 11-nm-thick Er metal film was coated onto the surface of a 0.8-mm-thick *Z*-cut pure congruent LN substrate followed by diffusion at 1100 $^oC$ for 100 h in air. Then, four groups of Ti strips, with thickness of 169nm and strip width from 4 to 7µm, were patterned onto the Er-diffused surface. Next, a 120nm thick MgO film was deposited over the Ti-strips. Simultaneous diffusion of Ti and Mg ions was then carried out at 1100$^o$C for 2h in a wet $O_2$ environment. Finally, VTE process was carried out by annealing the sample at 1100$^o$C for an additional 10 h in a Li-rich atmosphere, that is, Li-rich VTE.

The two facets were then polished, and end-fire coupling measurements show that waveguiding exists for all guides. All the waveguides are single-mode at 1.5µm wavelength, and just like proton-exchanged waveguides on a *Z*-cut LN, only TM mode was guided. Fig. 1(a) shows the TM mode patterns of the guides. In the width direction the mode field intensity follows a Gaussian function $A_x exp[-2(x/W_x)^2]$. In the depth direction the mode field intensity follows a Hermite-Gaussian function $A_y y^2 exp[-2(y/W_y)^2]$. The initial Ti-strip width dependence of $W_{x,y}$ is shown in Fig. 1(b). The measured waveguide loss is ~ 1.4dB/cm for the 7µm wide waveguide.

Optical absorption study shows that the VTE process resulted in ~ 1 ± 0.3 nm blueshift of the optical absorption edge, confirming that the VTE process has brought the crystal surface (and hence the waveguide layer) closer to the stoichiometric composition. Furthermore, VTE process simulation shows that the $Li_2O$ content in the waveguide layer is near-stoichiometric and has a homogeneous value of ~ 49.8 ± 0.1 mol%. The measured 1.5µm amplified simultaneous emission spectrum under 0.98µm wavelength laser diode excitation is a clear π-polarized spectrum, and is similar to that of a normal Er-doped LN, confirming that the Er ion presence in the waveguide layer is in the LN phase.

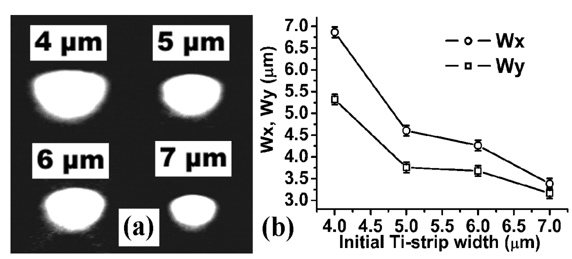


Fig. 1 (a) Near-field TM mode patterns of NS Ti:Mg:Er:LN strip waveguides at 1.5µm wavelength. (b) Mode size versus initial Ti-strip width.

The photorefractive effect of the NS waveguides was studied in comparison with that of the congruent waveguides. The congruent waveguides were fabricated by Ti indiffusion of 7μm wide, 106nm thick Ti strip into bulk Er (1 mol%)/MgO (1.5 mol%)-codoped *Z*-cut congruent substrate at 1060°C for 9h in wet $O_2$. The stability of the signal enhancement of small-signal (1μW) 1.531μm input light from a tunable laser under 0.98μm wavelength laser diode pump power was examined. The signal enhancement, defined as the ratio of the signal power at the output facet with pump light on to that with pump light off, was measured as a function of coupled pump power. The signal enhancement for the congruent waveguides drops significantly when the pump power exceeds 20mW. Under 220mW coupled pump power, a maximum signal enhancement of 1.5dB/cm was obtained for congruent Ti:Mg:Er:LN which lasts for ~1s, and then the value drops quickly. These features show that the optical damage is serious in the congruent waveguides. In contrast, for the NS Ti:Mg:Er:LN waveguides the maximum signal enhancement is 2.8dB/cm and is stable up to the maximum available coupled pump power of 216 mW. The stable enhancement implies that the photorefractive effect is suppressed in the NS waveguides.

Secondary ion mass spectrometry (SIMS) was used to analyze the surface profile of Ti ions [Fig. 2(a)] and the depth profiles [Fig. 2(b)] of all ions $^{7}$Li, $^{93}$Nb, $^{16}$O, $^{48}$Ti, $^{24}$Mg and $^{166}$Er in 6-μm-wide waveguides. The scattered curves in Fig. 2 represent the measured Ti or Er profiles and the overlapped solid lines denote the best fits. The fitted expressions are indicated for each Ti or Er profile. The Ti concentration follows a sum of two error functions along the lateral direction of the waveguide with a diffusion width 13 ± 0.5 μm, and a Gaussian function in the depth direction with a 1/e depth 5.1 ± 0.2 μm. The Er ion profile also follows a Gaussian function with a 1/e depth of 4.3 ± 0.2μm and a surface concentration of ~ $1\times10^{20}$ atoms/cm$^3$, and these values are comparable to those of normal congruent Ti:Er:LN devices [1]. The excellent Gaussian fittings in the depth direction show that the Ti and Er diffusion reservoirs were exhausted under the diffusion conditions adopted.

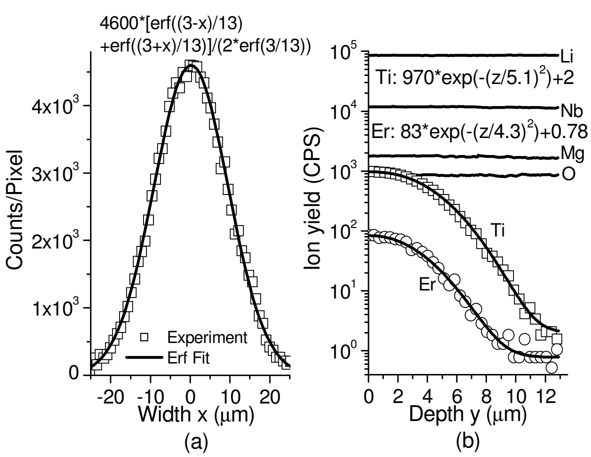


Fig. 2 (a) Surface $^{48}$Ti profile and (b) depth profiles of $^{7}$Li, $^{93}$Nb, $^{16}$O, $^{24}$Mg, $^{48}$Ti and $^{166}$Er in 6-μm-wide NS Ti:Mg:Er:LN strip waveguide

As shown in Fig. 2(b), the distribution of Mg ions in the waveguide layer is homogeneous. For application purposes this is highly desirable. By analyzing a standard MgO (5 mol% in melt)-doped congruent LN crystal using SIMS and referencing the relative ratios of the yields of Mg and Nb ions, the Mg concentration is evaluated to be $(3.9 \pm 0.6) \times 10^{20}$ atoms/cm$^3$ or 2.1 ± 0.6 mol%. This value is above the optical damage concentration threshold (~ 0.8 mol%) and is consistent with the absence of photorefractive effect measured results. Based upon the law of mass conservation and known Mg ion concentration, the 1/e Mg diffusion depth is evaluated to be 20 ± 3μm, indicating that the Mg diffusion is much faster than the Ti or Er diffusion in the depth direction, hence the Mg diffusion reservoir was also exhausted.

## III. Conclusion

We have demonstrated NS Ti:Mg:Er:LN single-mode strip waveguides using in-diffusion and VTE process. The NS waveguides are optical-damage-resistant, support TM mode only, and retain the LN phase. To compensate the refractive index decrease arising from the Mg in-diffusion and the VTE process, thick Ti-film is required. The SIMS results show that all of the Er, Ti and Mg diffusion reservoirs were exhausted, and all of the diffused ion depth profiles are either the desired homogeneous or Gaussian types with adequate diffusion depths. No photorefractive effect was observed in the NS waveguides with up to 216mW 0.98μm pump light. With further optimization the combined in-diffusion and VTE method would open a way towards the fabrication of new NS devices.

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