Excimer Laser Micromachining of $LiNbO_3$ for Optical and Microwave Applications

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In this paper, for the first time, excimer laser micromachining is applied to create new electro-optical devices called substrate integrated modulators, consisting of new optical and microwave waveguides on $LiNbO_3$ substrates. The fact of having both optical and microwave waveguides, offers the possibilities to modulate high-frequency optical signal (wavelength of 1.55 μm) by either millimeter or microwave signal (frequency of 60 GHz). Because $LiNbO_3$ is transparent between 370 nm to 5000 nm, 248 nm KrF excimer laser is one of the best candidates for performing fine micromachining of this material. Cutting the $LiNbO_3$ wafer, making holes, creating a ridge optical waveguide and fabricating a specific pattern of holes for microwave applications by 248 nm excimer laser are presented in this paper.

DOI: 10.2961/jlmn.2009.02.0001

Keywords: Lithium niobate; Micromachining; Optical and Microwave waveguides; Substrate integrated modulators; Excimer laser.

1. Introduction

$LiNbO_3$ substrate offers the ability to fabricate effective new proposed electro-optical devices such as substrate integrated optical modulator where both optical and microwave waveguides are present [1-3]. The optical waveguide may be placed inside the microwave waveguide region and interaction between the optical and microwave signals can be used for modulation purposes. One of the general methods for fabricating optical waveguides in conventional optical modulators requires to perform in-diffusion of titanium in X-cut or Z-cut $LiNbO_3$ substrates [4-5]. In addition, the usual microwave waveguides for the electro-optical modulators are coplanar. By performing micromachining of $LiNbO_3$ substrate, one can change the conventional optical and microwave waveguides, opening the possibilities to fabricate new types of geometry.

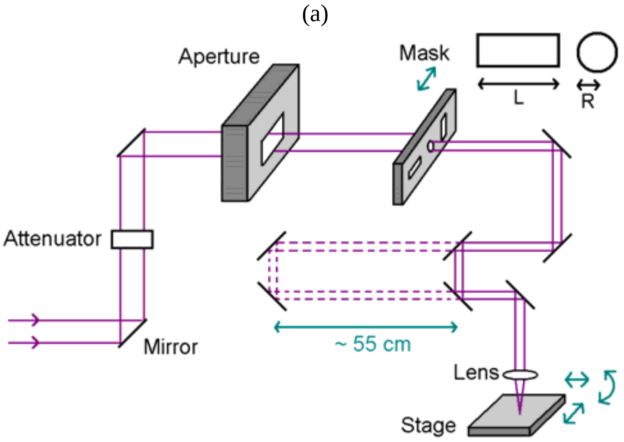
In the optical part of the device, after the in-diffusion process of titanium, etching the $LiNbO_3$ around the optical waveguide can improved device performance by enhancing the interaction between the optical and microwave signals because more microwave fields would cross the optical waveguide regions. Based on this approach, new and efficient electro-optical modulators were recently proposed by the authors [1]. For instance, in conventional $LiNbO_3$ modulators, changing coplanar line to substrate integrated waveguide (SIW), operating frequency could be significantly increased. Because of their required specific geometry, micromachining process must be utilized to fabricate SIW structures. However, conventional photolithography and liquid etch cannot be used because of low wet etching rate of about 0.5 μm/hour [6]. Lasers offer the possibility to micromachine the $LiNbO_3$ in three dimensions with high aspect ratio and rapidly fabricate prototypes without the time consuming mask design and fabrication.

Because of the transparency range of $LiNbO_3$ between 370 nm to 5000 nm, KrF excimer laser at 248 nm is one of the best options for micromachining.

Laser micromachining is foreseen for the fabrication of various new devices based on the concept of substrate integrated circuits (SICs). This technique may be applied to other substrates such as GaAs and InP to design new types of large bandwidth photodetectors, as suggested in reference [2]. For telecommunication applications, excimer lasers micromachining at 193 nm, 248 nm and 355 nm for Si, InP and X-cut and Z-cut $LiNbO_3$ substrates was recently performed by Greuters and Rizvi [7]. Femtosecond laser may also be used to microfabricate semiconductors and metals [8]. Three dimensional optical waveguides such as Y-splitters were fabricated using femtosecond laser [9-10]. Also, to increase the bandwidth of conventional modulator to 40 Gb/s, two grooves were created in the back side of $LiNbO_3$ substrate using KrF excimer laser micromachining [11].

In this paper, methods for dicing and performing complete and incomplete holes of X-cut $LiNbO_3$ wafers are presented. Then, the applications of laser micromachining of optical ridge waveguides (Section 3) and new microwave substrate integrated waveguides (section 4) are presented. The system used in this work is shown in Fig. 1. It consists of a Resonetics KrF laser micromachining system and X-Y stages and mask controlled by a user friendly software [12]. In Fig. 1(b), using the lens with a focal length (f) of 7.5 cm and the small variations of lens-stage distance (I), large variations in mask-lens distances (O) can be set while keeping the imaging condition $O^{-1} = f^{-1} + I^{-1}$,to

(a)



(b)

Fig. 1 Excimer laser micromachining system; (a) Picture of the laser and control system, (b) Optical beam schematics; circular and rectangular mask are shown.

obtain different beam sizes and demagnification factor $F = O/I$ on the substrate. In all experiments, no particular care such as applying a gas flow was used to limit small debris accumulation on the surface.

2. Wafer dicing

For the fabrication of new electro-optical modulators based on SIC with the optical and microwave interaction, large wafers are preferred for designing devices having both long and short waveguides. According to the desired 60 GHz frequency for microwave part of our design [2] and also because of simple fabrication processes used in X-cut wafers, a 220 µm X-cut $LiNbO_3$ wafer was selected.

Two methods for dicing the wafer by excimer laser were tried. Single scan cutting of the wafer using circular or rectangular masks resulted into low quality cuts with large edge roughness. Multiple scan of a rectangular mask scanned along the long edge L gave much better quality cuts. The scanning speed V of the target is determined by

$$V = \frac{LD_pN_p}{FD_S} \qquad (1)$$

where F is demagnification factor, D_p is the depth created by one pulse determined by the laser output energy, N_p is number of pulse per second and D_S is the desired slot depth.

Fig. 2 X-Cut $LiNbO_3$ wafer with 76.2 mm diameter and 0.22 mm thickness.

In Fig. 2, a 0.22 mm thick X-cut $LiNbO_3$ wafer was diced over a 76.2 mm length. High quality cutting was obtained by performing multiple scanning of a rectangular-mask over the substrate surface. By using N_p =100 pulses/s, L/F = 600 µm and D_p = 0.05 µm/pulse, etching about 5 µm at every scan was obtained and the wafer was cut by performing 44 scans at a speed of 0.6 mm/s. In Fig. 2 shows also a 25 mm by 25 mm square cut.

3. Hole drilling

Fabrication of the electro-optic modulator requires drilling two types of via holes into the wafer, namely, incomplete holes for ridge optical waveguide fabrication and complete ones for connecting the substrate surface to the bottom and for their use in the fabrication of microwave waveguides.

Fig. 3 shows a typical incomplete hole of about 30 µm diameter micromachined with 75 pulses at a fluence on the target of 1.75 J/cm^2, as estimated by the demagnification factor of 15.6 and the fluence on the circular mask of 0.225J/cm^2. An average ablation rate of 0.04 µm/pulse is deduced by measuring the depth of 3 µm.

Fig. 4 shows a scanning electron microscope image of a complete 80 µm diameter hole throughout the whole wafer thickness of 220 µm. At a fluence on the target of 3 J/cm^2, this hole takes 55 seconds at a repetition rate of 100 pulse per second. Even if some small debris are observed around the hole, their presence would not affect the device performance. The shape of this via hole is not perfectly circular, probably due to the elliptical shape of the laser output beam. In addition, the hole diameters at the entrance/top and exit/bottom of the substrate are not the same. This taper angle of ~ 4 degrees is due to a fix focal point during the process. In an optical image of the complete hole, a slight dark area surrounding the hole was observed. This area may probably be related to the light scattered by the small debris and to some bulk heating effects by the excimer laser micromachining yielding to an out diffusion of Lithium. Even if this last effect may alter the refractive index of $LiNbO_3$ surrounding the hole area by about +/- 0.001, we do not anticipate it would affect the performance of the circuit used for our optical and microwave applica-

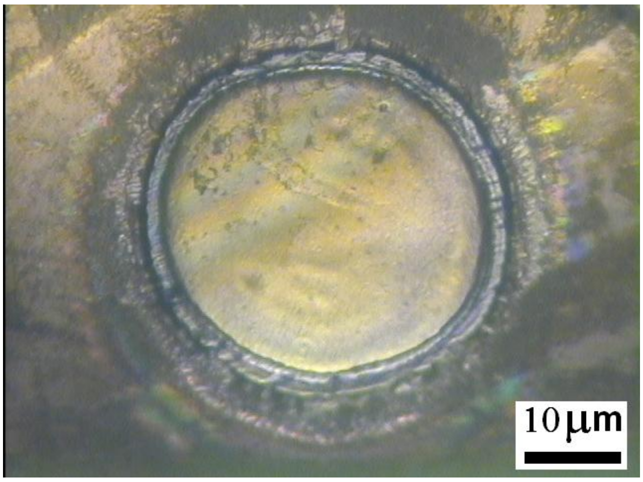


Fig. 3 Incomplete hole with 30 μm diameter and 3 μm depth.

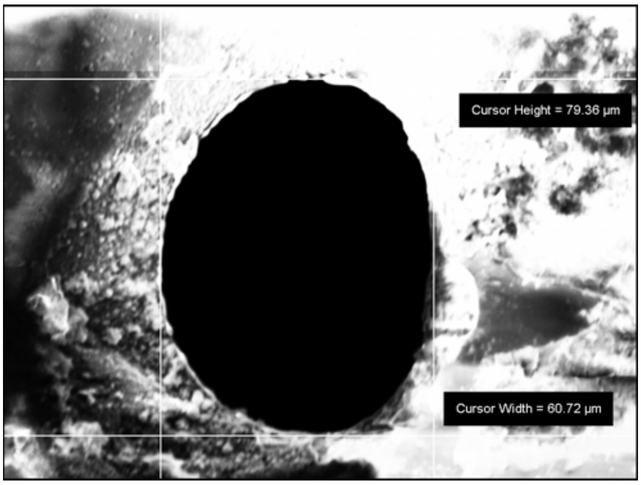


Fig. 4 SEM image of complete 80 μm diameter hole from entrance/top view.

tions. Actually, in microwave applications using SIW, most of the main mode power is in the middle of the structure, far from the micromachining parts. In the optical applications using a ridge waveguide, Titanium in-diffusion can be used to have low loss optical waveguide.

4. Optical applications

Optical ridge waveguide opens the possibilities to design low driving voltage electro-optical modulators because of the relatively large interaction between microwave and optical signals. Excimer laser micromachining offers the possibility to easily fabricate ridge waveguides with the desired geometry, width and etching depth. As an example, Fig. 5 shows a 10 μm width optical ridge waveguide fabricated using a rectangular mask. Tentatives to make high quality ridge waveguide with circular masks of any dimensions failed resulting in non uniform width which would eventually affect the optical propagation. Scanning speed

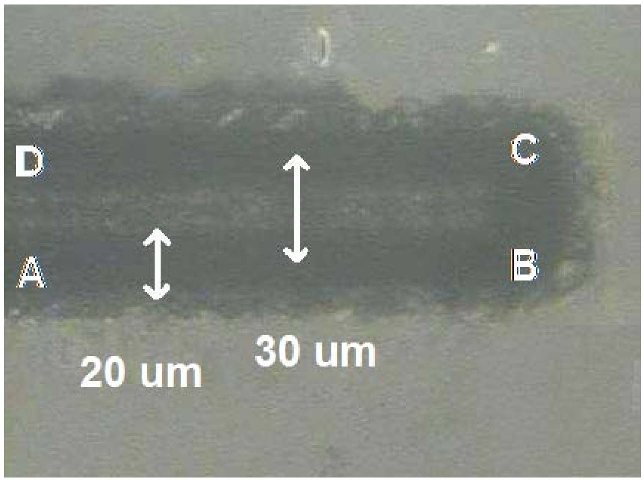


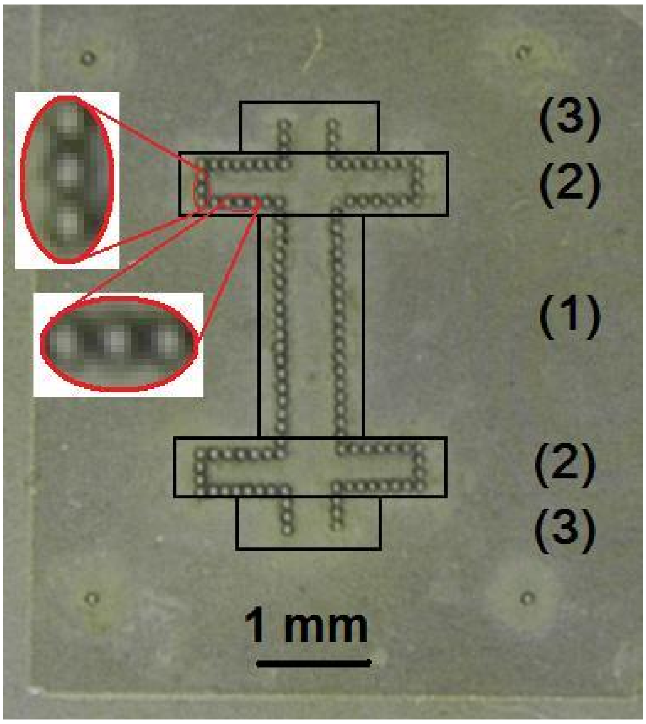
Fig. 5 Laser micromachining of 10 μm $LiNbO_3$ optical ridge waveguides by scanning a 20 μm width line.

of 450 μm/s, laser energy of 300 mJ and 100 pulses per second were programmed to obtain a high quality 10 μm ridge waveguide with a depth of about 5 μm. The ridge waveguide was fabricated by scanning a 20 μm width line in one direction and returning with the distance of 30 μm (from A to D in the figure). It is important to mention that to improve the quality of ridge waveguide just single-scan was applied instead of multiple-scan as it was used for cutting the wafer. The reasons of using single scan are because of the low edge roughness and low depth of the grooves around the ridge waveguide.

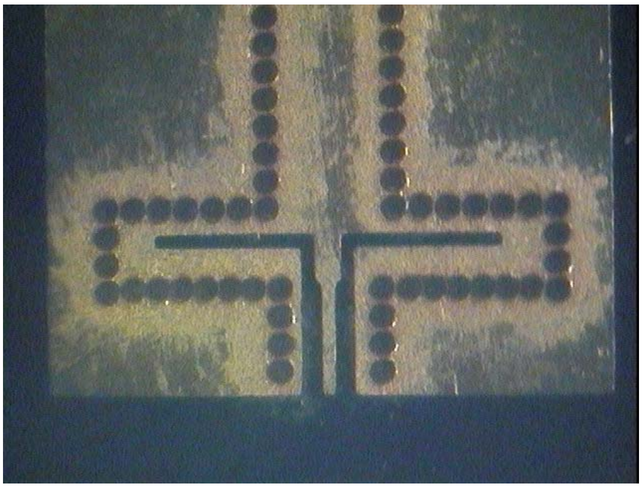
5. Microwave applications

The fabrication of conventional coplanar microwave waveguides in $LiNbO_3$ used in some electro-optical devices is relatively easy although the performance of these waveguides for some new applications, such as 60 GHz optical modulators is not good enough. Indeed, in these conventional $LiNbO_3$ modulators, coplanar lines forming the microwave waveguides are designed to be as close as possible to the optical waveguides yielding to an increase interaction for the modulation purpose. Also, some techniques such as fabrication of thick conductor coplanar waveguides are used to increase the bandwidth of conventional electro-optical modulators [5]. To further increase this interaction between the optical and microwave waveguides and the device efficiency such as low insertion loss and high bandwidth, non-planar structures using three dimensional excimer laser micromachining are proposed. These non-planar structures, integrated with the other microwave waveguides, may be converted to planar form by using the SIC concept. As an example, substrate integrated waveguide (SIW) is the planar form of non-planar rectangular waveguide [13]. This new integrated waveguide will be obtained by drilling some holes in the $LiNbO_3$ substrate and can be used for measurement purpose.

Fig. 6 (a) shows a pattern of holes designed to have a SIW in the middle of structure and coplanar waveguides on both sides of it. The effective SIW width as a microwave waveguide is related to the hole diameters and distance between the holes [13]. The hole diameter is 85 μm on the



(a)



(b)

Fig. 6 (a) Hole pattern for microwave waveguide applications having about 80 μm diameter and 120 μm between the holes. (b) Half part of microwave waveguide after metallization of the hole pattern.

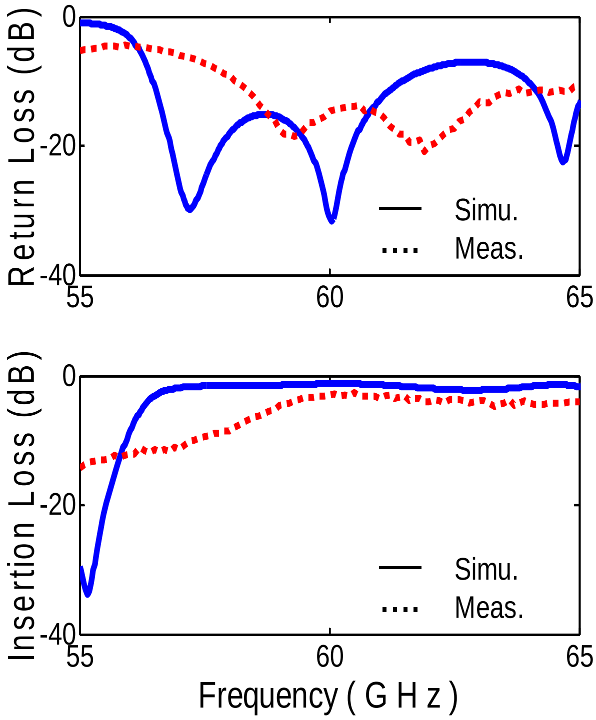


Fig. 7. Microwave losses from simulation and measurement.

front surface and this diameter decreases with a 4 degree angle to about 50 μm on the other side of the 220 μm thick substrate. This taper angle increases the effective waveguide width, although it is acceptable for our application at 60 GHz. The distance between the holes is about 120 μm. This pattern after metallisation can be used to create an integrated microwave waveguide for electro-optical phase modulator. Distances between holes were designed for a microwave application to have optimum insertion and return losses of 1 dB and 15 dB, respectively. As noted in Fig. 6 (a), distances between the holes in the horizontal direction is slightly greater by 5% than the ones between the holes in vertical direction. This difference, which is not critical for our design, comes from the elliptical shape of the focused beam. To complete the microwave waveguide, gold metallization of the top and bottom of substrate as well as in the inner parts of the holes was performed by sputtering. Fig. 6 (b) shows half part of the device after metallization. In order to have access to the 60 GHz microwave probes for excitation, some metallic parts from region (2) and (3) of Fig. 6 (a) were removed. This fabricated waveguide can be connected to the probing station for measurements. The slot and strip width of the excitation parts are 76 μm and 70 μm, respectively. In region (1), some holes to suppress undesired mode were drilled and metalized. SIW width in region (3) is 450 μm.

In the figure, the main SIW placed in the middle of structure (region (2)) has a 566 μm width. It is in this part of circuit that the enhanced interaction between the optical and microwave signals occurs. Two parts with large distances of via holes in region (2) connecting to the main waveguide are cavity resonators and can be used to increase the bandwidth of modulator. The width of SIW in region (2) is 2mm.

Fig. 7 shows a relatively good agreement between the microwave scattering parameter measurement results and simulations based on computer simulation technology (CST) software [14]. In addition, this fabricated microwave device has good characteristics as the frequency range over which the return loss is low (taken here to be less than –10 dB) lies between 58 and 65 GHz, which is particularly large for this type of device operating around 60 GHz. Moreover, the frequency range over which the insertion loss is high (taken here to be higher than -3 dB) is also large (59 to 62 GHz). Even if simulations and measurements of the return loss show a slight shift of 2 GHz of dips positions, these are acceptable for these types of microwave devices. These differences are probably caused by the decreasing main SIW width and precision in fabrication. It is anticipated that this frequency and dips shift of the return loss would not affect the performance of the system (e.g. radio over fiber system), because the bandwidth is large enough. Simulation results of the elliptical hole shape and taper angle effect by CST microwave software suggest that they are not the primary cause of the frequency shift. Now, looking at the insertion loss, cut-off frequencies f_c obtained from simulation and measurement results are around 57 GHz and 59 GHz, respectively. This difference in term of f_c and slop of the curves before f_c are probably due to the precision of fabrication and are acceptable for microwave applications. In addition, an increasing insertion loss at frequencies over f_c may be obtained from the incomplete metallization inside of the holes.

6. Conclusion

In this paper, for the first time, excimer laser micromachining of some optical and microwave waveguides such as SIW was performed on $LiNbO_3$ substrates. Wafer dicing, complete and controlled depth holes, optical ridge and microwave non-planar waveguides were fabricated and characterized. Device performance was found to be in good agreement with simulation results. With this laser process, adapted design can be easily implemented for substrate integrated microwave waveguide devices.

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(Received: February 12, 2009, Accepted: April 17, 2009)