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Fabrication of $LiNbO_3$ Phase Gratings by Excimer Laser Ablation through a Silica Phase Mask

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Lithium niobate ($LiNbO_3$) wafer phase gratings were fabricated by excimer pulsed ablation through a transmission silica phase mask grating. Surface morphology of the $LiNbO_3$ phase gratings was studied using an atomic force microscope as well as an optical microscope. Crystal structures and the diffraction patterns of the gratings were characterized by X-ray diffraction and using a He–Ne laser beam, respectively.

KEYWORDS: $LiNbO_3$, phase grating, excimer laser, ablation, phase mask

$LiNbO_3$ (LN) is an important material for the preparation of new types of optical-electric devices due to its pyroelectric, piezoelectric and nonlinear optical properties. In integrated optics, a LN planar waveguide has received great attention because of the large refractive index difference between the thin film and the substrate, which allows confinement of the light in the films with a tight mode.[1–3] Recently, a distributed Bragg reflector (DBR) made of LN has been developed to realize an integrated waveguide laser,[4] which is one of the most important components for applications in optical communication and instrumentation. The above-mentioned Bragg grating reflector in the LN waveguide laser was fabricated by the dry etching technique. This method is complex, expensive and not suitable for industrial environments. Therefore, development of a practical fabrication method for the Bragg reflector in an optical waveguide is important.

A series of techniques have been developed to produce Bragg gratings in a photosensitive fiber or a planar waveguide,[5] including holographic and nonholographic writing, and much progress has been made during the past few years.[6–10] The writing of this kind of Bragg grating is based on photorefractive index processing, which can be came out in a Ge-doped silica fiber or a planar waveguide. In the photolithographic method,[9,10] a silica phase mask was employed to produce Ge-doped fiber Bragg gratings by UV exposure. This method is suitable for industrial production due to the low mechanical sensitivity of the grating writing apparatus and because it is efficient even with low-coherence laser sources.

Excimer laser pulses, which have a high incident power density at UV wavelengths, such as 248 nm, have been employed to produce LN thin films or waveguides from a LN bulk crystal target.[11,12] This method is also called excimer laser ablation because the film is deposited by the ablation of the LN target. In this letter, we report the direct etching of LN phase gratings by excimer pulses through a silica phase mask grating. The morphology of the gratings is studied using an atomic force microscope (AFM) as well as an optical microscope. The crystal structures of the gratings are analyzed from their X-ray diffraction patterns and a He–Ne laser beam is used to characterize the diffraction of the phase gratings.

The fabrication of LN gratings was performed in a pulsed laser ablation apparatus employing a commercial KrF excimer laser (Lambda Physik Model LPX205i), which delivered 50 ~ 300 mJ of energy per 30 ns pulse in a 7 mm × 22 mm rectangular beam. A schematic drawing of the experimental setup employed in this work is shown in Fig. 1(a). A cylindrical lens was placed in front of the silica phase mask to converge the long axis of the laser beam to about 5 mm at the surface of the LN wafer. A $5 \times 5\ mm^2$ square filter with a thickness of about 100 μm was placed between the mask and the LN wafer. The $5 \times 5\ mm^2$ phase mask grating used in the present demonstration consisted of equal-width lines and spaces with a 2000 ± 10 nm period, and was formed by reactive ion

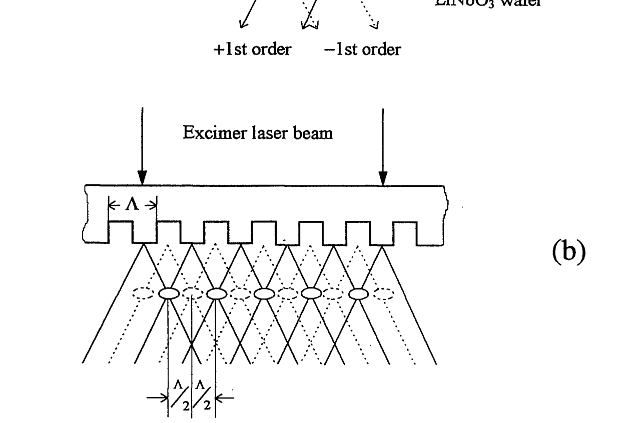

Fig. 1. (a) A schematic drawing of the apparatus for etching a phase grating at the surface of $LiNbO_3$ wafer. (b) The interference patterns of the +1st and −1st order diffracted light from the phase mask grating.

etching. The etched channels in the silica were about 260 ± 5 nm deep. Then, the 248 nm zero-order diffracted beam of the mask was nulled below 10% and 80% of the transmitted light was contained in the +1st and −1st order diffracted beams. Figure 1(b) shows the interference pattern of the ±1st order diffracted light from the phase mask. There are two types of interference pattern behind the mask. One is formed by the unetched lines and the other is formed by the etched lines, which has a π phase shift relative to the former interference pattern. Hence the period of the ideal diffracted light (Λ_1) behind the phase mask is half of the mask period, i.e., $\Lambda_1 = \Lambda_1/2 = 1000$ nm in our experiment.

A 10 mm × 15 mm rectangular *z*-cut LN (110) wafer, 1 mm thick, was polished carefully and was cleaned in an acid solution before it was placed, with its *a*-axis parallel to the direction of the mask grating lines, in contact with the mask.

Figure 2 shows an optical microscope image of the morphology of the LN phase grating prepared using one excimer pulse with an incident energy of about 150 mJ, which results in an incident energy density of about 600 mJ/cm^2. The grating contains two kinds of lines. One is the dark, wide lines with a period of about 2000 nm and the other is the weak, narrow lines between the former ones. Based on the observations discussed above, these two kinds of periodic lines should be etched by the interference patterns of the unetched and etched lines of the mask grating, respectively. The reason that latter lines are weaker than the former is that the bottom of the etched lines in the mask is uneven, which results in considerable loss of light.

Figure 3 shows an AFM image of the as-prepared LN grating. Compared with the unexposed LN wafer, the surface of the grating is uneven although the etched lines are sharp. The depth of the channels is about 100 nm. The physical mechanism responsible for the excimer pulse ablation at the surface of the LN wafer is a thermal fusion and air annealing process. The incident power of an excimer pulse is high (20 MW/cm^2) enough to fuse a layer of the LN wafer. The interference pattern formed by the plus- and minus-order lines contains a sinusoidal of energy spectrum with a maximum power of about 40 MW/cm^2. A thin layer of LN crystal will be periodically fused and ablated by the incident light, which is intense and periodic with a sinusoidal power spectrum. The fused LN will spray from the bottom of the trough and be annealed at the LN surface. This process can also be inferred from the observation of small clusters on the surface of the silica mask grating.

The crystal structure of the ablated clusters on the surface of the LN grating is characterized by X-ray diffraction as shown in Fig. 4. It is found that there exist three new crystal phases ($Li_{1.9}Nb_2O_5$, $Li_3NbO_8 \cdot 6H_2O$ and Li_3NbO_4) at the LN grating surface besides the phase of substrate LN (110). The formation process of these three new phases is not understood clearly. Their presence simply indicates that some of the ablated LN clusters have been annealed resulting in other crystal structures after being exposed to an excimer pulse.

Diffraction patterns of the as-generated LN gratings are characterized using a He–Ne laser beam. Figure 5 shows two typical diffraction patterns of the LN phase gratings. We find that the transmission spectrum of the grating is clear and varies with the grating depth. The depth of the phase grating in Fig. 5(a) is about 200 nm, which yields the strength of the zero-order diffraction point being about half of the minus- or plus-order diffraction strength. In Fig. 5(b), the depth of the grating is about 150 nm, which was obtained using a pulse incident energy of 180 mJ. The zero-order diffraction in this grating is much stronger than the plus- or minus-order diffraction.

Several LN gratings with different depths were ob-

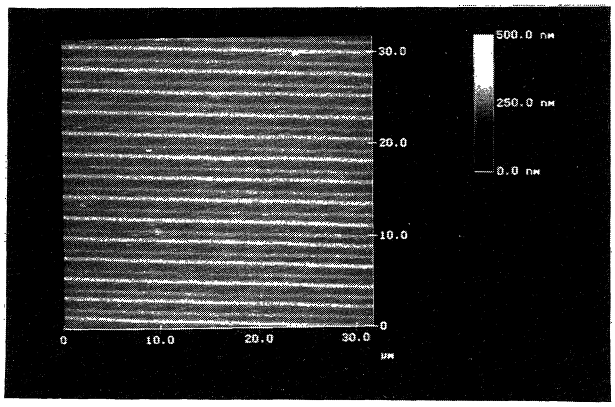

Fig. 3. An AFM image showing morphology of the LN grating.

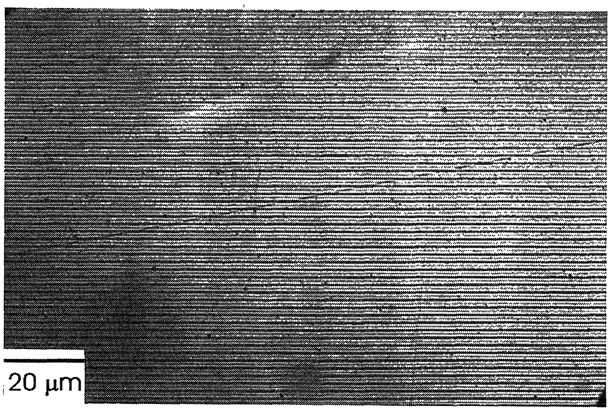

Fig. 2. An optical micrograph of the LN phase grating.

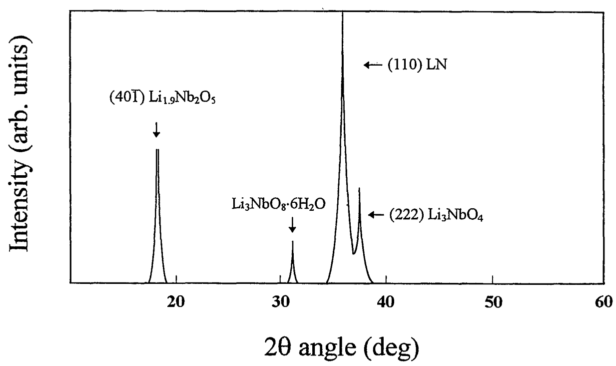

Fig. 4. The X-ray diffraction spectrum of the as-etched LN phase grating.

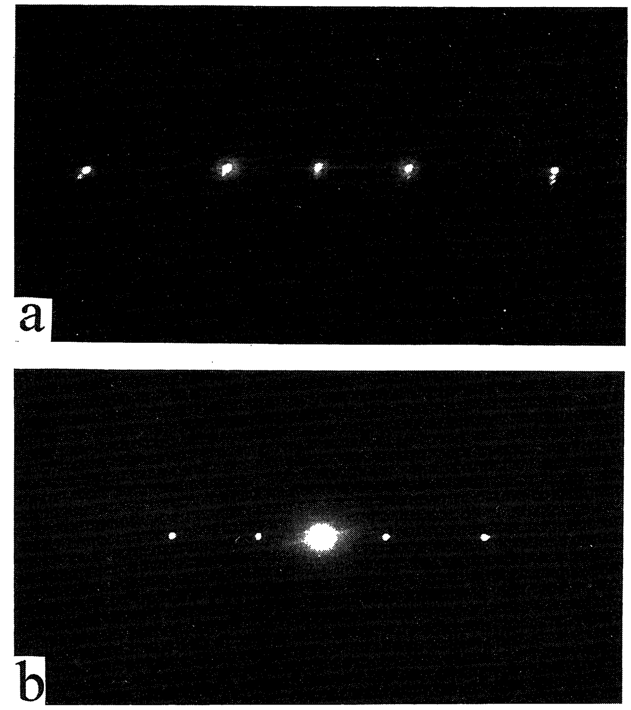

Fig. 5. The He–Ne laser beam diffraction patterns of the LN gratings fabricated using the pulse laser with an incident energy of (a) 210 mJ and (b) 180 mJ.

tained by using different excimer pulse incident energies. The depth of the grating channels is increases with the incident power of the laser pulse. However, the depth of a grating etched by one excimer pulse is limited because the LN surface is damaged heavily when the incident energy density is greater than 50 MW/cm^2. Therefore, a few pulses with lower incident energy should be employed to fabricate high-quality LN phase gratings. We suggest that this method can also be applied to produce Bragg gratings in LN waveguides.

In conclusion, we have presented a simple method for direct fabrication of LN phase gratings at the surface of LN wafers using an excimer pulse. The morphology of the gratings was studied using an AFM, as well as an optical microscope. The crystal structures of the gratings were characterized by X-ray diffraction and three new crystal phases were found in the grating surface besides the substrate phase of LN (110). Finally, the diffraction patterns of the gratings were analyzed using a He–Ne laser beam.

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