Order-of-magnitude reduction of the photorefractive response time in rhodium-doped $Sr_{0.6}Ba_{0.4}Nb_2O_6$ with a dc electric field

Koichi Sayano and Amnon Yariv

California Institute of Technology, Department of Applied Physics, 128-95, Pasadena, California 91125

Ratnakar R. Neurgaonkar

Rockwell International Science Center, P.O. Box 1085, Thousand Oaks, California 91360

We present what is to our knowledge the first report on the photorefractive properties of Rh-doped $Sr_{0.6}Ba_{0.4}Nb_2O_6$ and experimental results showing a reduction of the photorefractive two-beam coupling response time by more than an order of magnitude with an external dc field of 10 kV/cm.

Doped $Sr_{0.6}Ba_{0.4}Nb_2O_6$ (SBN:60) using Fe, Ce, Ce–Ca, and Cr has been shown to be photorefractive with high gain and real-time response.[1-3] Cr-doped SBN:60 crystals have been shown to have response times of near 0.2 sec at 0.25 W/cm², which is approximately an order of magnitude faster than what was measured in Ce-doped samples, but their photorefractive gain ranged from 3 to 6 cm⁻¹ compared with more than 10 cm⁻¹ in Ce-doped SBN:60. Applying an electric field enabled the gain of Cr-doped SBN:60 to approach 10 cm⁻¹, but its response time increased to over 1 sec. In this Letter, we present the first report to our knowledge on the photorefractive properties of Rh-doped SBN:60 and, in addition, results showing significant reduction of the photorefractive response time of this material by applying a dc electric field of up to 10 kV/cm in the direction of the electro-optic axis.

The crystal was grown by the Czochralski method, poled by cooling it through its cubic-to-ferroelectric phase-transition temperature of approximately 75°C with an applied electric field of 8 kV/cm, and cut and polished to an optical-quality cube measuring 6.5 mm × 6 mm × 5.5 mm. The crystal was doped with approximately 1.5% by weight of Rh in the flux. When exposed to coherent light of 514.5 nm, strong beam fanning was observed, indicating high two-beam coupling gain, which resulted in amplification of scattered light.

The two-beam coupling experiment illustrated in Fig. 1 has been used to characterize the photorefractive properties of various materials and to develop a new generation of phase-conjugate and image-processing applications.[4-7] A weak signal beam with intensity $I_2(0)$ is mixed with a strong pump beam $I_1(0)$ coherent to the signal beam in the photorefractive medium, which sets up a periodic space-charge grating that follows the light interference pattern from the drift and diffusion of charges. The space-charge grating is converted to a 90° phase-shifted index grating from the electro-optic effect, which results in the photorefractive two-beam coupling amplification of I_2 in

the direction of the electro-optic or c axis. This can be characterized by

$$I_1(z) = I_1(0)\exp[-(\Gamma + \alpha)z],$$
$$I_2(z) = I_2(0)\exp[(\Gamma - \alpha)z], \qquad (1)$$

where α is the absorption coefficient and Γ is the two-beam coupling constant, which is given by

$$\Gamma = \text{Re}\left(\frac{i\omega}{4c}n_0^3 r_{\text{eff}}E_{\text{sc}}\right)$$

$$= \frac{\omega}{4c}n_0^3 r_{\text{eff}}mE_N \frac{E_0 + iE_d}{E_0 + i(E_d + E_N)}[1 - \exp(-t/\tau)] \qquad (2)$$

for the one-carrier, one-species case of electrons being the dominant charge carrier and only one donor type being present. The response time of the material is given by

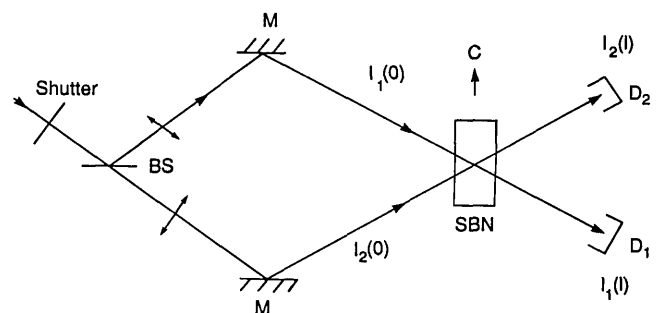$$\tau = t_0 \frac{E_0 + i(E_d + E_\mu)}{E_0 + i(E_d + E_N)}, \qquad (3)$$

Fig. 1. Experimental configuration of the two-beam coupling experiment. $I_1(l)$ and $I_2(l)$ were measured simultaneously and in real time to obtain the photorefractive coupling constant and response time. The beam polarization was in the same plane as the c axis, with $I_1(0) + I_2(0) \approx 0.25$ W/cm² and $m < 0.01$. BS, beam splitter; M's, mirrors.
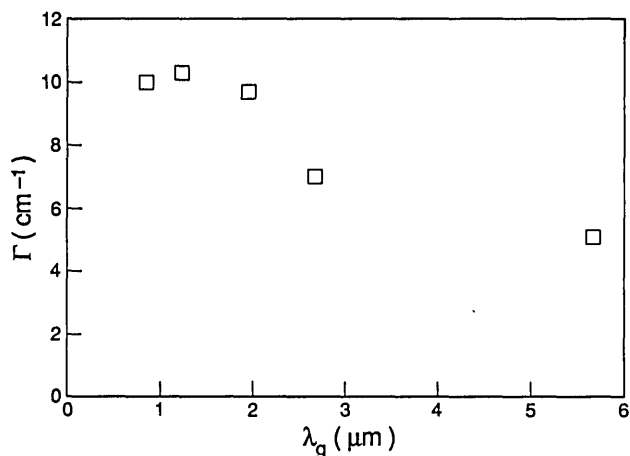
Fig. 2. Photorefractive gain coefficient of Rh-doped SBN:60 as a function of grating wavelength for $E_0 = 0$. The peak at approximately 1.25 μm indicates a trap density N_A of 2×10^{22} m^{-3}.
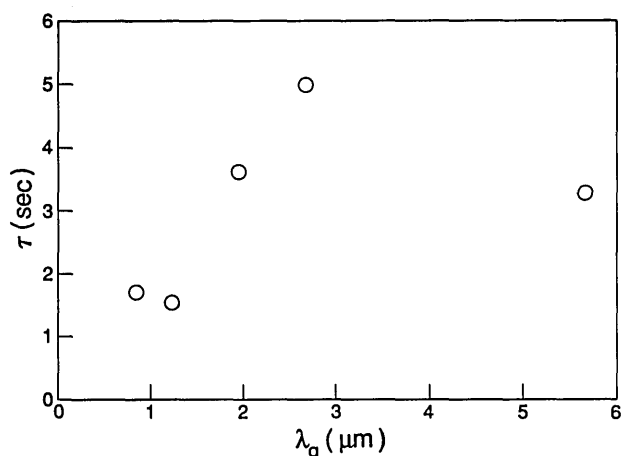

Fig. 3. Response time τ of Rh-doped SBN:60 for no applied field.

where

$$t_0 = \frac{h\nu N_A}{sI_0(N_D - N_A)}. \qquad (4)$$

The imaginary part of the complex τ indicates an oscillatory factor in Γ in addition to the exponential decay. In Eqs. (2) and (3), E_0 is the externally applied dc electric field, m is the modulation index, and the characteristic fields are given by

$$E_N = \frac{eN_A}{\epsilon K}\left(1 - \frac{N_A}{N_D}\right) \approx \frac{eN_A}{\epsilon K} \text{ for } N_A \ll N_D,$$

$$E_d = \frac{k_B TK}{e},$$

$$E_\mu = \frac{\gamma N_A}{\mu K}, \qquad (5)$$

where $K = 2\pi/\lambda_g$ is the wave number corresponding to the grating period, γ is the electron recombination rate, μ is the electron mobility, e is the magnitude of

the electron charge, k_B is Boltzmann's constant, N_A is the trap density, N_D is the donor density, and s is the photoionization cross section.

The photorefractive gain and response time of the Rh-doped SBN:60 crystal are shown in Figs. 2 and 3 for various grating periods and no applied electric fields. The 514.5-nm line of an argon laser was used, polarized in the plane of the c axis to take advantage of the large r_{33} electro-optic coefficient. $I_1(0)$ was 0.25 W/cm^2, with $m = I_2(0)/I_1(0) < 0.01$ to avoid pump depletion. Both beam intensities $I_1(l)$ and $I_2(l)$ were measured simultaneously in real time to obtain Γ as a function of time and τ. As shown in the plots, the maximum gain of the Rh-doped crystal is 10.5 cm^{-1} at its optimum grating wavelength of 1.25 μm, which is comparable with that of Ce-doped SBN:60. By differentiating Eq. (2) with respect to λ_g and using the value for $\lambda_{g,\,max}$ obtained from Fig. 2, the trap density was determined to be approximately 2×10^{22} m^{-3}. The exponential time constant of the crystal at its optimum grating period was approximately 2 sec for a total beam intensity of 0.25 W/cm^2.

When an external dc field is applied, we can see from Eq. (3) that in the limit of large E_0, τ approaches t_0, which is the time required to generate N_A photoexcitations per unit volume from energy deposition considerations.[8] In the $E_\mu > E_N$ case, τ approaches its limit from above as the dc field is increased. For typical values of $N_A = 2 \times 10^{22}$ m^{-3}, $\epsilon = 570\epsilon_0$, $T = 295$ K, $\lambda_g = 1.51$ μm, and $\gamma/\mu = 2 \times 10^{-10}$ V-m, $E_N = 1.55$ kV/cm, $E_d = 1.06$ kV/cm, and $E_\mu = 10$ kV/cm.[9] Figure 4 shows the expected behavior of τ/t_0 as a function of E_0 under these conditions.

The experimental results of the gain and response time of Rh-doped SBN:60 with an applied electric field are shown in Figs. 5 and 6 for $\lambda_g = 1.51$ and 0.84 μm. The electric field, which varied from 0 to 10 kV/cm, was applied in the direction of the c axis since high reverse voltages would tend to reduce the polarization and ultimately depole the crystal. Fields significantly beyond 10 kV/cm were not attempted owing to considerable arcing across the surface of the crystal. For
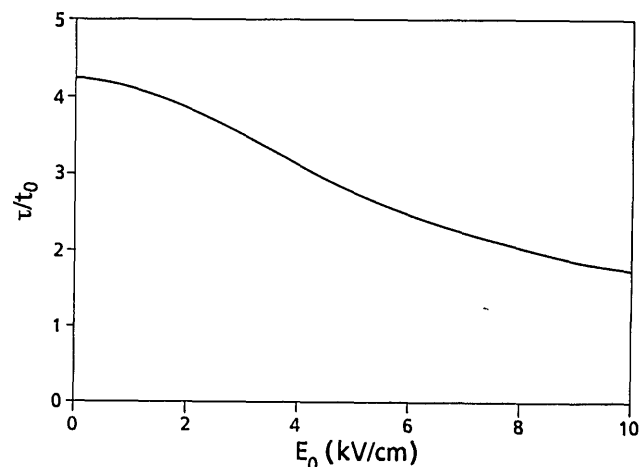

Fig. 4. Expected response time as a function of applied field for $E_d = 1.06$ kV/cm, $E_N = 1.55$ kV/cm, and $E_\mu = 10$ kV/cm, showing τ/t_0 approaching unity for large E_0.
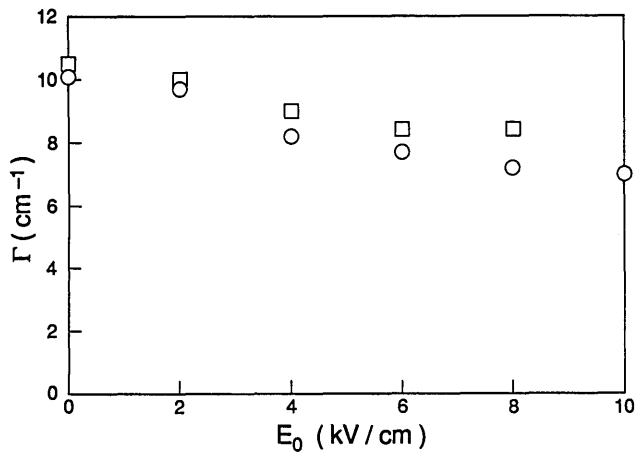
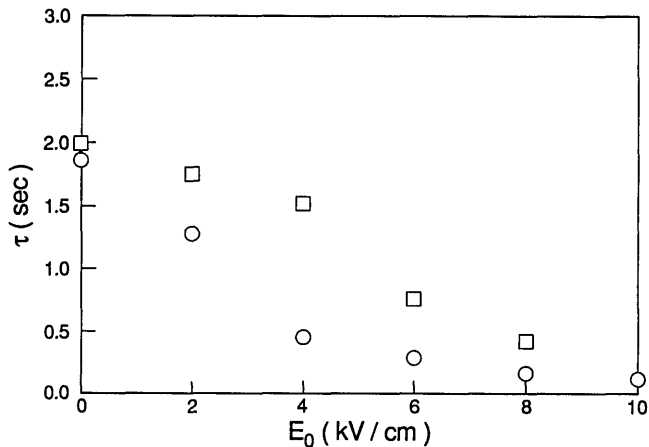Fig. 5. Measured gain coefficient as a function of E_0 for λ_g = 1.51 μm (circles) and 0.84 μm (squares).

Fig. 6. Experimental response time of the SBN crystal for λ_g = 1.51 μm (circles) and 0.84 μm (squares), which decreased from 2 sec at E_0 = 0 to approximately 0.1 sec for E_0 = 10 kV/cm.

both grating periods, the gain drops from Γ = 10 cm^{-1} at E_0 = 0 to near 8 cm^{-1} at E_0 = 10 kV/cm. Although Eq. (2) predicts that Γ increases with E_0, we can attribute the small decline in this case to causes such as fanning losses from the large gain and increased scattering due to the electric field.

The advantage of this procedure, however, is in the more than an order-of-magnitude reduction of the response time, which was observed to decrease from 2.0 sec at E_0 = 0 to approximately 0.1 sec at E_0 = 10 kV/ cm. Strong beam fanning was also observed to set in faster as the time constant was reduced through increased E_0, making this material especially suited for high-gain, fast-response applications such as field-enhanced optical limiters and real-time image processing. According to the theoretical model, the photoexcited charges are transported through drift and diffusion in the conduction band. The presence of the dc field in the background would tend to drive the free electrons into the traps, contributing to the faster grating formation that was observed.

In summary, we have demonstrated a significant improvement in the response time of Rh-doped SBN:60 through the application of an external dc field. A reduction in τ by a factor of 20 with approximately a 20% loss in gain has been observed. This gives a significant advantage in the development of photorefractive devices that rely on real-time response and introduces another element of control of the photorefractive effect.

References

1. G. A. Rakuljic, A. Yariv, and R. R. Neurgaonkar, Opt. Eng. **25**, 1212 (1986).
2. G. A. Rakuljic, K. Sayano, A. Agranat, A. Yariv, and R. R. Neurgaonkar, Appl. Phys. Lett. **53**, 1465 (1988).
3. K. Sayano, A. Yariv, and R. R. Neurgaonkar, Appl. Phys. Lett. **55**, 328 (1989).
4. K. Sayano, A. Yariv, and R. R. Neurgaonkar, J. Appl. Phys. (to be published, 1990).
5. N. V. Kukhtarev, V. B. Markov, and S. G. Odulov, Opt. Commun. **23**, 338 (1977).
6. N. V. Kukhtarev, V. B. Markov, S. G. Odulov, M. S. Soskin, and V. L. Vinetski, Ferroelectrics **22**, 949 (1979).
7. N. V. Kukhtarev, Sov. Tech. Phys. Lett. **2**, 438 (1976).
8. P. Yeh, Appl. Opt. **26**, 602 (1987).
9. G. A. Rakuljic and A. Yariv, Proc. Soc. Photo-Opt. Instrum. Eng. **881**, 146 (1988).