

# Femtosecond holography in lithium niobate crystals

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Spatial gratings are recorded holographically by two femtosecond pump pulses at 388 nm in lithium niobate (LiNbO<sub>3</sub>) crystals and read out by a Bragg-matched, temporally delayed probe pulse at 776 nm. We claim, to our knowledge, the first holographic pump-probe experiments with subpicosecond temporal resolution for LiNbO<sub>3</sub>. An instantaneous grating that is due mostly to the Kerr effect as well as a long-lasting grating that results mainly from the absorption caused by photoexcited carriers was observed. The Kerr coefficient of LiNbO<sub>3</sub> for our experimental conditions, i.e., pumped and probed at different wavelengths, was  $\approx 1.0 \times 10^{-5}$  cm<sup>2</sup>/GW. © 2005 Optical Society of America

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Ferroelectric lithium niobate (LiNbO<sub>3</sub>) crystals are one of the most investigated materials for widespread and promising applications in nonlinear optics, e.g., for parametric amplification and second-harmonic generation.<sup>1</sup> LiNbO<sub>3</sub> also shows photorefractive properties,<sup>2</sup> which are characterized by a change in its refractive index that results from an optically induced separation of electrons and the linear electro-optic effect. The ability to record holograms makes LiNbO<sub>3</sub> crystals attractive for many applications such as holographic data storage, optical information processing, phase conjugation, and wavelength filters.<sup>3,4</sup>

Pulses with temporal durations of tens of picoseconds and peak intensities of 0.1 to 1 GW/cm<sup>2</sup> were previously used to investigate the photorefractive effects in various materials, e.g., bismuth silicate (Bi<sub>12</sub>SiO<sub>20</sub>),<sup>5</sup> barium titanate (BaTiO<sub>3</sub>),<sup>6</sup> and potassium niobate (KNbO<sub>3</sub>).<sup>7</sup> Femtosecond pulses were used for nonvolatile spectral holography in LiNbO<sub>3</sub>,<sup>8</sup> but pump-probe experiments that allow its ultrafast material response to be studied have not been conducted to our knowledge. In this Letter we investigate holograms recorded in LiNbO<sub>3</sub> with femtosecond pulses at 388 nm. Grating-recording experiments have been conducted extensively in LiNbO<sub>3</sub> at low intensities ( $\approx 1$  W/cm<sup>2</sup>) with continuous-wave lasers and at high intensities (up to  $\approx 10$  MW/cm<sup>2</sup>) by nanosecond pulses.<sup>9,10</sup> At these intensity levels, the photorefractive effect is still the dominant nonlinear effect; however, holographic recording with even more intense pulses will reveal other nonlinear material responses. The enhanced temporal resolution obtained with femtosecond pulses and accumulated knowledge about two-photon absorption<sup>11,12</sup> enable us to draw conclusions about the participating nonlinear processes.

The experimental setup is illustrated in Fig. 1. Two pump pulses at  $\lambda_p = 388$  nm are incident symmetrically onto a 70  $\mu$ m thick LiNbO<sub>3</sub>:Fe sample ( $c_{Fe} \approx 5.6 \times 10^{19}$  cm<sup>-3</sup> and  $c_{Fe^{2+}}/c_{Fe^{3+}} \approx 0.01$ ) with a recording angle  $2\theta_p = 8^\circ$  outside the crystal. The grating vector is oriented perpendicularly to the crystal's polar axis. The pump pulses are polarized parallel to the polar axis of the crystal and have the same intensity with peak values  $I_p$  up to  $\approx 170$  GW/cm<sup>2</sup> per pulse inside the sample. The temporal and cross-sectional FWHM of the pump pulse intensity are  $\approx 0.22$  ps and  $\approx 0.7$  mm inside the sample. The weak, Bragg-matched probe pulse at  $\lambda_r = 776$  nm is displaced by a time  $\Delta t$  by use of a delay stage; it has a FWHM cross section of  $\approx 3.5$  mm and approximately the same temporal duration as the pump pulse. The optimal overlap of the pulses is obtained by maximizing the detected diffracted pulse energy, and this determines  $\Delta t = 0$ . Diffraction efficiency  $\eta$  is defined as the energy ratio of the diffracted and transmitted pulses.

Experimental data of  $\eta(\Delta t)$  are plotted as circles in Fig. 2. Each circle represents the value of the diffrac-

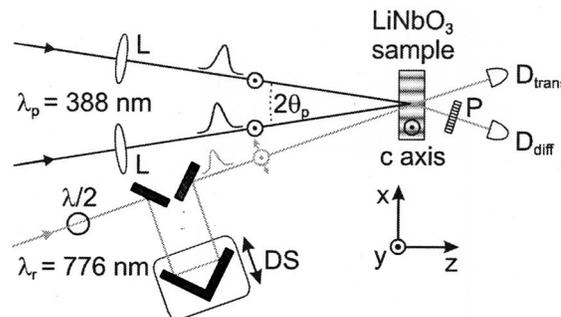


Fig. 1. Schematic illustration of the holographic pump-probe setup in LiNbO<sub>3</sub>:  $\lambda_p$ ,  $\lambda_r$ , wavelengths of pump and probe pulses, respectively; D, photodiode; DS, delay stage; L, lens;  $\lambda/2$ , half-wave plate for  $\lambda_r$ ; P, polarizer.

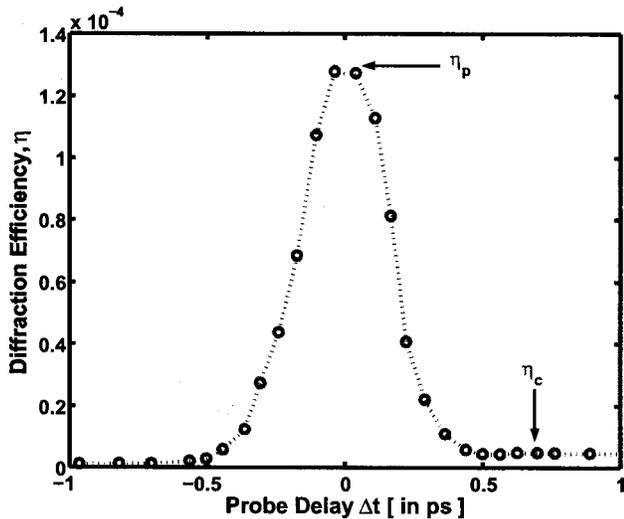


Fig. 2. Diffraction efficiency for  $I_p \approx 23 \text{ GW/cm}^2$  and for pump and probe pulses polarized parallel to the crystal polar axis in a  $\text{LiNbO}_3:\text{Fe}$  sample with thickness  $70 \mu\text{m}$ . A theoretical fit yields the Kerr coefficient  $n_2 \approx 1.0 \times 10^{-5} \text{ cm}^2/\text{GW}$  for  $\text{LiNbO}_3$ . The dotted curve is a guide to the eye.

tion efficiency averaged over 100 single-pulse measurements. After each measurement, uniform illumination is applied to ensure a reproducible starting point for the next measurement. The diffraction efficiency increases rapidly toward a peak value  $\eta_p$ . At  $\Delta t \geq 0.5 \text{ ps}$ ,  $\eta$  remains constant at the value  $\eta_c$  for almost 1 ns; for  $\Delta t \geq 1 \text{ ms}$ , no diffracted energy can be detected. For a single pair of recording pulses, the energy absorbed is too little to induce any significant photorefractive grating component under our experimental conditions. Doping of the crystals with various amounts of photorefractive impurities does not change the results. Changing the probe light's polarization to be perpendicular to that of the pump pulses gives qualitatively the same curves, with  $\eta_p$  reduced by a factor of  $\approx 2.5$ .

In general, light diffraction can originate from index and absorption gratings. An instantaneous response can be due to either pump-induced changes in the refractive index because of the Kerr effect or two-color two-photon absorption (involving one pump photon and one probe photon).<sup>11,12</sup> Longer-lasting effects can arise from charge separation and the electro-optic nonlinearity (photorefractive effect) as well as from index and absorption changes at 776 nm attributed to spatial modulation of the concentration of excited carriers.

From previous studies we know that after the pump pulses come through there is a long-lasting absorption that results from charge carriers excited by two-photon pump absorption (involving two pump photons).<sup>11</sup> In our experiment, the photorefractive effect is obviously negligible; otherwise a permanent grating would exist. Furthermore, as the measured  $\eta$  is constant on a picosecond-to-nanosecond time scale, there is also no obvious contribution from a free hot carrier grating.

Based on these facts, we modeled the data shown in Fig. 2, where we have taken into account the dif-

ferent diameters of pump and probe pulses and their spatial and temporal Gaussian shapes as well as the highly nonlinear absorption of the pump pulses. For the longer-lasting effects, the value  $\eta_c$  is explained within the experimental accuracies without any fit parameter by an absorption grating resulting from the spatially modulated carriers that we characterized earlier.<sup>11,12</sup> The instantaneous response is the combination of the two-color two-photon absorption and the Kerr effect. The two-color two-photon absorption is known from earlier measurements.<sup>12</sup> With Kerr coefficient  $n_2$  as the only fitting parameter, we end up with  $n_2 \approx 1.0 \times 10^{-5} \text{ cm}^2/\text{GW}$ , which is close to the documented value for 532 nm (Ref. 13) ( $\approx 0.83 \times 10^{-5} \text{ cm}^2/\text{GW}$ ). The index grating from the Kerr effect accounts for  $\sim 80\%$  of  $\eta_p$ , and we attribute the other 20% to two-color two-photon absorption. The strong dependence of  $\eta_p$  on the probe polarization confirms that  $\eta_p$  comes predominantly from the Kerr effect, which is known to be strongly dependent on light polarization, while the absorption changes are more-or-less isotropic.<sup>12</sup>

The main reason for the attenuation of the pump light is two-photon pump absorption, and the absorption coefficient is  $\beta_p 2I_p$ , with  $\beta_p \approx 3.5 \text{ cm/GW}$  at 388 nm.<sup>11</sup> The values of  $\eta_p$  and  $\eta_c$  are plotted on logarithmic scales as functions of the pump pulse intensity in Fig. 3. The dependence of  $\eta_p(I_p)$  is fitted with the function  $\eta_p(I_p) \propto I_p^b$ , where  $b$  is a fit parameter. The data show a turning point of the intensity dependence that lies somewhere near  $\beta_p 2I_p d = 1$  ( $d$  is the crystal thickness), with  $b \approx 1.25$  for  $\beta_p 2I_p d > 1$  and  $b \approx 2.3$  for  $\beta_p 2I_p d < 1$ . Dependence  $\eta_c(I_p)$  is fitted with the same function, and the extracted exponent  $b$  is  $\approx 2$ .

According to coupled-wave theory of volume grating,<sup>14</sup> diffraction efficiency  $\eta$  depends, for  $\eta \ll 1$ , quadratically on the product of effective grating thickness  $L$  and the grating amplitude,  $\Delta n$  for index gratings and  $\Delta\alpha$  for absorption gratings. This is true

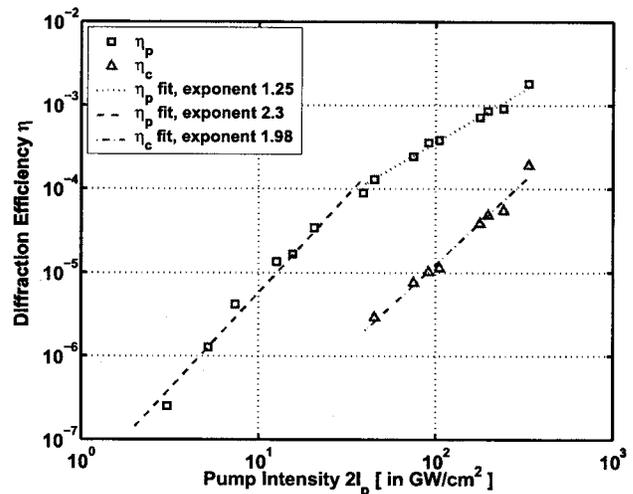


Fig. 3. Summary of measured values of  $\eta_p$  and  $\eta_c$  for different pump intensities  $I_p$  in the  $70 \mu\text{m}$   $\text{LiNbO}_3:\text{Fe}$  sample. All pulses are polarized along the polar axis of the sample.

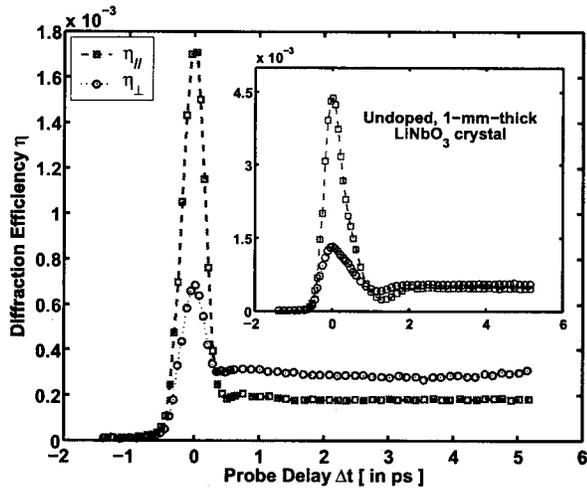


Fig. 4. Diffraction efficiency  $\eta$  as a function of probe delay  $\Delta t$  with peak pump intensities  $I_p \approx 170 \text{ GW/cm}^2$  for the  $70 \mu\text{m}$  thick crystal. Data acquired from a 1 mm thick, undoped  $\text{LiNbO}_3$  sample are plotted in the inset. The pump pulses are polarized along the polar axis, and  $\eta_{||}$  ( $\eta_{\perp}$ ) is measured when the polarization of the probe pulses is parallel (perpendicular) to that of the pump pulses.

only if  $\Delta n$  and  $\Delta\alpha$  are constant throughout the volume of the material. For high pump intensities, strong two-photon pump absorption leads to nonuniform intensity and therefore to nonuniform gratings. Effective interaction length  $L_{\text{eff}}$  is reduced, and this effect is weaker for the Kerr grating ( $\Delta n \propto I_p$ ) than for the carrier grating ( $\Delta\alpha \propto I_p^2$ ). The experimental results indicate that  $L_{\text{eff}} \propto I_p^{-0.5}$  for the Kerr grating and  $L_{\text{eff}} \propto I_p^{-1}$  for the carrier grating.

For the low-intensity region  $\beta_p 2I_p d < 1$ , we have  $L_{\text{eff}} \approx d$  for both Kerr and carrier gratings and therefore end up with  $\eta_p \propto I_p^2$  and  $\eta_c \propto I_p^4$ , which is consistent with the experimental observation although in this range  $\eta_c$  is too small to be measured.

In Fig. 4 we show the polarization dependence of the measured diffraction efficiency for  $I_p \approx 170 \text{ GW/cm}^2$ ; the data of  $\eta_{||}$  ( $\eta_{\perp}$ ) are acquired when the polarization of the probe pulses is parallel (perpendicular) to that of the pump pulses. Plotted in the inset is the result of the same pump-probe experiment carried out in a 1 mm thick undoped  $\text{LiNbO}_3$  crystal. As mentioned above, the strong polarization dependence of  $\eta_p$  is a manifestation of the dominant role played by the Kerr grating. All four curves in Fig. 4 show a distinct feature that cannot be observed for low pump intensity (as in Fig. 2): a dip between the descending  $\eta$  and the constant  $\eta_c$ . The reason for the dip of  $\eta$  remains unclear. We point to the possibility of the existence of a transient grating of hot free carriers. The dip can be present because the two

index gratings that are due to the Kerr effect and to the free carriers partially cancel each other. As the lifetime of free carriers inside  $\text{LiNbO}_3$  is thought to be smaller than 1 ps, we need even shorter pulses to produce conclusive results. It is worth nothing that, for the highest pump intensities used (in Fig. 4) and for a probe pulse of a reduced diameter (0.7 mm, like that of the pump pulses), diffraction efficiencies of several percent are expected.

We performed pump-probe holographic experiments in  $\text{LiNbO}_3$  crystals with femtosecond pulses. Both an instantaneous and a long-lasting grating were observed. We conclusively attribute the instantaneous component to the Kerr effect (contribution,  $\approx 80\%$ ). Furthermore, the excited carriers generate an absorption grating that lasts as long as milliseconds.

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