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Light-induced backward scattering in $LiNbO_3$:Fe,Zn

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We investigated the light-induced backward scattering in doubly doped lithium niobate crystals and observed an intensity threshold effect. It will be shown that scattering microregions are locally recorded in the sample by holographic interaction due to the existence of the threshold effect. Experimental results of multilayer recording point out that this property could be used for high-density multilayer-like bit data optical storage while keeping high signal-to-noise ratio. © *2002 American Institute of Physics.* [DOI: 10.1063/1.1529083]

Lithium niobate materials are widely studied because of their excellent electro-optic, acousto-optic, or nonlinear properties. In this crystal, the photovoltaic effect plays an important role for the photorefractive effect. It results in some interesting phenomena such as optical amplification, light-induced scatterings, wave generation.[1] Among these interactions, the scattering effects[2–5] have been extensively studied particularly the forward scattering. These effects differ from other well-known stimulated interactions such as Brillouin scattering requiring high intensity levels. It had been thought for a long time that photorefractive light-induced scatterings did not depend on the incident light intensity. However in 1995, Zhang *et al.*[2] found a threshold effect for the light-induced forward scattering in $LiNbO_3$. Nevertheless, few studies concern light-induced backward scattering and in particular, no threshold effect has been reported.

In this letter, we report on the threshold effect for the light-induced backward scattering and point out that holographic microregions are formed in the sample near the focal point of the incident beam. Our results demonstrate that combining the traditional bit data storage with this threshold effect and the holographic property of the microregion, one can access three-dimensional data storage of high capacity and signal-to-noise ratio. Each holographic microregion can contain several bits. The microregion was induced by a beam above the threshold intensity level and characterized by the localized backward scattering.

It is well known[1] that strong scatterings, also called "beam fanning," can occur under coherent beam propagation in photorefractive crystals. This effect results from self-diffraction and coherent amplification of the incident beam which experiences phase noise gratings owing to the two wave mixing interaction between the incident beam and its scattered beams. Both defects and bulk inhomogeneity of crystals act as scattering centers for the incident beam. In addition, small-scale fluctuations[6] of the photoelectric parameters of crystals also play the role of optical scattering centers. For example, small-scale spatial variation of the photogalvanic tensor is considered as a key parameter for light-induced backward scattering in c-cut lithium niobate.[6] When a focused light illuminates the crystal, the backward scattering takes place because of the small-scale stochastic refractive index modulation (of the order of the optical wavelength), which results from the spatial variation of the photogalvanic tensor.

Our experimental setup implemented in order to study the light-induced backward scattering is shown in Fig. 1. The beam provided by a frequency-doubled Nd:YAG laser ($\lambda = 532$ nm) was expanded by means of a spatial light filter (SLF) and a collimating lens (L1). Then the beam was focused by a doublet lens (L2) with a 40-mm focal length into a codoped c-cut $LiNbO_3$ crystal (4 mm thickness, doped with 0.05 wt % Fe and 0.8 wt % Zn). Note that the converging pump beam propagates along the negative c axis of the crystal as in this way backward scattering would be induced while the so-called "scattering self-wave" is forbidden.[6] A laser power meter (LPM1) or a recorder (R) was used to monitor the backward scattering extracted by a beam splitter (BS), while another laser power meter (LPM2) watched the variation of the incident beam intensities. The crystal was

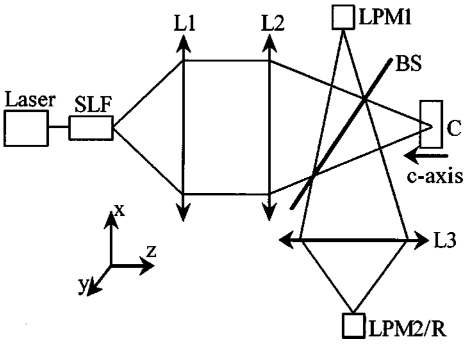

FIG. 1. Experimental setup. SLF: spatial light filter; L1, L3: optical lens; L2: doublet lens; BS: beam splitter; LPM1 and LPM2: laser power meter; R: recorder; C: crystal.

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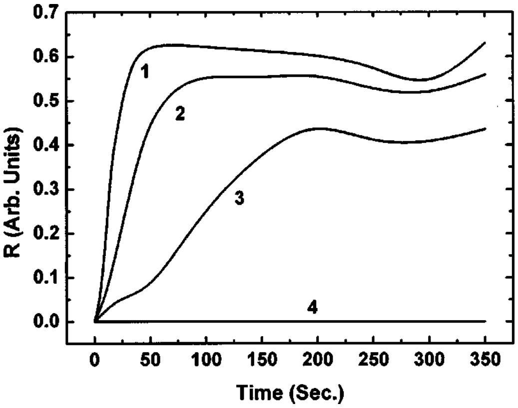

FIG. 2. Temporal evolution of the light-induced backward scattering with different writing light intensities. R is defined as I_r/I_i, where I_r is the backward scattering light intensity and I_i is the incident light intensity. Curves 1, 2, 3, and 4 correspond to the results with incident light intensities of 10.3, 6.2, 2.2, and 0.44 W/cm^2, respectively.

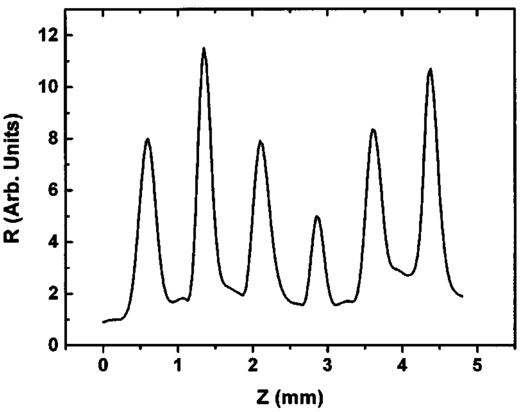

FIG. 4. Spatial resolution of the noise grating along z direction. R is defined as the same as that in Fig. 2. The readout light intensity was kept at 0.13 W/cm^2.

slightly tilted to prevent specular reflection from entering LPM1.

Experimental results of temporal evolutions of the light-induced backward scattering are plotted in Fig. 2 for incident light intensities ranging from 0.44 to 10.3 W/cm^2. It can be stated that, under a threshold value of 0.44 W/cm^2, light-induced backward scattering does not appear no matter how long the sample is illuminated. This threshold effect is shown to be similar to the one we observed for the forward scattering.[2]

In addition, we studied the decay processes of a noise grating recorded with a 14.4 W/cm^2 focused beam by characterizing its backward scattering. The readout beam intensity was set to be 0.13 W/cm^2 (smaller than the threshold value) in order to avoid rewriting during readout. An additional beam was served as an erasing beam. It is found that the decay time constant of the noise grating strongly depends on the erasing beam intensities. The higher the erasing intensity is, the smaller the decay time constant, as shown in Fig. 3. The results also indicate a long dark decay time constant more than 50 h (curve 4 of Fig. 3). We also notice that when the writing beam intensity is equal to the erasing one, the rise time constant is much smaller than the corresponding decay time constant. For example, we used a focused beam of 14.4 W/cm^2 to record a noise grating within 15 s, while measuring a 200 s decay time for the same erasing intensity.

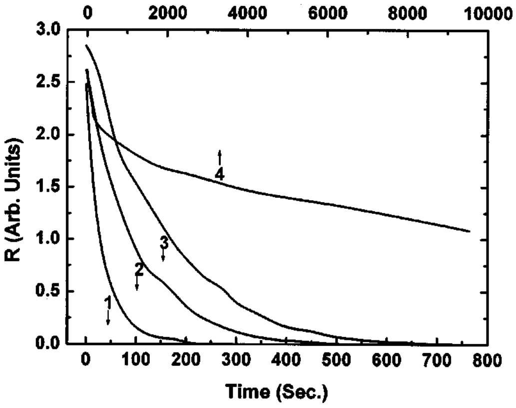

FIG. 3. Decay processes of a noise grating recorded with a 14.4 W/cm^2 writing intensity. Curves 1, 2, 3, and 4 correspond to the results with erasing beam intensities of 14.4, 7.9, 4.5, and 0.0 W/cm^2, respectively.

Although the threshold effects for both the forward and backward light-induced scattering are similar, we will show that the location of the noise grating differs. While the noise grating for the light-induced forward scattering occurs throughout a cumulative interaction involving the whole illumination region, the light-induced backward scattering clearly originates locally thanks to threshold effects and the photogalvanic tensor variations induced near to the focal point in c-cut crystals. This has been confirmed by a scanning experiment that shows the location of the noise grating in the sample with respect to the focal spot of the writing beam. For this purpose we performed the following experiment using a 22 W/cm^2 focused writing beam. After recording the first noise grating, the crystal was moved along z direction (the coordinate was illustrated in Fig. 1) without changing the focal point in the x-y plane. At this new location, we recorded another noise grating while the former was not readout. We sequentially wrote several noise gratings by moving the crystal along the z direction step by step with an equal distance between two neighboring noise gratings. During this recording procedure, the previously recorded noise gratings are not completely erased by the later recording beams owing to the asymmetry in the rise and decay time constants (as already shown in Fig. 3). Finally, we were able to readout these noise gratings separately by moving the crystal back to the recording position. Again the readout beam intensity was set to be 0.13 W/cm^2 in order to avoid rewriting during readout. Figure 4 shows one of our experimental readout results, in which the spacing distance between two neighboring noise gratings is ~0.8 mm. In one of our experiments, we recorded 14 noise gratings along the z direction within a 4 mm deepness. In addition, we also studied the transverse size of the recorded noise grating in x-y plane. It was found in the order of 0.08 mm. All these experimental results confirm that noise gratings are locally created and form holographic microregions in the crystal volume. It is important to note that the recording and readout behavior of the noise-grating microregions appear to be similar to those of the so-called multilayer optical bit data storage.[7–10]

Additionally, we observed that light-induced backward scattering also shows angular selectivity. By using the angular multiplexing technique we recorded five noise gratings at one microregion in the crystal with an angular distance of 0.1 degree. Every noise grating could be successfully and separately reconstructed. Because a noise grating can stand for one bit, one micro-region contains several bits.

In conclusion, a threshold effect for the light-induced backward scattering was observed in $LiNbO_3$:Fe,Zn crystal. The holographic microregion was found to be locally formed near the focal point of the writing beam as a result of the threshold effect and multilayer microregions were successfully recorded in our crystal sample. These experimental results show a new promising way to realize multilayer bit-data optical storage with a high signal-to-noise ratio.

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[1] P. Güner and J. P. Huignard, *Photorefractive Materials and Their Application, Topics of Applied Physics* (Springer, Berlin, 1988), Vol. 62.
[2] G. Zhang, J. Xu, S. Liu, Q. Sun, G. Zhang, Q. Fang, and C. Ma, Proc. SPIE **14**, 2529 (1995).
[3] V. V. Obukhovsky, Ferroelectrics **89**, 231 (1989).
[4] V. V. Lemeshko and V. V. Obukhovsky, Ferroelectrics **174**, 249 (1995).
[5] G. Zhang, G. Zhang, S. Liu, J. Xu, Q. Sun, and X. Zhang, J. Appl. Phys. **83**, 4392 (1998).
[6] V. V. Obukhovskiiv, A. V. Stoyanov, and V. V. Lemeshko, Sov. J. Quantum Electron. **17**, 64 (1987).
[7] Y. Kawata, H. Ueki, Y. Hashimoto, and S. Kawatav, Appl. Opt. **34**, 4105 (1995).
[8] A. Toriumi, S. Kawata, and M. Gu, Opt. Lett. **23**, 1924 (1998).
[9] D. Psaltis and F. Mok, Sci. Am. **273**, 70 (1995).
[10] L. Hesselink, S. S. Orlov, A. Liu, A. Alella, D. Lande, and R. R Neurgaonkar, Science **282**, 1089 (1998).