Refractive index modulation in periodically poled MgO-doped congruent LiNbO$_3$ crystal

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An optical diffraction method is exploited to characterize periodically poled MgO-doped congruent LiNbO$_3$ crystal fabricated by electric induced technique. The optical diffraction patterns indicate that the refractive index changes occur in periodic domain structures. Light diffraction from this type of refractive index modulation is simulated, thus providing an effective and nondestructive technique to determine the refractive index changes and domain structures. From the normalized diffraction intensity, we estimate the refractive index change to be in the magnitude of $10^{-5}$. © 2008 American Institute of Physics. [DOI: 10.1063/1.3042100]

Congruent LiNbO$_3$ is one of the first ferroelectric crystals that has found many applications in the field of nonlinear optics and acoustics. The realization of engineered domain structure in a signal crystal, in fact, has opened the way to many applications of scientific and technological interests such as nonlinear frequency converters, photonic band-gap devices, electro-optic Bragg switches, and data storage.$^{1-4}$ Domain inversion in ferroelectric materials such as LiNbO$_3$ can be achieved by applying an external electric field along the $c$ axis of the crystal. The method to generate defined domain patterns is electric field poling via structured electrodes, which transfers the electrode structure into a domain structure.

However, LiNbO$_3$ crystals possess photorefractive properties that cause change in optical characteristics upon exposure to laser radiation. A highly interesting material for many applications is MgO-doped LiNbO$_3$ because of its reduced optical damage.$^{5,6}$ Recently periodically poled Mg-doped LiNbO$_3$ (PPMgLN) crystal has been anticipated as the most practical quasi-phase-matched material.$^7$ The reason for this is not only the significantly reduced photorefractive properties compared to those of congruent LiNbO$_3$ but also the reduced poling field strength.$^5$ This makes possible the fabrication of thicker periodically poled LiNbO$_3$ devices for high power visible light radiation.

The process of domain reversal in ferroelectric crystals is a strain and an internal electric field in the domains induced by the application of a high voltage. The internal strain and electric field are related through the piezoelectric and electrostrictive effects.$^9,10$ The strain gives rise to a change in the refractive index $n$ directly through the elastooptic and electro-optic effects. The poling process induces a periodic modulation of the refractive index, which links to the domain inverted structures. The evaluation of the refractive index modulation with the periodic domain inverted structures therefore becomes an important topic. In this work we propose a nondestructive method in measuring the magnitude of the refractive index modulation, as well as the domain sizes of the domain inverted structure.

The samples were cut from $c$-cut optically polished, 0.5 mm thick wafers obtained from 5 mol % MgO doped congruent LiNbO$_3$ crystal. The PPMgLN was fabricated using the room temperature electric field backswitch poling technique$^7$ with several 80 ms voltage pulses; the domain inversion period is 18 $\mu$m. This PPMgLN structure is a bulk periodic grating with equal positive and the negative spacing. The sample is illuminated with a laser beam at the wavelength of $\lambda=532$ nm and the laser polarization was chosen to be parallel to the crystal’s polar axis ($z$ axis) in order to probe the refractive index behavior. The diffraction pattern can be observed on a screen placed behind the sample. A sketch of the experimental setup is given in Fig. 1. The diffraction patterns of light need to be produced by a periodic structure of refractive index or absorption coefficient. The ferroelectric domain boundaries can be visualized by applying light diffraction method.$^{11,12}$ From measurement of the diffraction intensity, it is possible to estimate the refractive index variation and domain inverted width of the PPMgLN.

Using standard diffraction calculations and neglecting absorption, we can simplify the far-field diffraction intensity distribution as

$$I(\theta) = \left( \frac{2 \pi w}{\lambda} \sin \frac{\theta}{2} \right)^2 \frac{\sin(N\delta/2)}{N \sin(\delta/2)} \cos^2(\Phi/2), \quad (1)$$

where $\delta=(2 \pi \Lambda/\lambda) \sin \theta$, $\Phi=(4 \pi/\lambda)[w \cos(\theta/2) \sin(\theta/2)] + \Delta nd$.

FIG. 1. Schematic of the diffraction experiment: $w$ is the domain width, the period is $\Lambda$, $d$ is the sample thickness, and the screen position is $L$. 

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Here $\theta$ is the diffraction angle, $\Lambda$ is the period of the grating, $w$ is the domain inverted width, $d$ is the thickness of the sample, $N$ is the number of the periods of the grating that take part in the diffraction, and $\Delta n$ is the refractive index change. The interference term $[\sin(N\delta/2)/N \sin(\delta/2)]^2$ shows prominent maxima when the dominator is zero, $\delta/2 = m\pi$, where $m$ is an integer. The diffraction angle of the $m$th diffracted beam can be obtained by

$$\theta_m = \arcsin^{-1} \frac{\Lambda}{m}. \quad (2)$$

It is easy to see that the intensity $I(\theta_m)$ can be determined from the PPMgLN grating structures (inverted domain width $w$ and period $\Lambda$) and $\Delta n$ can be deduced from the intensity $I(\theta_m)$. The intensity of the diffraction maxima is extracted from illuminating six grating lines. The diffraction orders were investigated using probe laser beam with wavelength of 532 nm and power of 100 mW. The diffraction pattern is shown in Fig. 2. To explain this observation, we should understand the formation of the diffraction pattern. The diffraction patterns in the above experiment were formed by diffracted waves from the periodic grating. The ratio of the strength of the boundary diffraction waves to the total strength of the incident beam determines the normalized magnitude of the diffraction peaks. The detector was placed behind the sample and the intensities of the first, second, and third diffraction orders were measured, respectively. The diffracted intensity peak in function of the diffraction order $m$ is shown in Fig. 3. No optical damage was observed in the PPMgLN sample. For domain width of $w=8.85 \, \mu m$ and the solid curve for is for $w=9.20 \, \mu m$. From Fig. 5, one can see that the inverted domain width affects the refractive index change $\Delta n$ very little. Thus estimating $\Delta n$ from Eq. (1) is almost the same for the PPMgLN sample. For domain width of $w=8.85 \, \mu m$ and normalized diffraction intensity of $I_1=0.75$, we have $\Delta n=4.26 \times 10^{-5}$, while for $w=9.20 \, \mu m$, we have $\Delta n=4.33 \times 10^{-5}$. It is worth noting that the presence of a modulation in the refractive index can affect the wavelength conversion efficiency. A numerical analysis of the simulation of this effect on second harmonic generation is proposed in Ref. 14.

In conclusion, using the far-field diffraction patterns, we investigate the refractive index changes and the domain
structures of the PPMgLN. Measurements of the intensity of diffracted intensity may provide a sensitive way to determine the refractive index modulation and the domain structures. By means of optical diffraction measurements we obtained variation in the refractive index $\Delta n$, which is about $4.26 \times 10^{-5}$, and domain width, $w=8.85 \pm 0.02 \mu m$, for the tested PPMgLN sample.

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