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# Near-stoichiometric Ti:D:$LiNbO_3$ (D = $Mg^{2+}$, $Sc^{3+}$, $Ga^{3+}$, $Zr^{4+}$) Optical Waveguides for Integrated Optics

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Near-stoichiometric (NS) Ti:D:$LiNbO_3$(D=$Mg^{2+}$, $Sc^{3+}$, $Ga^{3+}$, $Zr^{4+}$) strip waveguides were fabricated by D-diffusion-doping, Ti-diffusion and post vapor-transport-equilibration. We exemplify Ti:Zr:$LiNbO_3$ to demonstrate its implementation. We show that the waveguide is NS, well supports both TE and TM single-modes, and $Zr^{4+}$ concentration in the waveguide is above optical-damage threshold.

$LiNbO_3$ (LN)-based devices suffer from the photorefractive effect, which limits both pumping and operating wavelengths and hence hinders development of novel devices. Low threshold concentration of photorefractive-damage-resistant dopant is desired. A near-stoichiometric (NS) LN doped with higher than 0.8 mol% $Mg^{2+}$ [1], 0.4 mol% $Sc^{3+}$ [2], 0.5 mol% $Ga^{3+}$ [3] or only 0.085 mol% $Zr^{4+}$ [4] has been shown to effectively suppress the photorefractive effect. An NS Ti:D:LN (D = $Mg^{2+}$, $Sc^{3+}$, $Ga^{3+}$, $Zr^{4+}$) waveguide is more promising than a congruent one. Here, we exemplify the Ti:Zr:LN one to demonstrate the implantation of such waveguide.

The NS Ti:Zr:LN waveguide was fabricated starting from a congruent LN with a technological process in sequence of $Zr^{4+}$-diffusion doping, Ti diffusion and post Li-rich vapor-transport-equilibration(VTE). A 100±2 nm thick $ZrO_2$ film was coated onto surface part of a commercial Z-cut congruent LN plate, followed by an anneal at 1060 °C for 10 h. Then, an array of 200-μm-separated Ti strips with a width 8 μm and a thickness 100±2 nm were delineated on the $Zr^{4+}$-diffused surface, followed by an anneal at 1060 °C for 10 h and the subsequent Li-rich VTE at 1100 °C for 10 h.

The material composition in the waveguide layer was roughly evaluated from the refractive index measured at the undoped surface part of the sample and on the basis of the $Li_2O$-content-dependent Sellmeier equation. The result shows that the waveguide is in an NS environment. The end-fire experiment shows that the waveguide well supports both TE and TM single-modes at 1.5 μm wavelength as shown in Fig. 1(a). Analysis shows the light intensity of the guided mode follows a Gauss function $A_x\exp[-2(x/W_x)^2]$ in the width direction x and a Hermite-Gauss function $A_y y^2\exp[-2(y/W_y)^2]$ in the depth direction y. The TE mode size ($W_x \times W_y$ =4.7 × 4.9 μm$^2$) is similar to the TM mode size ($W_x \times W_y$ = 4.7 × 4.8 μm$^2$). From the measured insertion loss, reflection loss and the coupling loss evaluated from the known mode size, the waveguide loss was evaluated as 0.6/0.8 dB/cm for the TE/TM mode. Fig. 1(b) shows the $Ti^{4+}$ profile on the waveguide surface.

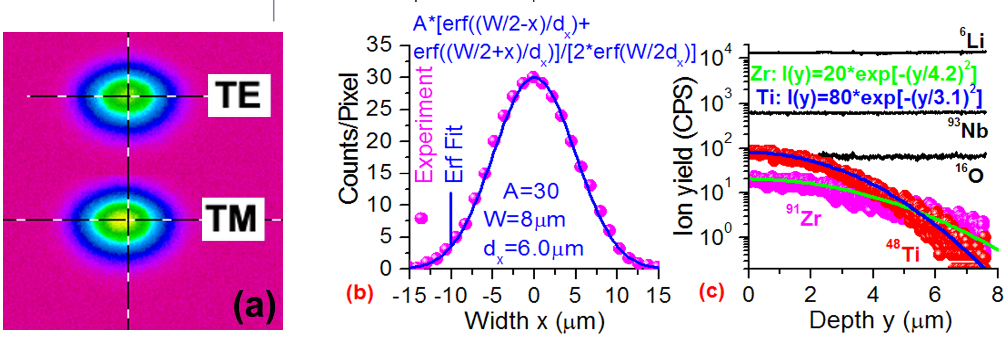


**Fig. 1. (a) Mode images at 1.5 μm wavelength, (b) Surface Ti profile and (c) depth profiles of Li, Nb, O, Zr and Ti in 8-μm-wide NS Ti:Zr:LN waveguide.**

Fig. 1(b) shows the depth profiles of $^{6}Li$, $^{93}Nb$, $^{16}O$, $^{91}Zr$ and $^{48}Ti$ in the waveguide. The fitting results show that the Ti ions on the waveguide surface follows a sum of two error functions with a diffusion width $d_x$ = 6.0 ± 0.2 μm. Both the $Ti^{4+}$ and $Zr^{4+}$ profiles can be well fitted by a Gaussian function with a diffusion depth $d_{Ti}$ ($d_{Zr}$) = 3.1 ± 0.1 μm (4.2 ± 0.1 μm). The fitting expressions are indicated. From the law of mass conservation, the $Zr^{4+}$ concentration at the waveguide surface was evaluated as 4.2 ± 0.2 mol%, which is ~49 times higher than the optical-damage threshold of NS Zr:LN, $C_{th}$ = 0.085 mol%. Moreover, the $Zr^{4+}$ concentration at the 1/e $Ti^{4+}$ concentration depth is 1.5 mol%, which is ~ 18 times higher than $C_{th}$. In words, the $Zr^{4+}$ concentration in the waveguide is above optical-damage threshold and the waveguide is expected to be optical-damage-resistant.

By using similar method we have also fabricated NS Ti:Mg:LN, Ti:Sc:LN and Ti:Ga:LN strip waveguides. The realization of active and passive NS Ti:(Er:)LN waveguides doped with $Mg^{2+}$, $Sc^{3+}$, $Ga^{3+}$ or $Zr^{4+}$ constructs a technical platform for the development of novel active and passive LN-based devices.

References

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