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Generation of submicron surface gratings on $LiNbO_3$ by ultrashort UV laser pulses

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Abstract. Ablation of submicron surface structures on $LiNbO_3$ by short ultraviolet laser pulses (0.5 ps, 248 nm) is presented. Gratings with a period of 360 nm and a modulation depth of 80 nm are fabricated on the sample surface by single-laser-shot exposure. The structures are projection imaged by a Schwarzschild objective in air. The modulation depth can be varied by applying multiple-pulse exposure.

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Optically pumped Ti:Er:$LiNbO_3$ distributed Bragg reflector (DBR) waveguide lasers have been recently demonstrated with single frequency emission at 1531 nm and 1561 nm [1]. In contrast to Fabry–Pérot-type waveguide lasers with dielectric end-face mirrors, they can be easily combined in integrated optical circuits (IOC) with further active (e.g. modulators) and passive (e.g. directional couplers) devices on the same substrate. Such compact optical circuits designed for specific applications have widespread potential in future optical communication and measurement systems.

The key components of the DBR lasers are narrow-band Bragg reflector gratings with a period of about 350 nm. They were previously fabricated by using holographic grating definition in a photoresist followed by a set of dry etching processes [2]. This is a relatively complicated, time-consuming and expensive fabrication technology. As a simple alternative, laser ablation techniques seem to be very attractive. They use excimer lasers of short wavelength, providing a lateral resolution of several hundred nanometers. In addition, the strong UV absorption of many materials results in a small penetration depth of the laser beam, enabling exact control of the ablation depth.

Several excimer laser ablation experiments using different wavelengths and pulse durations have already been performed with $LiNbO_3$ surfaces [3–7]. Even the fabrication of periodic line structures of 2-μm spacing has been demonstrated recently by nanosecond excimer laser irradiation through a phase mask [6]. However, heat diffusion seems to prevent the fabrication of sub-μm grating structures if the thermal diffusion length L is not negligible compared to the period of the structure to be fabricated. As L is given by $L = (2D_{\mathrm{th}}\tau_{\mathrm{p}})^{1/2}$, with the thermal diffusivity $D_{\mathrm{th}} = 1.4 \times 10^{-2}\,\mathrm{cm^2 s^{-1}}$ [8], pulses with a duration of $\tau_{\mathrm{p}} < 1$ ns should allow grating fabrication also in the sub-μm range.

In this article, fabrication of surface gratings with periods of 360 nm, with ultrashort (≈ 500-fs) laser pulses at 248 nm is reported for the first time.

1 Experiment

Ablation experiments were performed with a short-pulse KrF-laser system operating at 248 nm (described elsewhere [9]). It deliveres 0.5-ps-long pulses of 10-mJ energy. The irradiation of the sample was done by using a mask projection set-up (Fig. 1) with an achromatic, Schwarzschild-type reflective objective with a numerical aperture of 0.4. This guarantees high-power transmission in the UV and prevents pulse front distortion of femtosecond pulses.

For the ablation of the periodic structures a transmission grating (55 lines/mm Cr on quartz) was imaged onto the samples. The zeroth order of the diffraction pattern was blocked in order to increase the created line density by a factor of 2. With the arrangement shown in Fig. 1 the image projected onto the sample had a period of about 360 nm. The

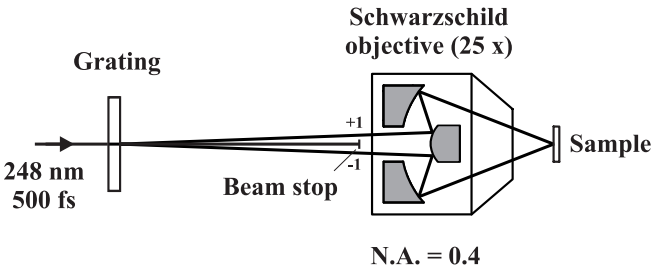

Fig. 1. Mask projection set-up with Schwarzschild-type reflective objective

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fluence was varied with a dielectric attenuator between 50 and 200 mJ/cm^2.

$LiNbO_3$ wafers (X-cut) of congruent composition were used as samples. All experiments were performed in air.

2 Results

The formation of grating structures is observed at fluences above 50 mJ/cm^2. This is also the ablation threshold fluence observed for large-area ablation [5]. Figures 2 and 3 show ablation patterns generated at a fluence of 170 mJ/cm^2 recorded by atomic force microscopy (AFM) and scanning electron microscopy (SEM), respectively. With single-pulse ablation, a surface modulation (peak to valley) of 80 nm with a lateral period of about 360 nm is achieved (Fig. 2). After 5 pulses a modulation depth of about 180 nm was measured (Fig. 3). No further enhancement was achieved even after irradiation with 25 pulses.

The surface morphology of the ablated grating, shown in Fig. 3, is comparable to that obtained with the dry etching technique [2]. However, the grating period varies by about 5 nm over the entire ablated spot of 50-μm diameter. This is probably due to the non planar wavefronts of the interfering beams producing a parabolic spatial chirp of the period.

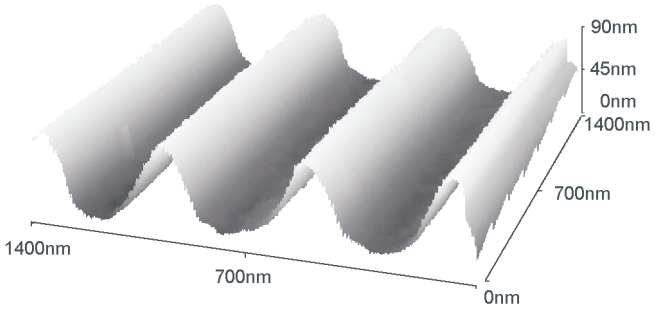

Fig. 2. Surface morphology of a periodic structure ablated on a X-cut $LiNbO_3$ surface with a single pulse at a fluence of 170 mJ/cm^2, recorded by AFM

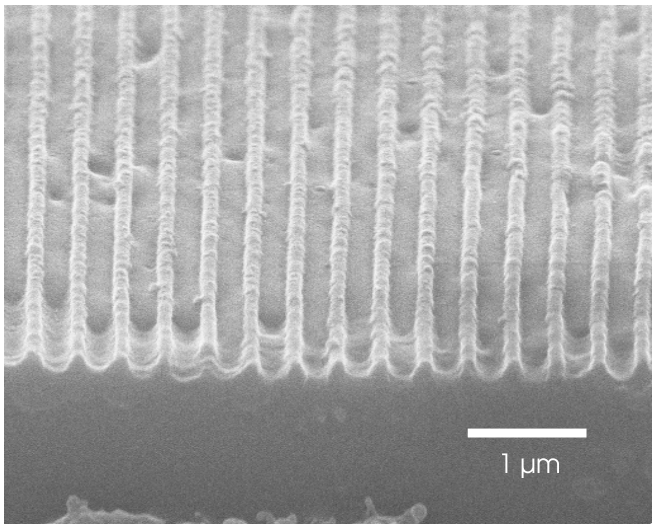

Fig. 3. SEM photograph of a grating structure ablated on a X-cut $LiNbO_3$ surface with 5 pulses at a fluence of 170 mJ/cm^2

3 Discussion

The observed single-pulse modulation depth of 80 nm is much larger than the ablation rate of about 20 nm/pulse measured in [5] for large area ablation with the same laser parameters. This can be explained by considering that the recoil pressure pushes the molten material out of the grooves to the nonirradiated regions, forming elevated stripes. (In the case of large-area irradiation this process is limited to the outer rim of the spot). A similar description is given in [6] for the mechanism of nanosecond pulse structuring at moderate fluences (thermal fusing and air annealing process). There are some indications that the principle of material removal by evaporation from a melt is similar for nanosecond and picosecond pulses of the same energy, though the primary steps of absorption and energy distribution may be different. Also for glasses [10] and metals [11] surface melting has been observed even in the case of sub-ps pulses.

The period of the generated grating is close to the spatial resolution limit of the imaging system. The objective transmits only the two first-order diffraction beams, resulting in a nearly sinusoidal pattern. The melt ejection out of the troughs reduces with an increasing groove depth, so that the profile stabilizes after some pulses.

4 Conclusion

Sub-micrometer-structuring of $LiNbO_3$ is possible by using picosecond or femtosecond UV laser pulses. Grating structures with periods of about 360 nm can be created with single pulses with a wavelength of 248 nm. The modulation depth can be adjusted by varying the fluence and the number of pulses. This method seems to be appropriate to the fabrication of Bragg reflectors in $LiNbO_3$-based waveguides.

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