Periodic surface structures fabricated by one excimer laser pulse through a silica phase mask grating

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RECENTLY, excimer laser devices, which have higher-energy density output in pulsed ultraviolet (UV) light (193 or 248 nm), have been employed to generate some thin film structures[1, 2]. The principle of this technique, which is also called pulsed laser deposition (PLD) technique, is that the exposed material could be ablated out of the sample by the focusing laser beam, and redeposit on a substrate to form thin-film structures under certain conditions. On the other hand, researchers have obtained high-quality Bragg gratings in photosensitive fibers by using excimer laser pulses[3, 4]. Being a kind of most important optical crystals, LN and LT are UV absorbent materials, and the incident laser energy will be transferred to heat after its entering an LN or LT sample. A thin layer of the sample will be fused and peeled out of the sample by the laser beam which has a higher incident energy density. However, if the laser energy is suitable, the fused layer will not be ablated out of the sample; instead their regrowth on the exposed surface and a pattern could be formed. Therefore, we suggest that periodic surface corrugations may be formed after the sample is exposed by two interference laser beams with a certain incident energy density. In this note, we demonstrate a method for fabricating periodic surface structures in some important crystals by an excimer laser pulse. Experimental results show that quite good periodic surface gratings have been obtained in LN and LT monocrystal wafers. This technique, very simple and suitable for mass production, is valuable in both science and potential applications in a near future.

1 Experimental setup and results

The experimental setup used in this note is shown in fig. 1. The UV beam coming from a KrF excimer laser (Lambda Physik Model LPX205) had a pulse period of 30 ns in a rectangular beam (7 mm × 22 mm) at 248 nm. After traveling through a cylindrical lens, which was made of silica and had a focal length of 180 mm, the laser beam was reflected by a mirror and

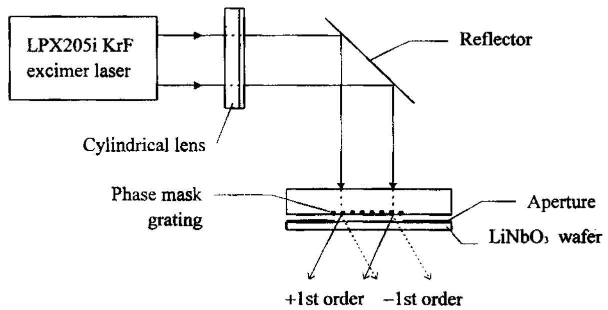

Fig. 1. Experimental setup of the crystal grating's fabrication by excimer laser pulse.

entered the phase mask. The mirror was made of glass coated with aluminum film, and had a reflectivity more than 90% to the wavelength of 248 nm. The cylindrical lens was used to compress the rectangular beam to a square beam (7 mm × 7 mm) so as to enhance the laser energy density. A 4.5 × 4.5 mm^2 capture (thickness of 500 μm) was put between the mask and the sample. Only a single pulse was used in our experiments.

The phase mask grating (5 mm × 5 mm) was made of pure quartz glass (2 mm thick, with a transmittance larger than 95% to the UV light) and consisted of equal-width lines and spaces with a period of 2 μm and a depth of 260 nm, which was designed to null the zero-order diffraction of the 248-nm wavelength. This means that the main diffraction energy of the laser beam was distributed to the minus and the plus first-order diffraction after the laser beam got through the mask grating. The interference fringe this time will have a period of $d/2$, where d is the period of the mask grating. According to the equation of $h = \lambda/2\ (n-1)$, given as $= 248$ nm, $n = 1.47$, we obtain the depth of corrugation $h = 270$ nm. Being limited by the etching technique, the grating could not be etched as an ideal square period, and the corrugations would also have an error etched depth. These will result in the failure of fully nulled zero-order diffraction. In spite of those errors mentioned above, a strong interference fringe could also be formed if the main energy of the laser beam is distributed to the plus and minus first-order diffraction. What we testified in our experiment is that the energy distributed in zero-order is about 16%; plus or minus first-order is about 32%, and other higher-diffraction order is about 20%. The real depth of the mask grating is (260 ± 10) nm.

The LN and LT monocrystal wafers, which were cut in (006) lattice orientation, had a square area of 10 mm × 40 mm, and 1 mm in thickness. The samples were polished carefully and put on a located position. After being exposed by one excimer laser pulse, they were investigated under an optical microscope and an atomic force microscope. Some results are as follows.

Figure 2 shows an optical microscope morphology of the LN wafer grating exposed by a laser pulse with an energy of 250 mJ. One can find that a periodic surface structure has been formed in the exposed area. However, it is worth noticing that two different patterns have been formed. The first is found in the middle of the exposed area (fig. 2(a)), which has a period of 2 μm, the same as that of the mask, and has an equal corrugation's depth. The other structure is dispersed at the edge of the exposed area. Corrugations in this area have a period of 1 μm (half of the mask's period). The depths of these corrugations, however, are changing periodically, e.g. a shallow one exists between two deep corrugations (fig. 2(b)). Although the formation of this structure has not been clearly understood, we can give our explanation according to the experimental situation as follows.

As discussed above, when the laser pulse enters the mask vertically, the interference fringe, which is formed by the ± 1-order diffraction beam, will have a period half the mask's under ideal conditions. If the zero-order is not nulled, an interference fringe that has the same period as that of the mask will be formed by the zero and the minus (or plus) first order, because the mask used in our experiment is designed for an ideal condition, i.e. zero order is nulled when the laser pulse enters the mask vertically. However, the zero-order diffraction beam will become higher as the incident angle increases. In fact, the laser beam could not be modified to an ideal vertical incident angle. Although the center part of the laser beam enters the sample vertically, the edge part of the laser beam will have a small incidence angle. In our experiment, as the angle $\theta = \arcsin(\lambda/2\Lambda) = 3.95$ (here Λ is the period of the mask), the interference fringe that has the same period as the mask's could be formed by the zero-order and 1-order ? diffraction beams. Therefore, two kinds of periodic patterns could exist in one exposed area. The following is the AFM morphology of the as-fabricated LN grating.

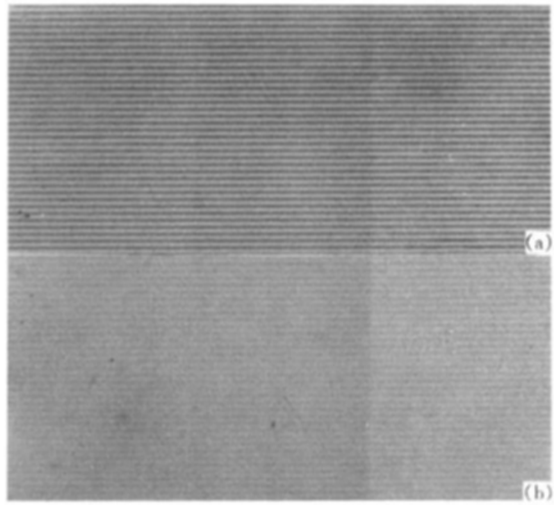

Fig. 2. The optical microscope image of the as-etched LN wafer grating. (a) Middle region of the exposured area; (b) edge region of the etched area.

Surface morphology of the LN grating is very clear in the observation of AFM (shown in fig. 3). One can find from the 2D picture (fig 3(a)) that the corrugations (in the middle of the exposed area) are periodical and have an even depth. Section analysis (fig. 3(b)) shows that the corrugations have nanometer-scaled sleek wave-like surface with a depth of 110 nm.

Because the results of LT wafer gratings are similar to those of LN, only different from the incidence energy laser pulse for the same depth of the corrugations, we do not discuss them here in detail.

2 Analysis and discussion of the mechanism

To understand the formation and physical mechanism of the grating, in this section, we employ an AFM to study the edge area of the as-etched grating. Fig. 4 shows an AFM morphology of the edge area in the exposed LN region. One can find from fig. 4(b) that the wave-crest of the corrugations is higher than the original crystal surface (see the horizontal line in the figure), and the area above the horizontal line is as nearly equal to that under the horizontal line. This result provides a basis for our proposal of the physical mechanism of the grating's formation, i.e. it is formed after the regrowth of the fused LN thin layer by the excimer laser pulse.

When the laser pulse has a suitable incident energy density, the process of the surface is a physical fused process. Because the laser pulse has a very short lifetime, the power density of the laser pulse will be much higher. For example, as a laser pulse that has an energy of 200 mJ enters an area of 0.25 mm^2, the power density of the laser pusle is about 50 MW/cm^2. The sample's surface will be fused at once by this high-power density laser beam. If the energy of laser beam has a periodical space distribution, the material in the fused area will be lashed to

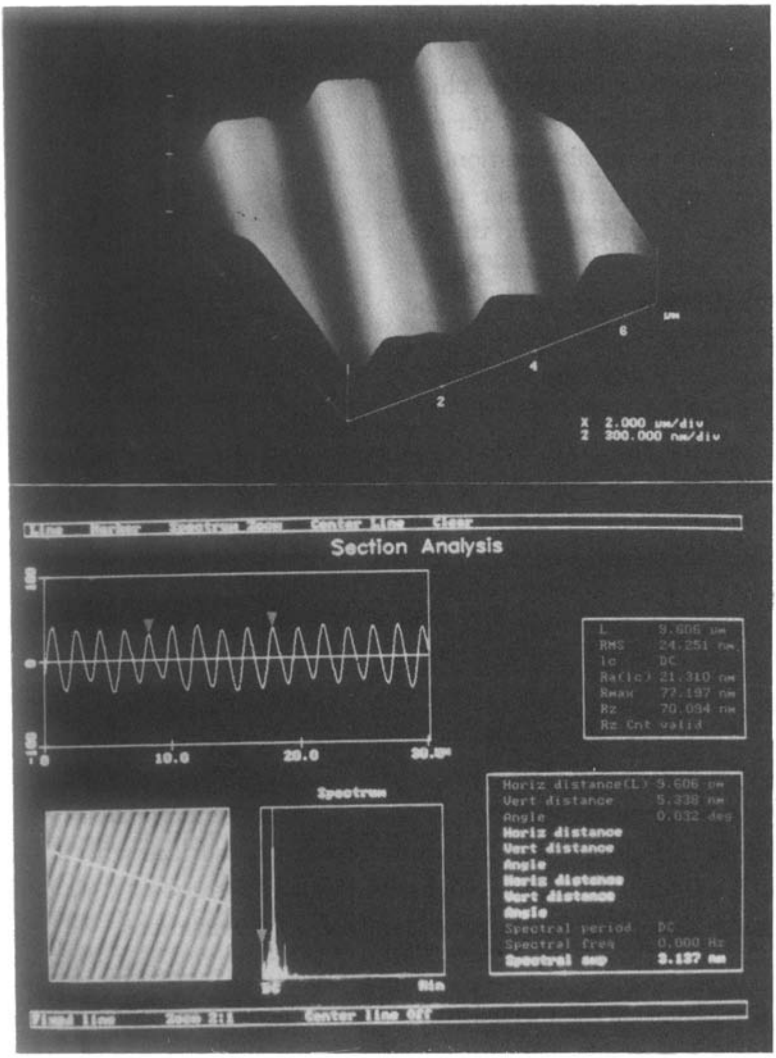

Fig. 3. Atomic force microscope (AFM) morphology of the LN grating. (a) Three-dimensional view of the grating; (b) section analyses of the grating.

its sides and regrow there. Then a periodic geometry surface structure could be formed. In the AFM photograph, one can find that the whole matter at the sample's surface is not reduced——they just have a new distribution to form a geometry surface grating.

For the reason that the laser pulse just has a lifetime of several ten nanoseconds, the fused thin layer of the LN wafer will regrow in the air at once. This means that the exposed area annealed in the air. However, why do the corrugations have so smooth surfaces? This may need further investigation in spite of its possible relating both to the monocrystal structure and the surface smooth finishment of the sample.

In summary, we have demonstrated the direct fabrication of periodic structures that have sleek wave corrugations on top of LN wafer surface by a single excimer laser pulse. This technique may have potential applications both in laser processing and in laser generation of inte-

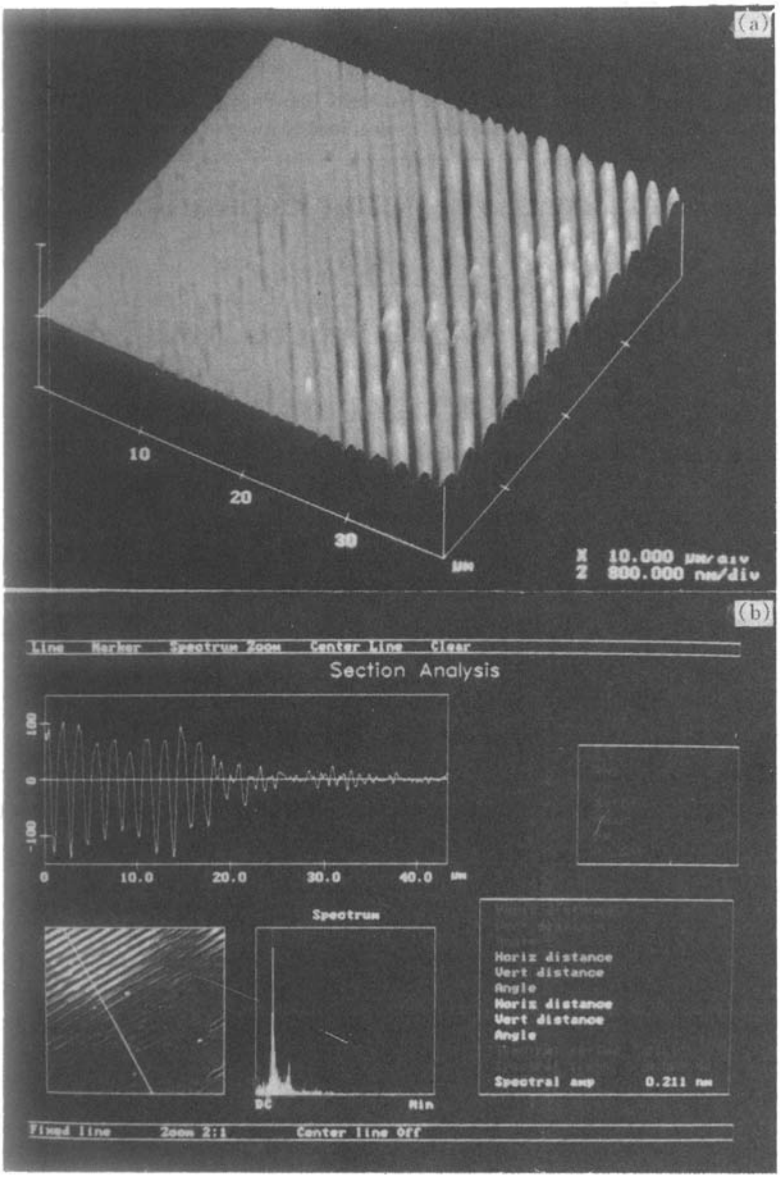

Fig. 4. Boundary morphology of the periodic structures under AFM. (a) Three-dimensional image of the boundary area; (b) section analyses of the same area.

grated optical devices, such as grating couplers and grating lenses.

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