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Photorefractive effect in lithium niobate crystals

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Abstract

Phase-grating formation in iron-doped lithium niobate crystal was studied. Growth is observed to be oscillatory with a time period of over several seconds; oscillatory growth had intensity variations of smaller time scales overriding it.

Keywords: Nonlinear optics, photorefractive crystals and phase conjugation.

1. Introduction

The change in local refractive index caused by light-induced electrostatic field of the order of 10^5 V/m in certain nonlinear optical materials is termed as photorefractive (PR) effect. The PR effect may be explained as follows: (i) Light induces separation and migration of charges that originate either from impurity (intrinsic) levels or by dopants (extrinsic) in the crystal. (ii) The separation of charges results in a strong electrostatic field. (iii) The electrostatic field causes a change in the refractive index of the crystal by the linear electro-optic (Pockel's) effect.

The PR effect was discovered in lithium niobate[1] when apparent optical damage was found to be reversible by heating the crystal. The PR properties of a material can be demonstrated by illuminating the material with two coherent laser beams. This forms a spatially varying modulated intensity profile throughout the material. The high spatial resolution of the volume gratings that can be recorded with the PR process indicates the potential use of such materials for information storage.

In two-beam coupling (TBC) configuration, two beams from a laser source interfere in the volume of the PR crystal. The interference pattern causes nonlocalized $\pi/2$ shifted distribution of charges forming volume gratings in the crystal. These phase gratings are used for hologram storage in the PR crystal. It has been recognized[2] that the volume nature of thick holograms permits the interference of an incident light beam with its own diffracted beam inside the recording medium. The dynamical theory of Ninomiya[3] explains the resulting characteristics.

The diffraction efficiency of the hologram grating has been previously measured by briefly interrupting the writing process at regular intervals of time[4] or reading by a single wave incident upon the hologram[5]. Magnusson and Gaylord[6] proposed the dynamic theory to describe the recording and readout characteristics of volume gratings. It was supposed that the volume nature of the thick holographic grating allows the interference of an incident light beam with its own diffracted beam inside the recording medium. The dynamic theory satisfactorily explains the oscillatory behaviour of the growth pattern of the gratings. An oscillatory diffraction efficiency upon readout has also been shown theoretically and experimentally to be possible due to changes in the multiple internal reflections as a result of crystal thermal expansion caused by the absorption of laser light[7].

In the case of two waves simultaneously writing and being scattered by a shifted grating, an additional $\pi/2$ phase is introduced into the scattered waves. The scattered waves are therefore in and out of phase with the incident waves and hence gain or lose energy. The beam that gains or loses energy is determined by the phase shift of the grating ($\pm\pi/2$). This in turn is dependent on the sign of the charge carriers, the sign of the electro-optic effect, the interaction geometry of the PR material, and the polarization states of the interacting waves. The description of the PR effect was shown by making use of the diffusion and the hopping models[8-11]. The complex amplitude $\boldsymbol{E}(x)$ of the steady-state electric field in the absence of an intrinsic or applied field is given by

$$\boldsymbol{E}(x) = -\frac{k_B T}{q} m \frac{\boldsymbol{k}}{1+(k/k_0)^2} \sin(\boldsymbol{k}.x) \tag{1}$$

where $k_B T$ is the thermal energy of the crystal lattice, q, the charge of the mobile charge carriers, $\boldsymbol{k}_0$, a constant of the material that depends on the number density N of charge carriers available for charge migration and m, the modulation index of the interfering waves.

We had carried out a TBC experiment to study the diffraction efficiencies of PR iron-doped lithium niobate crystals (IDLN). As expected, the observations of the growth of grating in IDLN were seen to be oscillatory. Apart from the oscillatory growth pattern we had observed intensity fluctuations at smaller time periods[12]. Wenji *et al.*[13] have found similar oscillations in the growth of phase grating by TBC in the IDLN crystal.

The oscillatory growth behaviour in lithium niobate crystal has been analytically explained by considering the bulk photovoltaic effect[14], but this analysis does not explain our observations of intensity fluctuations of smaller time periods. The results of the observation are briefly described.

2. The two-beam coupling experiment

The schematic experimental layout of TBC is shown in Fig. 1. The direction of the crystal axis is indicated by C. The two beams, I_3 and I_4, from an argon laser (Spectra Physics-171, with a Fabry–Perot etalon) are made to interfere in the IDLN crystal ($20 \times 10 \times 2$ mm, the iron doping in the crystal is 0.02% mol. wt). Due to PR effect, a phase grating is continuously written till it reaches saturation. The saturation time depends on the intensity of the beams, the mobility, and the number of charge carriers. Figure 2 shows the typical growth and decay of the phase grating in the IDLN crystal. The growth and decay of the grating were made at detector D_1 by noting the dc-level changes (with respect to ground) on the digital oscilloscope. The decay characteristics

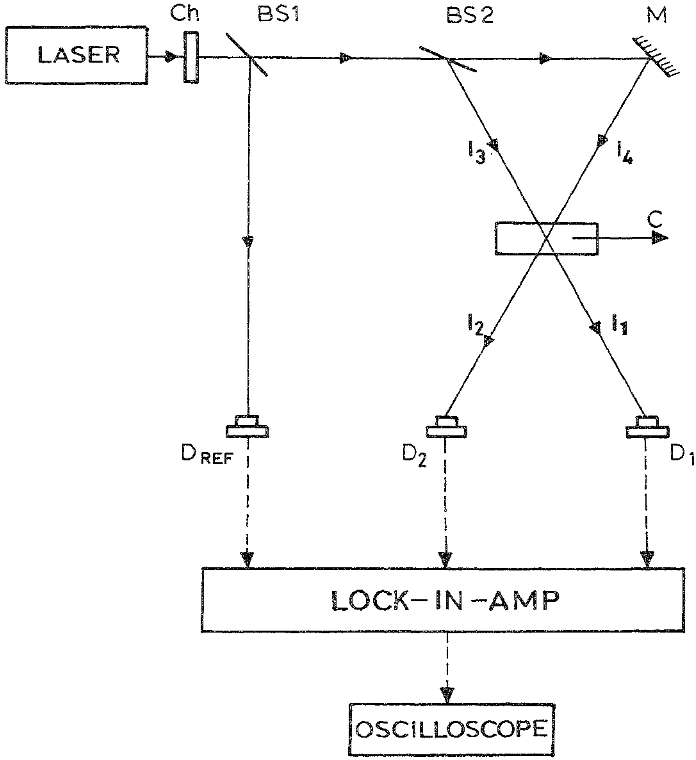

FIG 1 Experimental configuration to measure the growth of phase grating in iron-doped lithium niobate crystal. D_1, D_2 and D_{REF} are the detectors to measure the intensities of I_1, I_2, and I_{REF}. The ac and dc variations of I_1 and I_2 are measured by constantly eliminating the noise at the source (I_{REF}) and are stored in the digital oscilloscope.

are studied by cutting off I_4. The intensities of the two beams were 15 mW each, the reference beam of 15 mW, and the overall laser power 50 mW ($\lambda = 488$ nm).

The TBC experiment was then extended to measure phase conjugate signal by four-wave mixing (FWM) process. A third beam counterpropagating with I_4 is diffracted in the direction of I_3 to form the phase conjugate signal. The signal was measured with the

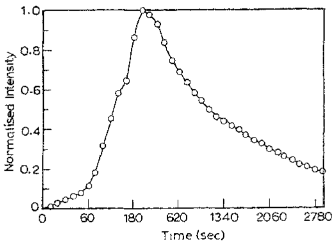

FIG. 2. The growth and decay of phase grating in IDLN crystal are shown. The dc-level changes of the intensity I_1 are measured

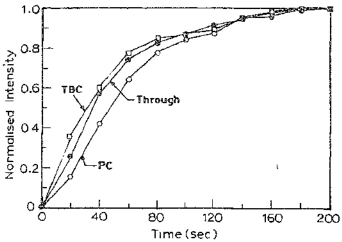

FIG 3 The growth of the phase conjugate signal and the 'through' beam by the FWM geometry, and the growth characteristics of two-beam coupling by the TBC geometry are plotted.

overall laser power maintained at 50 mW, with the three beams having equal intensity. The growth of I_1 is simultaneously monitored and is named as the 'through beam'. Figure 3 shows the normalized curve of the TBC grating growth obtained as mentioned earlier, phase conjugate signal, and the 'through' beam. Efficiencies of the order of 10^{-1} of TBC, $\sim 10^{-2}$ of the 'through' beam and nearly 10^{-3} in the case of phase conjugate signal of FWM were obtained.

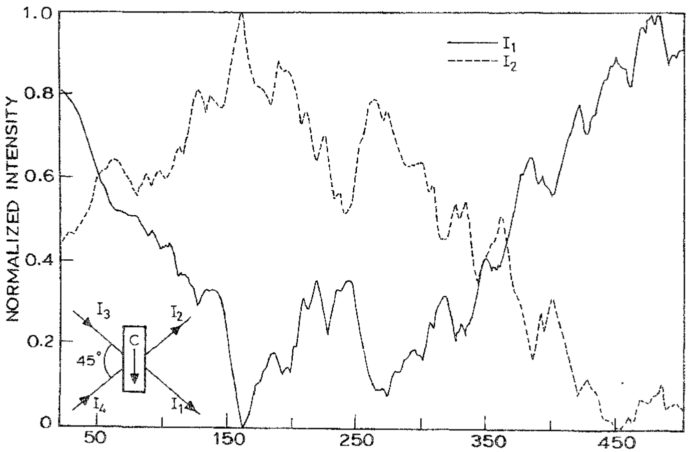

FIG. 4 The ac variations of the two waves, I_1 and I_2, are shown. Inset shows the writing beams polarized perpendicular to the plane of incidence.

The TBC experiment was repeated maintaining the laser power at 50 mW but the intensity ratio of I_3 and I_4 was 4:1. The ac-level changes of I_1 and I_2 were monitored. It is observed that the oscillatory growth curve of the phase grating is seen to be modulated by intensity 'fluctuations' of smaller time periods. The oscillatory pattern has a period of oscillation >30 s while the intensity fluctuations are <3 s. Figure 4 shows the oscillatory energy coupling between I_1 and I_2 of the TBC experiment in IDLN. The time period of these intensity fluctuations was observed to vary on changing the intensity ratios and varying the angles of interaction of I_3 and I_4. Figures 5 and 6 show two such temporal intensity fluctuations at smaller time periods. The intensity ratio of I_3 and I_4 was 5:1 with the angle of interaction being 60°. In all the above experiments, the polarization of the two beams was perpendicular to the plane of incidence. The reference wave is subtracted from I_1 and I_2. The normalization of the curves is governed by the expression

$$I_{OUTPUT} = \frac{I_{VALUE} - I_{MIN}}{I_{MAX} - I_{MIN}} \tag{2}$$

where I_{MAX} and I_{MIN} are, respectively, the maximum and minimum values of intensities. The intensity fluctuations showed a characteristic dependence on the angle of interaction, intensities of the input signals (I_3 and I_4), and the overall laser power (a threshold process).

3. Conclusion

TBC experiment to study the growth of the volume phase grating in IDLN crystal was carried out. The growth of the phase grating was oscillatory as expected with a time period of several seconds. Prominent temporal fluctuations of much smaller time periods that depended on the intensity ratios and the angle of interaction of the two beams were seen to override the oscillatory growth pattern of the phase grating. The time periods of

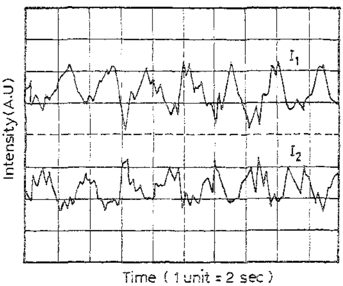

FIG. 5 The intensity fluctuations of I_1 and I_2 in the TBC geometry with a different intensity ratio of the input beams, I_3 and I_4.

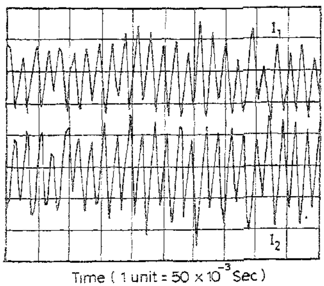

FIG. 6 The intensity fluctuations of I_1 and I_2 in the TBC geometry at a different angle of incidence of the input beams, I_3 and I_4.

these fluctuations decrease with increase in the angle of interaction of the two incident beams.

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