LETTER Special Section on Evolution of Microwave and Millimeter-Wave Photonics Technology

Ridge-Type Zn-Indiffused Mach-Zehnder Modulator in $LiNbO_3$

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SUMMARY A ridge-type Zn-indiffused Mach-Zehnder modulator operating at 1.55 μm wavelength is demonstrated on a z-cut $LiNbO_3$ substrate for the first time. The measured results show that the values of voltage-length product can be reduced from 9.6 V-cm to 8.1 V-cm with the etched depth of 1.7 μm.

key words: *Zn-indiffused waveguide, Mach-Zehnder modulator, ridge structure*

1. Introduction

Integrated Mach-Zehnder modulators are essential components in optical communication systems and waveguide sensors [1]. For the demands on high-speed and low driving voltage operations, commercially available optical modulators were fabricated with Ti indiffusion (TI) in $LiNbO_3$. As we know, the TI modulators have such advantages of low propagation and small polarization dependent losses. However, the typical diffusion temperature (> 1050°C) and diffusion time (> 8 hr), still make low product throughput and out diffusion suppressing is needed. Moreover, the photorefractive characteristics not only cause the unstable bias voltage of modulators used in the short wavelengths (< 0.8 μm) but also limit the conversion efficiency of wavelength converters via nonlinear optics [2]. Recently, an alternative Zn indiffusion (ZI) process has been proposed to make waveguide devices exhibiting higher damage-resistant, which use for the efficient wavelength converters and waveguide lasers [3], [4]. There, the wavelength converters employing the mechanism of difference frequency generation (DFG) are key elements in wavelength-division-multiplexed (WDM) and all-optical time-division-multiplexed (OTDM) networks [3], [5].

In this paper, a ridge-type Zn-indiffused Mach-Zehnder modulator operating at 1.55 μm wavelength is demonstrated on a z-cut $LiNbO_3$ substrate for the first time. The results show that the overlap integral factors between electrical and optical fields can be improved from 0.37 to 0.43 with a ridge structure of 1.7 μm etched depth. Also, the values of voltage-length product can be reduced from 9.6 V-cm to 8.1 V-cm due to a reduction of switching voltage. Moreover, the Zn indiffusion process can make a well single extraordinary polarization waveguide with non-degraded EO coefficient at 1.32 μm and 1.55 μm wavelengths [6], [7]. In comparison to the traditional TI waveguide devices, the ZI waveguides will be of a great attractive for the integrated optical modulator utilizing both the nonlinear and electrooptic (EO) properties in $LiNbO_3$.

2. Experiments

A top view and a cross-sectional view of the ridge-type Mach-Zehnder modulator are shown in Fig. 1. A ridge structure is formed before the Zn indiffusion on the z-cut $LiNbO_3$ substrate. Because of a thick Ta film of 3000 Å is resistant to chemical reactions during photon exchanged (PE) with pure benzoic acid and the following etching process with HF solution, it was used as a patterned mask for protecting the non-etched area. At a same PE temperature, the etched depth depends on the etching time and will be limited by the maximum PE depth.

Figure 2 shows the etched result of a trapezoidal profile by using the PE time of 6 hr at temperature of 220°C, and following etching with HF solution for 6 hr, in which the etched depth is about 1.7 μm. The non-etched area of about 14 μm wide in the parallel waveguide region is still enough to fabricate the parallel metallic-strips of 8 μm width. Figure 3 gives the surface photograph of the parallel waveguide region fabricated with deposited Zn film of 500 Å by lift-off

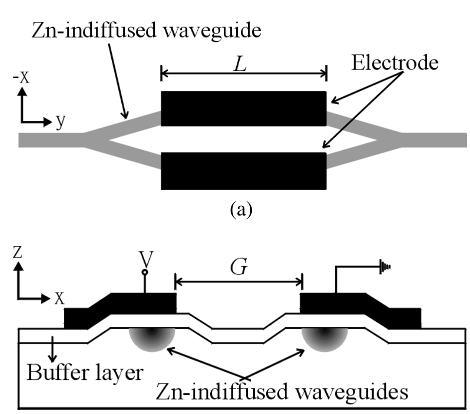

Fig. 1 Top view (a) and cross-sectional view (b) of the ridge-type Mach-Zehnder modulator.

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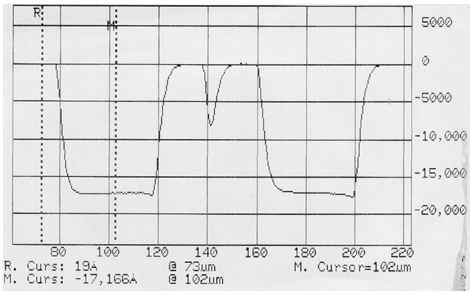

Fig. 2 Step profile after wet etching.

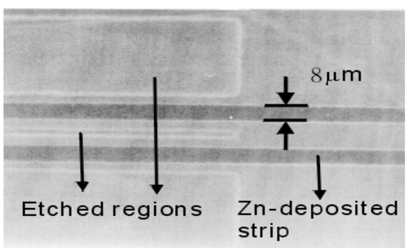

Fig. 3 Optical microscope photograph of Zn-deposited strips on the ridge structure.

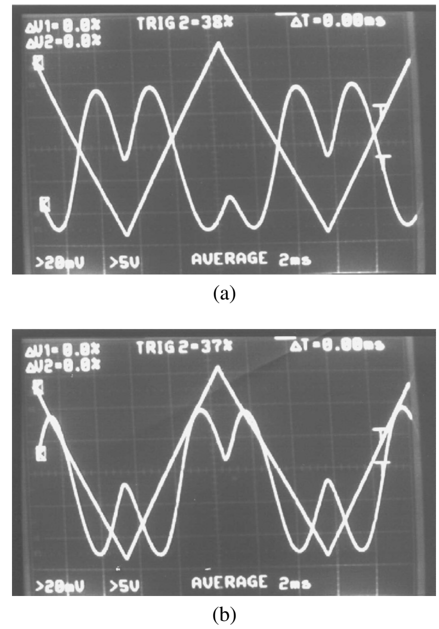

Fig. 4 The measured response curves for (a) the conventional, and (b) the ridge modulators, where the sinusoidal curve is for the optical signal (20 mV/div), and the sawtooth curve is for the applied voltage signal (5 V/div).

process. With the pre-deposited Ni film of 50 Å, an adhesion between the Zn film and substrate can be improved. After thermal diffusion of 850°C for 100 min, and substrate end faces polished, a SiO_2 buffer layer of 2000 Å is deposited onto the waveguide by an E-gun evaporator, then an Al electrode of thickness 3000 Å is deposited and patterned. A laser light source of 1.55 μm is coupled into the front end face of waveguide with a 40× lens and the output beam is imaged onto an InGaAs photodetector or a CCD camera also with a 40× lens. A sawtooth voltage is applied across the electrodes, and the output optical signal response can be measured for switching voltages.

3. Results and Discussions

The optical modulators prefer to use extraordinarily polarized light by employing the excellent EO coefficient r_{33} in $LiNbO_3$. In the TI modulator, the waveguides easily support both extraordinary and ordinary waves. If an incident light is random polarization, the output signal extinction ratio will be degraded due to the different EO coefficients of r_{33} and r_{13} be employed under the same applied voltages. Usually, a polarizer was put in front of the modulator to suppress the unwanted ordinary polarization. However, it will cause an additional reflection loss and need more packaging steps. In this report, the fabricated modulator of extraordinary polarization exhibiting polarization extinction ratio of about 44 dB, which itself can avoid the ordinary polarization disturbance even without using the input polarizer. Moreover, comparing with the TI waveguides of 1.55 μm wavelength diffused typically at 1050°C for 8 hrs, the proposed ZI waveguides can reduce process time, at least 6 hrs, by using a lower diffusion temperature of 850°C and a shorter diffusion time of 100 min. As a result, the process time is considerably shorter than that for TI process and has advantage in increasing the product throughput. As a modulator with the push-pull type electrodes on a z-cut substrate, the switching voltage V_π for a π phase change is defined as the expression:

$$V_\pi = \frac{\lambda G}{2n^3 r_{33} L \Gamma}$$

where λ is the optical wavelength, n is the refractive index of substrate, L is the length of modulation electrodes, G is the gap width between the electrodes, and Γ is the overlap integral factor between the electric and optical fields. Figure 4(a) shows the input voltage signal and measured response curve for the conventional modulator as reported in [7]. The response curve for the ridge one is shown in Fig. 4(b). The output modulated extinction ratios are both about 20 dB. There, the measured values of V_π are 16 V and 13.5 V for the conventional and ridge modulators, respectively. The corresponding values of voltage-length product are 9.6 V-cm and 8.1 V-cm at electrode length L of 6 mm. The results also show that the values of V_π can be reduced by increasing the values of Γ from 0.37 to 0.43 via etched structure of 1.7 μm depth at gap width G of 14 μm. It will be possible to further improve the characteristics of velocity and impedance matching by more optimizations on the designs of electrode arrangement and ridge structure [1]. Therefore, a large modulation bandwidth and low driving voltage optical modulator is achievable.

4. Conclusion

The measured results show that the values of voltage-length product can be reduced from 9.6 V-cm to 8.1 V-cm via ridge structure of 1.7 μm etched depth due to the enhancement on the Γ, which will benefit the lower driving voltage. Comparing with the TI waveguides, the ZI waveguides not only have the higher resistance to optical damage, but also save fabrication process including lower diffusion temperature and shorter diffusion time. Meanwhile, it will be of a great potential to make single-polarized optical modulator exhibiting both the nonlinear and EO properties for operating at long wavelengths (> 1.55 μm) in the same $LiNbO_3$ chip.

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