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Optical amplification characteristics of Ti-diffused waveguides on Erbium-doped $LiNbO_3$ crystal

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Abstract: We have first fabricated and characterized Ti-diffused channel waveguides on Er-doped $LiNbO_3$ single crystal. We achieved an optical gain of 2.1 dB/cm at 1531.4 nm signal light (TM mode) by optical pumping at 1480 nm with pump power of 200 mW/port for a 40 mm long Ti-diffused Z-cut 0.5 mol% Er-doped $LiNbO_3$ waveguide. The total gain of a pig tailed device was 3.8 dB.

Keywords: $LiNbO_3$, Optical amplifier, Er, Ti-diffusion, loss compensated waveguide

Classification: New functional devices and materials

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1 Introduction

A $LiNbO_3$ with a Ti-diffused optical waveguide plays important roles in an optical fiber communication, an optical signal processing and so on. Integrated $LiNbO_3$ devices can provide various functions, such as optical frequency control, millimeter-wave generation, etc [1, 2]. However, a propagation loss in Ti-diffused waveguide limits complexity or scale of optical circuits in the integrated devices. An optical amplification in devices is one of the possible solutions for the loss in the waveguides. A semiconductor-based device can have an active region with an optical gain. For the dielectric materials, such as a rare-earth doping in $LiNbO_3$ is a very attractive technique to realize the amplification. In particular, Erbium (Er) doping can provide the optical gain in the optical communication bands around 1550 nm.

Er-doping in the $LiNbO_3$ with Ti-diffused waveguide (Ti:Er:$LiNbO_3$) is expected as a useful approach for loss compensated optical waveguide devices. There were already similar trials to realize a waveguide amplifier in Ti:Er:$LiNbO_3$ [3, 4]. A previous reports, a thermal diffusion technique was used for the Er-doping, however, the thermal diffusion process of Er was so slow that it takes more than 100 hours with a diffusion temperature of 1100°C. Thus, the Ti-diffusion process should be carried out after Er-doping.

In contrast, we first proposed a waveguide with the optical gain using an Er-doped $LiNbO_3$ (Er:$LiNbO_3$) single crystal, where the Er-doping was done during a bulk crystal growth by Czochralski method. Therefore the Ti-diffusion process is simple as same as that of conventional $LiNbO_3$ crystal. In this paper, we prepared 0.2, 0.5 and 1.0 mol% Er:$LiNbO_3$ wafers for comparing their gain characteristics of Ti-diffused waveguides. The diameters of non-doped and 0.2 mol% Er-doped wafers are 3 inches, and that of 0.5 and 1.0 mol% are 2 inches, respectively. Actually, it became more difficult to fabricate the larger wafer in the higher Er-doped growth.

First, we measured absorbance of the Er:$LiNbO_3$ crystals by a spectrophotometer. Then, for clarifying the Ti-diffusion condition in Er:$LiNbO_3$, Ti-film and Ti-stripes were formed on the Er:$LiNbO_3$ and diffused to fabricate a slab and a single mode waveguides, respectively. Finally, we investigated an optical gain with forward and backward pumping by using 1480 nm laser diodes.

2 Absorbance of Er-doped $LiNbO_3$ crystal

In this work, we used 0.5 mm thick Z-cut Er:$LiNbO_3$ crystals with doping concentration of 0.2, 0.5 and 1.0 mol%. The absorbance of Er:$LiNbO_3$ crystals depended on the doping concentrations are shown in Fig. 1 and compared with non-doped one. High absorption peaks are observed at 1500 and 980 nm bands which correspond to energy levels of Er. The absorbance at the peaks increased with the doping concentration. These spectra were similar to the absorbance of Er-doped amorphous glass. We confirmed that the spectrum peak position and width of the absorption and the emission does not depend on the host materials because these mechanisms depended on the change of electric state in incomplete 4f shell (called transition of 4f-4f) [5].

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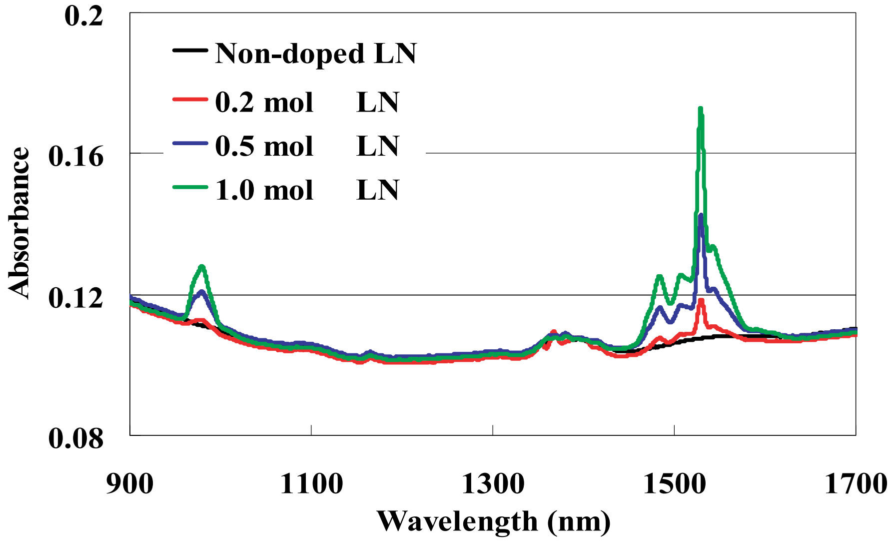

Fig. 1. Absorbance of $Er{:}LiNbO_3$ crystals (Z-axis, 0.5 mmt)

3 Fabrication of Ti-diffused optical waveguide on $Er{:}LiNbO_3$

We fabricated slab waveguides to estimate a Ti-diffusion coefficient. Ti films with 90 nm thickness were deposited on -Z face by an electron-beam evaporation method. A Ti-diffusion was carried out at 1000°C during 7, 10 and 15 hours in a platinum case to prevent from Li_2O out diffusion. We evaluated the refractive index change and the depth of slab waveguides by the prism coupling method. A Ti-diffusion coefficient of 0.2 mol% $Er{:}LiNbO_3$ is almost equal to that of non-doped one. However, that of 0.5 and 1.0 mol% $Er{:}LiNbO_3$ are smaller than that of non-doped one. We deduced that the diffusion temperature of 1000°C and diffusion time of 7 hours for 0.2 mol%, 8 hours for 0.5 mol% and 10 hours for 1.0 mol% were suitable for making a single mode channel waveguide for a signal light around 1550 nm.

From the experimental results of the Ti-diffusion coefficient of the slab waveguides, we decided Ti-diffusion conditions for the channel waveguides on $Er{:}LiNbO_3$ as follows. A Ti lift-off stripe pattern was 2–12 μm wide and 90 nm thick. A 250 ml/min of wet-O_2 gas was flowed in the diffusion. Both end faces of all samples were polished. Waveguide lengths were 40 mm long for 0.2, 0.5 mol% and 30 mm long for 1.0 mol%, respectively. A fiber-to-fiber precise measurement was carried out at an optical communication bands by cutback method where Ti-stripe widths are 5.5 μm for 0.2 mol% and 7 μm for 0.5 and 1.0 mol%, respectively.

And then, we measured the gain characteristics of $Ti{:}Er{:}LiNbO_3$ waveguides by using an experimental setup with the pump lasers of 1480 nm. A tunable signal light ($\lambda = 1520$ nm - 1565 nm, output power = 0 dBm, TM mode) and a pump laser light ($\lambda_p = 1480$ nm, output power < 200 mW/port) are combined with a WDM coupler, and launched into the waveguide by a fiber coupling. An amplified signal light is divided with another WDM coupler which was set behind the waveguide. The characteristic of the amplified

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signal was measured by a spectrum analyzer and a power meter, and recorded as a function of the launched pump power at specific wavelengths and as a function of the signal wavelength at specific pump power levels, respectively. The samples could be pumped from forward or backward (ports).

4 Characteristics of Er:$LiNbO_3$ with Ti-diffused waveguide

The characteristics of optical amplification using pump LDs of $\lambda_p = 1480$ nm are shown in Fig. 2 in the case of 0.5 mol% Er-doped $LiNbO_3$. By taking into account the propagation losses of the waveguide, it was possible to determine the net gain. The 0 dB level corresponds to an internal signal unit length; the waveguide-to-fiber coupling losses are not taken into account. Absorption of Ti:Er:$LiNbO_3$ waveguides was large at $\lambda = 1531.4$ and 1546.3 nm. The highest loss at $\lambda = 1531.4$ nm (non-pumped state) moved to the highest gain (more than 5 dB) by pumping at 200 mW/port. Furthermore, the positive net gain was achieved in any wavelengths from 1525 nm to 1565 nm. When the pump power was 200 mW/port, the gain exceeded 3.5 dB in the wavelength range 1544 nm $< \lambda <$ 1565 nm (the gain of 4.5 dB at $\lambda = 1546.3$ nm and 4.9 dB at $\lambda = 1561$ nm) indicating the possibility of developing a widely tunable waveguide laser based on these amplifiers.

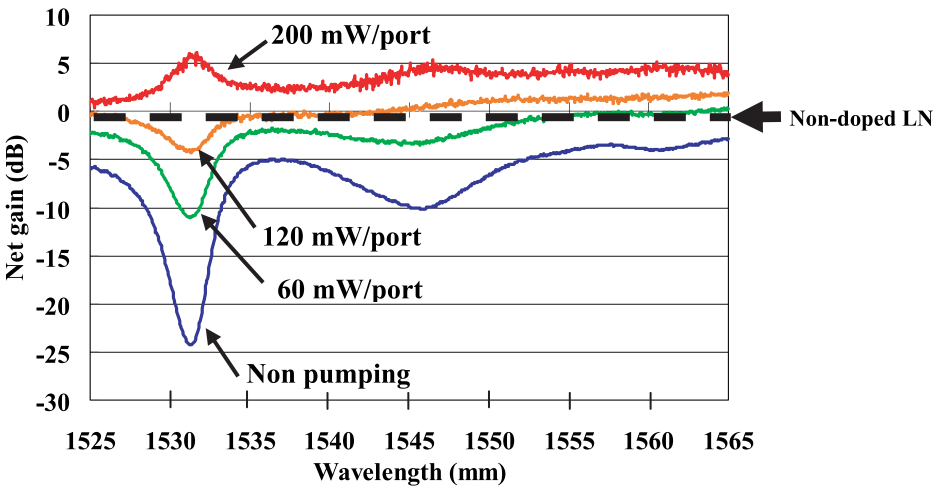

Fig. 2. Wavelength dependence of gain characteristics of Ti:Er:$LiNbO_3$ (0.5 mol%)

A shape of absorption and gain spectra of Ti-diffused 0.2 mol%-Er:$LiNbO_3$ were similar to that of Ti-diffused 0.5 mol% Er:$LiNbO_3$. However, the absolute value was smaller than that of 0.5 mol%. The gain spectra of Ti-diffused 1.0 mol% Er:$LiNbO_3$ was distinct from that of other Er-doping concentrations, because the amplification was not able to recover the large absorption. This would be due to concentration quenching, which causes the degradation of gain.

A propagation gain and a total gain of Ti:Er:$LiNbO_3$ ($\lambda_p = 1480$ nm) is shown in Fig. 3 ($\lambda = 1531.4$ nm). We defined the propagation gain (dB/cm),

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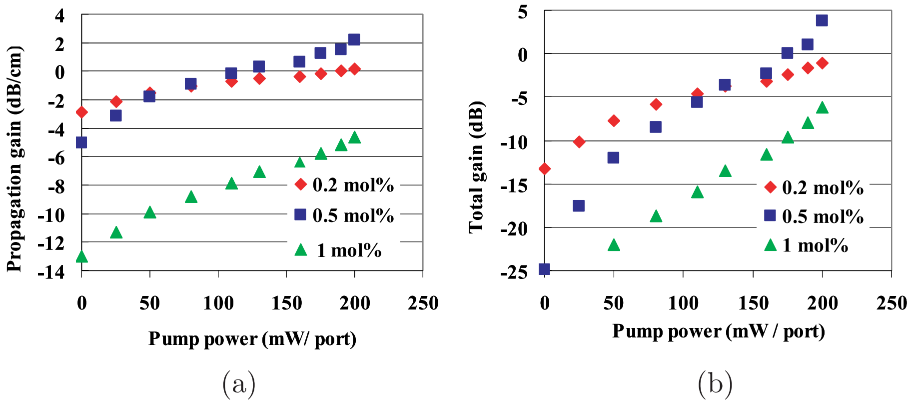

Fig. 3. (a) Propagation gain of 0.2, 0.5, 1.0 mol% Ti:Er:$LiNbO_3$ and (b) total gain (with the fiber to waveguide coupling loss) of 40 mm long waveguides (0.2, 0.5 mol%) and a 30 mm long waveguide (1.0 mol%)

which was the difference between the transmission power through an Er-doped channel waveguide (dB) and that through a non-doped channel waveguide (dB), divided by the length of waveguides (cm). The total gain was the difference between the transmission power and the input power, which included the fiber to waveguide coupling loss.

As shown in Fig. 3 (a), the amplification increased with the pump power and over 0 dB/cm propagation gain was obtained in 0.2 and 0.5 mol% waveguides, which could compensate the propagation loss or the inserion loss. Especially, 0.5 mol% Er-doped $LiNbO_3$ waveguide achieved the propagation gain of 2.1 dB/cm at 200 mW/port pump. In Fig. 3 (b), we achieved the loss compensated waveguide in 0.5 mol% at over 170 mW/port pump. Its total gain was 3.8 dB at 200 mW/port pump, which included the coupling loss and the estimated net gain. In the case of 1.0 mol% waveguide, we could not obtain the positive gain at the range of our experimental pomp power. When the pump power became higher, it seemed to saturate the propagation gain in 0.2 mol% waveguides. This is a particular feature of the amplification that uses three level system [5].

5 Conclusion

We have demonstrated Ti:Er:$LiNbO_3$ channel waveguide amplifiers by simple Ti-diffusion to Z-cut Er-doped $LiNbO_3$ crystals. In the 0.5 mol% Er-doped $LiNbO_3$ sample, an optical gain of 2.1 dB/cm at 200 mW/port of coupled pump power was achieved (waveguide length: 40 mm, signal polarization: TM mode, signal wavelength: 1531.4 nm, pump wavelength: 1480 nm). Including the coupling losses, we achieved the loss compensated waveguide when the pump power was 170 mW/port.

This result is very useful for composing more complicate and functional electro-optic waveguide circuits in the future.

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