Fabrication of a Y-splitter Modulator Embedded in $LiNbO_3$ with a Femtosecond Laser

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We describe a technique to integrate embedded microelectrodes and optical waveguides in Lithium niobate ($LiNbO_3$) using a femtosecond laser, and a Y-splitter modulator was demonstrated. The Y-splitter was fabricated by femtosecond laser direct writing and the embedded microelectrodes were fabricated by combining femtosecond laser ablation with selective electroless plating. The embedded microelectrodes give rise to homogeneous electric field across the optical waveguides, which could result in effective electro-optic overlap. The simple and flexible technique could open new opportunities for fabricating integrated 3D electro-optic devices.

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1. Introduction

Lithium niobate ($LiNbO_3$) has long been used in integrated optics due to its large nonlinear optical and electro-optical coefficients. Integrated electro-optic devices based on waveguiding structures have gained significant attention, such as optical switches [1], modulators [2-4] and electro-optically tuned quasi-phase-matched (QPM) devices [5-7]. Conventionally, the waveguide fabrication is based on ion diffusion or proton exchange, which permits fabrication of channel waveguides only close to the surface. Femtosecond laser microfabrication, as an emerging tool in last decade, has shown powerful capabilities of three-dimensional (3D) integration. Recently, it also has been demonstrated that optical waveguides in $LiNbO_3$ can be fabricated by femtosecond laser pulses [8-11], which opens the possibility to write 3D optical circuits in the crystal.

For fabrication of integrated electro-optic devices, it is crucial to design and fabricate electrodes. Currently, the electrodes are ordinarily fabricated based on lithographic methods, such as depositing thin layers of metals followed by pattern etching. However, due to the inherently planar nature of the lithographic process, this technique is limited to fabrication of 2D microstructures. M. Reich et al. [12] have reported topographical electrodes for poling lithium niobate by laser ablation as a simple patterning method superior to conventional surface electrodes. However, the topographical electrodes must be completely contacted with liquid electrolyte, which limited its application in integrated devices. As a simple and flexible technique, laser-induced selective electroless deposition has been widely studied over the past two decades [13-15]. Recently, we developed a technique of selective metallization in insulator substrates using femtosecond laser ablation and femtosecond laser assisted selective electroless plating [16-17]. The shape and dimension of the electrodes could be accurately controlled by changing the conditions of femtosecond pulsed laser ablation, which in turn leads to controllable electric field distribution inside $LiNbO_3$ crystal.

In this paper, we present a technique to integrate embedded microelectrodes and waveguides in $LiNbO_3$ using a femtosecond laser. Based on this technique, a Y-splitter modulator was demonstrated.

2. Experimental

Commercially available MgO-doped x-cut $LiNbO_3$ crystals were used in the experiments. A femtosecond laser micromachining workstation was used to fabricate optical waveguides and microelectrodes, which consisted of a 40 fs Ti:Sapphire laser (Legend USP, Coherent Inc.) operated at 800 nm wavelength and 1 kHz repetition rate, and a computer-controlled XYZ translation stage with a resolution of 1 µm.

In order to produce thermally stable waveguides in the low repetition rate regime, we used an approach of writing two parallel lines in close separation, which produces a guiding region between the double lines [9]. In comparison with the waveguides guiding light in irradiated region (type□), the waveguides guiding light between irradiated regions (type□) could preserve the nonlinearity of the bulk crystal [18]. The laser beam was focused with a 100× microscope objective (NA=0.90), and was incident along x axis of crystal and linearly polarized along the y axis (see Fig. 1). The waveguides were fabricated by consecutively writing two parallel lines separated by 10 µm with pulse energies of 0.3 µJ and a translating velocity of 100 µm/s. The focus was located at a depth of 50 µm.

In order to realize the electro-optic modulation, three embedded microelectrodes were integrated into the $LiNbO_3$ crystal, as shown in Fig. 1. The fabrication process of embedded microelectrodes mainly consists of four steps:

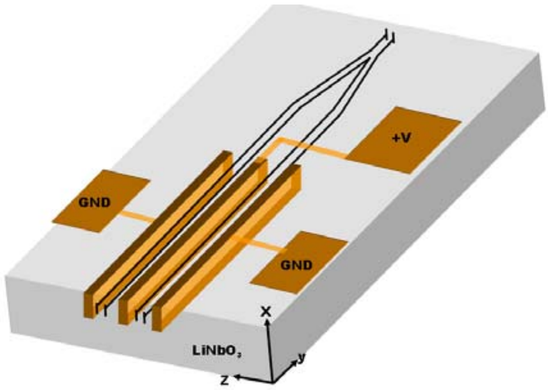

Fig. 1 Schematic layout of the Y-splitter modulator.

(1) micromachining of microgrooves on the surface of $LiNbO_3$ by femtosecond laser ablation; (2) formation of $AgNO_3$ films on substrates by dip coating in $AgNO_3$ solution; (3) scanning the femtosecond laser beam in the fabricated microgrooves for modification of the inner surfaces; and (4) electroless copper plating. Three metallic pads and connect lines, by which the modulator can be connected to an external electric source, were fabricated by the same technique.

The geometries of embedded electrodes are shown in Fig. 2(a) and Fig. 2(b). Using a matrix ablation technique [17], three U-grooves were fabricated with femtosecond pulsed laser beam focused with a 20× microscope objective (NA=0.45) at a scanning speed of 1 mm/s and pulse energies of 2 μJ. The inner surfaces of grooves coated with $AgNO_3$ films were modified by femtosecond laser direct-writing on the bottom surface of grooves at a scanning speed of 200 μm/s and pulse energies of 2 μJ. After electroless copper plating for 12 h, the grooves were well filled with copper. Usually, over-deposition of copper would occur, resulting in formation of undesirable copper films on the surface of crystal surrounding the embedded microelectrodes, which can be easily removed by mechanical polishing. Details of this investigation can be found elsewhere [16-17].

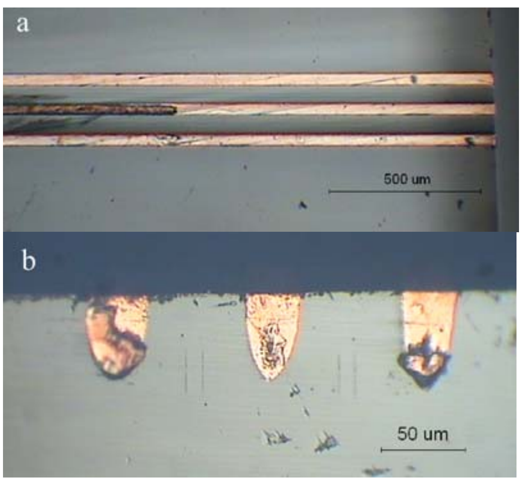

Fig. 2 Optical micrographs of the embedded electrodes (a) top view and (b) end view.

3. Results and discussion

A schematic diagram of the Y splitter modulator fabricated by femtosecond laser is presented in Fig. 1. The angle between the two branches is 1.2°, and the distance of the two branches is 80 μm. When a 633 nm He:Ne laser beam was coupled into the waveguide splitter with a 20× microscope objective (NA=0.40), the light was emitted from both branches of the splitter. The near-field beam profiles at the ends of the exit are present in Fig. 3(a), showing a horizontal size of 6 μm and a vertical size of 10 μm ($1/e^2$ intensity). By measuring the cone angle of the emerging beam, the estimated NA and refractive index change are approximately 0.03 and 2×10^{-4}, respectively. The propagation loss of waveguide was measured to be ~1 dB/cm by comparing the transmission through waveguides with different lengths in order to subtract the coupling losses.

After passing through the splitter, the two exiting beams propagated in the free space with a certain divergence angle, therefore, an interference pattern can be observed in the overlapping area of the two beams in far field. The device was examined using a He-Ne laser polarized in the extraordinary (z) direction by applying a varying dc voltage to the electrodes, and in the meantime, we collected the interference pattern of two branches of the Y splitter with a CCD camera. It can be seen that the interference fringes shift horizontally with the varying voltage. The results are shown in Fig. 3(b) and Fig. 3(c). The interference fringes will experience a π-shift if the voltage is changed by 20 V.

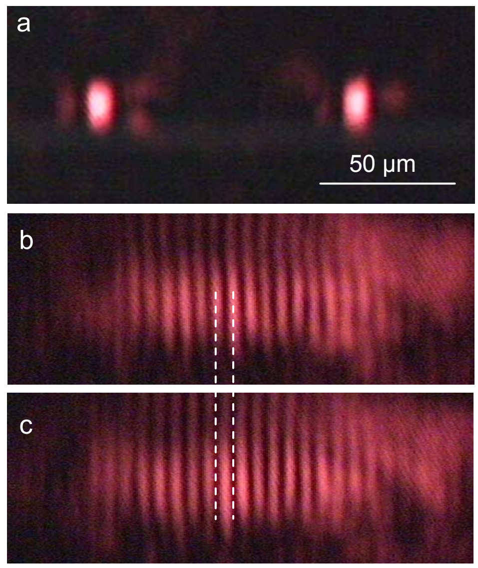

Fig. 3 (a) Near-field intensity distribution measured at the exit of modulator, and interference pattern of two branches of the Y splitter at different dc voltages of **(b)** 0 V and **(c)** 20 V. The attached white lines show the shift of the interference fringe.

A numerical simulation [19] based on finite element method was used to analyze the distribution of electric field of embedded electrodes with the geometry in Fig. 2(b), and a structure of conventional co-planar electrodes with the same width and gap was presented for comparison. The distribution of electric field of embedded electrodes and conventional co-planar electrodes are compared in Fig. 4(a) and Fig. 4(b), respectively. It could be seen that the electric field in waveguide regions created by the embedded electrodes is more uniform and intensive than that of the conventional electrodes. At the same time, the direction of electric field in waveguide regions created by embedded electrodes is nearly horizontal (z direction), which would lead to better electro-optic overlap and lower half-wave voltage compared to those of the co-planar structure.

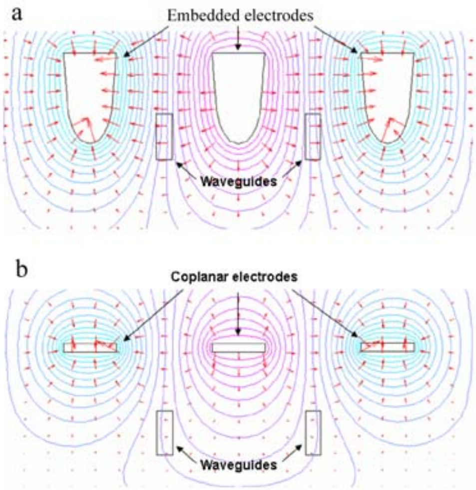

Fig. 4 Contour plots of the equipotential contour of (a) embedded electrodes and (b) co-planar electrodes.

4. Conclusion

In conclusion, a Y-splitter modulator based on integration of buried optical waveguides and embedded microelectrodes in $LiNbO_3$ using a femtosecond laser was demonstrated. The geometry of the embedded electrodes can be designed with great flexibility, and consequently control of the distribution of the electric field inside the crystal can be realized. The technique of electro-optic integration using femtosecond laser fabrication is promising for manufacturing of integrated electro-optic devices.

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