Journal of the Optical Society of Korea, Vol. 1, No. 1, March 1997, pp. 19~22

Thermal fixing of multiple holographic gratings in magnesium oxide doped lithium niobate crystal

Seung-Woo Yi, Sungdo Cha and Seung-Ho Shin
Department of Physics, Kangwon National University, Chunchon 200-701, Korea

(Received; February 4, 1997)

The photorefractive properties of 4% mol magnesium oxide doped lithium niobate have been investigated at room temperature. The recording and erasing time constants were measured as a function of intensity and analyzed by using the two active species (electron-hole) model. These results were used to compute the exposure schedule for multiple hologram recording. We have recorded gratings of five holograms by angular multiplexing at room temperature and fixed them by means of a thermal cycling procedure. The highest diffraction efficiency of a fixed grating is up to 50% of an unfixed one.

I. INTRODUCTION

The photorefractive effect has been studied intensively since the first observation of optical damage in $LiNbO_3$ by Askin *et al*[1]. $LiNbO_3$ should be a good recording material for a three dimensional high-capacity storage medium due to its high optical quality, easy to grow large samples[2]. One of the most important applications of the photorefractive effect is the multiple holographic grating storage that is useful in many areas, such as optical interconnection[3,4], optical neural networks[5], and optical clock distribution[6]. In general, multiple hologram recording in a photorefractive medium is based on Bragg diffraction by the volume holographic grating. Although many multiplexing methods are possible for a finite photorefractive crystal[7,8], angular multiplexing with enough angular separation can achieve a tolerable level of cross talk noise[9].

For practical applications, a nondestructive readout of the stored information should be achieved. There are several techniques for transforming a temporal grating to a permanent or semi-permanent grating, such as thermal fixing[10], electrical fixing[11], two-photon recording[12], and combined methods[13]. One of these, thermal fixing, which is based on the ionic compensation at elevated temperature, presents high enough quality for practical usage. After recording the holographic grating at room temperature, when the crystal is heated up to a proper elevated temperature, certain species of charged ions become mobile by thermal excitation. The ions compensate the space charge field built up by the electrons. These secondary charge carriers are stable at room temperature under exposure to high intensity as well as normal intensity reading beams.

Another important issue is fanning inside the crystal because beam fanning is the most significant noise source. Along with cross talk noise, it decreases signal to noise ratio (SNR). So, many crystal growers have tried to find proper dopant and doping level to reduce the fanning noise. It is well known that 4~5% mol. magnesium oxide doping greatly reduces optical damage effects and decreases the response time about 1/10 in comparing with an undoped crystal[14]. Beam fanning is also reduced[15].

In this paper, we have measured basic properties of magnesium oxide doped lithium niobate ($MgO:LiNbO_3$) to compute the exposure time schedule for each grating of multiple holograms. We discussed how to find the proper exposure schedule to make each grating's amplitude the same. We also tried to record multiple holographic gratings and fixed them using thermally excited ion movement at elevated temperature.

II. THEORY

In the usual configuration for holographic recording, the polarization of the writing beam is extraordinary, and the c-axis is in the incident plane to provide the largest effective electro-optic coefficient. The modulation of the refractive index is given by

$$n = n_e - 1/2\,[n_e^3 \gamma_{33} E_{sc}] \tag{1}$$

where n_e is the index of refraction for extraordinarily polarized light, γ_{33} is the effective electro-optic coefficient, and E_{sc} is the space-charge field. The amplitude of a recorded hologram in a photorefractive crystal as a function of time is proportional to the space-charge field, E_{sc}, and given as follows by Kukhtarev[16]

$$A_r = A_{r0}[1 - \exp(-t/\tau_r)] \tag{2}$$

where A_{r0} is the single grating amplitude at infinite time and τ_r is the recording time constant. In the erasing process, the grating amplitude A_r monotonically decays as

$$A_e = A_{e0} e^{-t'/\tau_e} \tag{3}$$

where A_{e0} is the initially recorded grating amplitude, t' is the total erasing time and τ_e is the erasing time constant. For a total of M holograms, the final amplitude of i-th hologram is given as

$$A_i = A_0 [1 - \exp(-t_i/\tau_r)] \exp\left(-\sum_{k=i+1}^{M} t_k/\tau_e\right), \tag{4}$$

where A_i is the final amplitude of the i-th grating that was recorded for time t_i and then erased during hologram recording from i+1-th to M-th. In general, all holograms should have equal amplitudes (i.e. $A_1 = A_2 = \cdots = A_{M-1} = A_M$) for practical applications. We need to use numerical methods to calculate the exposure schedule because these equations cannot be solved analytically. From the above constraint, the recursion relation can be obtained;

$$t_i = -\tau_r \ln[1 - e^{t_{i+1}/\tau} + e^{-t_{i+1}/\Delta\tau}] \tag{5}$$

where $1/\Delta\tau = 1/\tau_r - 1/\tau_e$. The first step to find the exposure schedule is to find the exposure time of the last (M-th) hologram. When the recording time of the last hologram is fixed, the total number of holograms M, that can be recorded in the crystal and the maximum diffraction efficiency of each hologram ν, are also fixed automatically. These two parameters are limited by the following simple relation[17].

$$M \beta \nu \approx 1, \tag{6}$$

where $\nu = A/A_0$ and $\beta = \tau_r/\tau_e$. The ratio of recording and erasing time constant β is constant at the same grating spacing. That means the maximum diffraction efficiency of one hologram after recording a total of M holograms should be less than $1/M$ of the single hologram's diffraction efficiency.

III. EXPERIMENTAL DETAILS

In the experiments, 4% mol doped MgO:$LiNbO_3$ was used to record the multiple holographic gratings. The crystal had dimensions of 5 mm × 10 mm × 10 mm and its c-axis was along the 10 mm long edge. To investigate photorefractive properties of the crystal at room temperature, the recording and erasing time constants were measured with the experimental configuration as shown in Fig. 1. The holographic gratings were recorded by Ar ion laser beams (λ_{Ar} = 514.5 nm). The diffraction efficiency was monitored using a low power He-Ne laser (λ_{He} = 632.8 nm). In this case, the incident angle of the reading beam was chosen to satisfy the grating equation, $\lambda_{Ar} \sin\theta_1 = \lambda_{He} \sin\theta_2$. The polarization of the recording beams were parallel to the plane of incidence (extraordinary polarization) and the polarization of the reading beam was perpendicular to the incident plane (ordinary polarization). These polarization conditions provide the largest effective electro-optics coefficient. The orientation of the crystal was chosen to have the c-axis in the plane of the sample and parallel to the grating vector. The optical erasing was done by a single beam with non-Bragg matching angle.

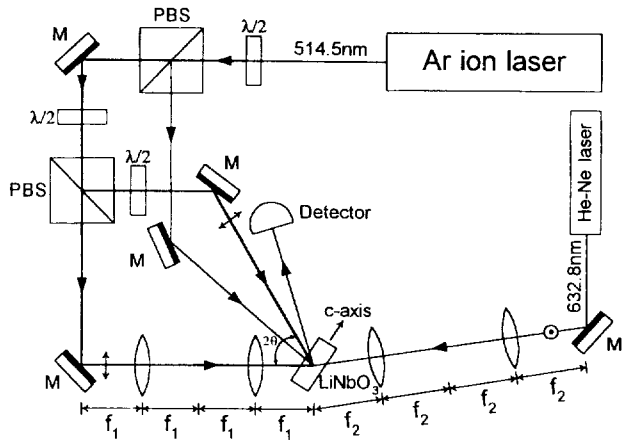

Fig. 1. Experimental setup for recording multiple holographic gratings in MgO:$LiNbO_3$, λ/2:half-wave plate, PBS:polarazing beam splitter, M:mirror, f_1 = 140 m, f_2 = 308 mm.

Five holographic gratings were recorded using the angular multiplexing scheme with 4f optical imaging system of the reference beam as shown in Fig. 1. This 4f angular tuning configuration consisted of a mirror and two lenses located at confocal distance. The reflecting mirror and the crystal were located at the focal points of the telescopic system. There should be a couple of sinc nulls for each grating due to the high modulation depth. So, we gave enough angle for every hologram to avoid inter-page cross-talk noise. After recording the grating at room temperature, we removed the crystal from the setup and put it into a temperature controlled oven to obtain a fixed grating. The oven was heated up to 170°C at a constant rate of 3°C/min. and kept for 30 minutes at elevated temperature. It is well known that the ion mobility increases notably around 145°C while optically excited electrons cannot move at temperatures below 180°C in this crystal[15]. After cooling to room temperature, there was no diffraction signal because of whole compensation. To wash out the old electron grating, we directed an erasing beam from an Ar ion laser (9.0 W/cm²) onto the whole area for 30 minutes.

IV. RESULTS AND DISCUSSION

Fig. 2 shows a typical recording and erasing curve with the recording beam set at θ = 25° to the crystal

surface normal, corresponding to a grating spacing of 0.61 μm. The ratio of the two recording beams (I_{r1}, I_{r2}) was 1:2.3 in intensity. This means the amplitude of the modulation depth m = 0.92, using the definition, $m = 2\sqrt{I_{r1}I_{r2}}/(I_{r1}+I_{r2})$.

For accurate curve fitting, we replot the erasing curve of Fig. 2 on a semi-logarithmic scale as shown in Fig. 3. It was found that two time constants are needed to perform a good fit to the data. This agrees well with the two species active center model[18]. Although two time constants are needed, one effective time constant, τ_{eff}, obtained with single exponential decay curve fitting can be used to approximate the time dependent behavior of the grating. We used this effective time constant, Eq.(2), and Eq.(3) to determine recording schedule. From the results of curve fitting, the effective recording and erasing time constants were obtained as $\tau_{r,eff}$ = 158 sec and $\tau_{e,eff}$ = 157 sec, respectively.

Fig. 4(a) shows the recording time constants as a function of recording beam intensities for two different

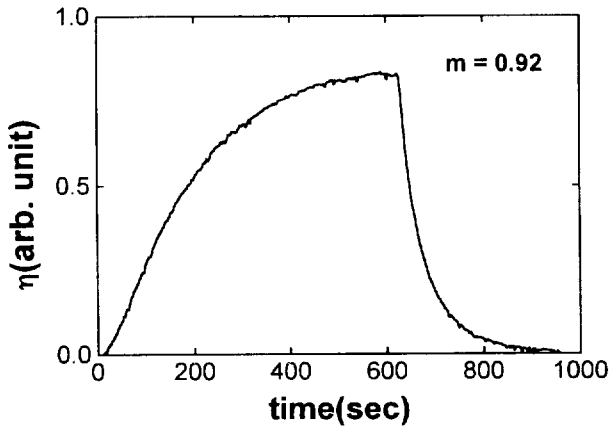

Fig. 2. The diffraction efficiency of typical holographic recording and optical erasing at room temperature. Total recording beam intensity is 2.94 W/cm^2 and the magnitude of modulation depth of two recording beams is m = 0.92.

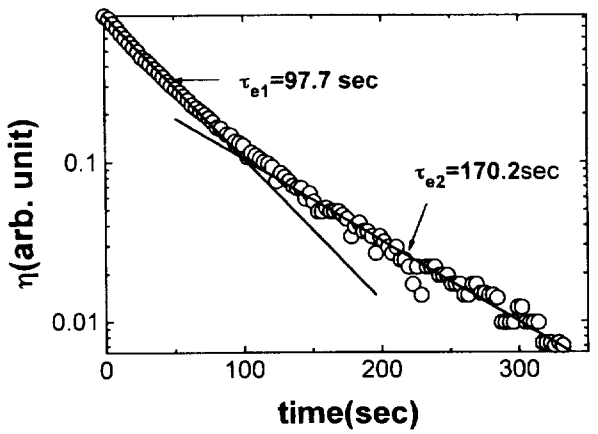

Fig. 3. Time constants of optical erasing for accurate curve fitting.

modulation depths. In the most photorefractive hologram recording, the material's fundamental limiting response time, τ, is given as a function of the total incident beam intensity, I, and other material parameters as follows[19];

$$\tau = \left(\frac{h\nu}{e}\right)\left(\frac{\lambda}{\Lambda}\right)\left(\frac{\gamma}{\alpha_p}\right)\frac{2}{\pi\eta}\frac{\varepsilon}{n^3 r}\frac{1}{I}, \tag{7}$$

where $h\nu/e$ is the incident energy per photon, Λ is the holographic grating spacing, γ is the coupling constant of two beam mixing, α_p is the photoexcitation absorption coefficient, η is the quantum efficiency, and ε, n, r are permittivity, refractive index and effective electro-optic coefficient, respectively. According to Eq.(7), the response time should be inversely proportional to the intensity (i.e. $\tau \propto 1/I$), with the low modulation depth approximation. If the grating has many harmonics, however, due to the high modulation depth, the power of the intensity should deviate from $1/I$. It is clearly shown in Fig. 4(a) that the slope of the curve for high modulation depth (m = 0.99) deviates more from $1/I$ than that for lower modulation depth (m =0 . 92). Fig. 4(b) also shows the erasing time constant as a function of erasing beam intensity for two different modulation depths (m = 0.99 and 0.92). It shows the same

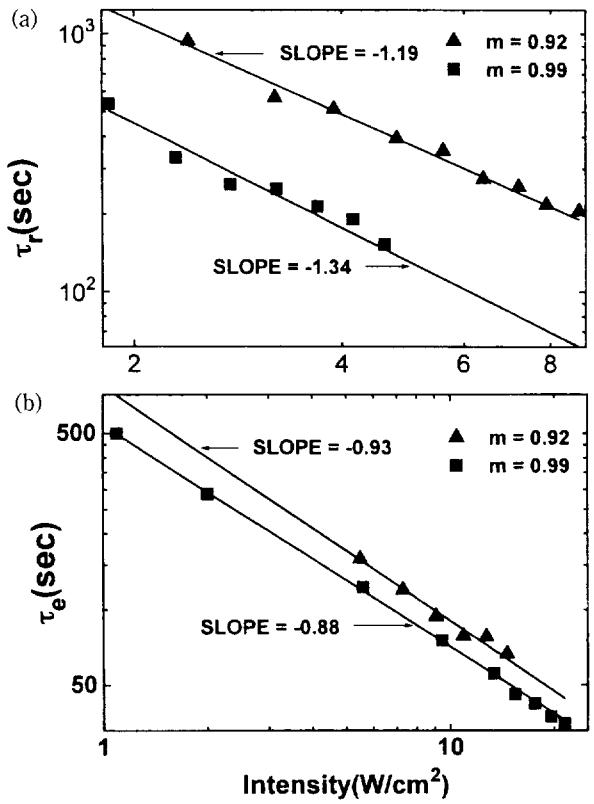

Fig. 4. Recording/erasing time constant as a function of recording/erasing beam power density for recording (a) and optical erasing (b).

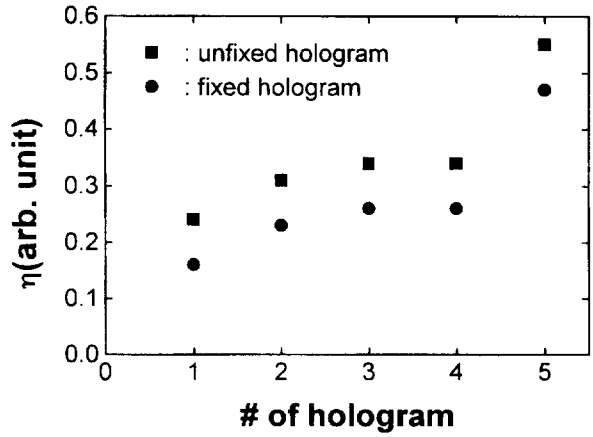

Fig. 5. Diffraction efficiencies of the unfixed and thermally fixed gratings.

deviation due to the harmonics as the plot of the recording time constant. By using this result, we found that the ratio of the recording time constant to the erasing time constant is given by $\beta \simeq 1$. In this case, the maximum amplitude of each grating, A_i is limited by $A_i \leq A_0/M$, where A_0 is the maximum amplitude of a single grating in the total number of gratings M.

We used this data to determine the exposure schedule for multiple hologram recording. From Eq.(6) and the experimental data, a maximum of 100 holograms can be stored in this crystal with $v = 0.01$. We tried to record 5 holograms because the diffraction efficiency should decrease during thermal fixing. In five hologram recording, the grating amplitude ratio was given by $v = 0.17$.

Fig. 5 shows diffraction efficiencies of unfixed and fixed holographic gratings with 5 holograms. The amplitude of the fixed grating reached about 50% of the unfixed grating's amplitude. After thermal fixing, the amplitude of this grating did not decrease under exposure to a strong Ar ion laser beam (10 W/cm^2) for several hours.

V. CONCLUSIONS

In conclusion, the photorefractive properties of magnesium oxide doped lithium niobate have been measured at the room temperature. We confirmed good photorefractive properties such as no fanning effect and fast response time. The thermal fixing of multiple holographic gratings has been performed successfully in the MgO:$LiNbO_3$. We found that the fixed grating's amplitude reached up to 50% of that of the original grating recorded at room temperature. In this experiment, the average absolute diffraction efficiency of fixed gratings is about 1%. More work is need to increase the total number of holograms that can be recorded in the crystal and the diffraction efficiency of the fixed grating.

ACKNOWLEDGMENTS

This work was supported by the Korea Science and Engineering Foundation (KOSEF) with the project No. 9604018.

REFERENCES

[1] A. Ashin, G. D. Boyd, J. M. Dziedsic, R. G. Smith, A. A. Bollmann, J. J. Levinstein and K. Nassau, Appl. Phys. Lett **9**, 72 (1966).
[2] P. Lerner, E. Legras and J. P. Dumas, J. Crystal Growth, **3/4**, 231 (1968).
[3] S. Wu, Q. Song, A. W. Mayers, D. A. Gregory, and F. T. S. Yu, Appl. Opt. **29**, 1118 (1990).
[4] A. E. T. Chiou and P. Yeh, Appl. Opt. **29**, 1111 (1990).
[5] N. Farhat, D. Psaltis, A. Prata, and E. Peak, Appl. Opt. **24**, 1469 (1985).
[6] D. Psaltis, M. A. Neifield, and A. Yamamura, In Digest of Conference on Optical Computing (Optical Society of America, Washington, D. C., 1989), p. 206.
[7] J. J. Amodei and D. L. Staebler, Appl. Phys. Lett. **18**, 540 (1971).
[8] R. Collier, C. Burchhardt, and L. Lin, *Optical Holography* (Academic, New York, 1971).
[9] W. J. Burke and P. Sheng, J. Appl. Phys. **48**, 681 (1977).
[10] D. L. Staebler, "Ferroelectric crystals," in *Holographic Recording Materials*, H. M. Smith ed. (Springer-Verlag, Berlin, 1977).
[11] F. Micheron and G. Bismuth, Appl. Phys. Let. **20**, 79 (1972).
[12] D. von der Linde, A. M. Glass, and K. F. Rogers, Appl. Phys. Lett. **25**, 155 (1974).
[13] S. W. McCahon, D. Rytz, G. C. Valley, M. B. Klein and B. A. Wechsler, Appl. Opt. **28**, 1967 (1989).
[14] D. A. Bryan, R. R. Rice, R. Gerson, H. E. Tomaschke, K. L. Sweeney, and L. E. Halliburton, Opt. Eng. **24**(1), 138 (1985).
[15] Seung-Ho Shin, Scott Campbell and Pochi Yeh, in Conf. on Lasers and Electro-Optics **12**, 307 (1995).
[16] N. V. Kukhtarev, V. B. Markov, S. G. Odulov, M. S. Soskin, and V. L. Vinetskii, Ferroelectrics **22**, 949 (1979).
[17] D. Psaltis, D. Brady, and K. Wagner, Appl. Opt. **27**, 1752 (1988).
[18] M. Carrascosa and F. Agullo-Lopez, Appl. Opt. **27**, 2851 (1988).
[19] P. Yeh, Appl. Opt. **26**, 602 (1987).