Ronchi-grating-based measurement of photorefractive recording response time

Ivan de Oliveira[1] and Jaime Frejlich[2,*]

[1]*Faculdade de Tecnologia/Universidade Estadual de Campinas (UNICAMP), Limeira-SP, Brazil*

[2]*Laboratório de Óptica, Instituto de Física "Gleb Wataghin" (IFGW)/UNICAMP, Campinas-SP, Brazil*

**Corresponding author: frejlich@ifi.unicamp.br*

Received August 31, 2011; revised October 27, 2011; accepted November 21, 2011;
posted November 21, 2011 (Doc. ID 153459); published January 13, 2012

We report on a simple technique for the measurement of the recording response time in photorefractive materials. Three different material samples were successfully measured, and their response times, as well as their dependence upon the recording/measurement light irradiance, were also determined and compared with available data in the literature in order to assess the reliability of this technique. © 2012 Optical Society of America

OCIS codes: 160.5320, 050.1950.

The recording time (τ_{sc}) in photorefractive materials is an important parameter because it is proportional to the dielectric relaxation time $\tau_M = \epsilon\varepsilon_0/\sigma$ [1–3] that, in turn, depends on the dielectric constant ϵ (ε_0 being the permittivity of vacuum) and on the conductivity (or photoconductivity if light is involved) σ. Thus, measuring τ_{sc} allows straightforwardly computing σ without requiring electrodes on the sample. As σ is usually very weak in most photorefractive materials, its measurement via τ_{sc} by means of optical techniques is far easier and more reliable than direct electric techniques. The parameter τ_{sc} is usually measured by recording and/or erasing a hologram on the sample. Holographic recording, however, is not an easy task because it requires specific equipment and special manpower.

In this Letter we propose a simple technique for measuring $\tau_{sc} \approx \tau_M$ that does not require holographic recording at all but uses a large period Ronchi grating instead. The Ronchi grating (a pattern of regularly alternating metallic strips evaporated on a transparent glass-plate substrate) with a period of $\Delta \approx 50$ μm and the photorefractive sample under analysis are firmly fixed to each other with silicon glue (along the borders only, so as to keep the interface between the photorefractive sample and the Ronchi–glass-plate substrate clear for measurements) and the whole is illuminated with an adequate wavelength light in order that a rectangular pattern of light be projected onto the photorefractive crystal and light be diffracted through the Ronchi and photorefractive gratings, as illustrated in Fig. 1. The evolution of the diffracted light from this grating–photorefractive-crystal ensemble is recorded and measured. As the time evolution of the diffracted light is due only to the recording on the photorefractive crystal, the corresponding photorefractive recording time τ_{sc} can thus be easily computed. For a rectangular shaped mask of light with clear and opaque strips of equal size, as the one used here, only the odd spatial Fourier harmonic terms are nonzero, with the value of the first Fourier harmonic being ninefold larger than the third one and 25-fold larger than the fifth harmonic. Still, as the Ronchi grating is at a large distance (1.5 mm) from the crystal surface, compared to the 50 μm period, the projected rectangular shape of the Ronchi grating is sensibly smoothed, thus further reducing the influence of the higher spatial Fourier terms. We may, therefore, assume that we are mainly dealing with a sinusoidal pattern of light roughly formed by the first harmonic (50 μm period) component of the rectangular pattern projected onto the photorefractive crystal. That is to say that an index-of-refraction sinusoidal grating of period equal to that of the Ronchi grating is mainly being recorded. For such a large period, the approximation $\tau_{sc} \approx \tau_M$ [1] is verified and the diffraction efficiency is of the Raman–Nath type, as indicated by the low value of the $Q = 2\pi\lambda_0 d/(\Delta^2 n_0) < 10$ parameter [4,5], and as experimentally confirmed because of the number of diffraction orders that are actually observed. In this case, the diffraction of the Nth order (the zero-order position is defined by the laser beam before the Ronchi grating is placed in the setup) is computed from [6]

$$\eta_N \propto J_N^2(m), \qquad m \equiv 2\pi n_1 d/\lambda_0, \tag{1}$$

where J_N is the ordinary Bessel function of order N, m and n_1 are the phase and the index-of-refraction modulation amplitudes in the photorefractive crystal, respectively, d is the crystal thickness,and λ_0 is the recording (and measurement) light wavelength in vacuum. Because of the presence of a fixed phase-shifted amplitude Ronchi grating together with the dynamic photorefractive grating under analysis, data were actually fitted with

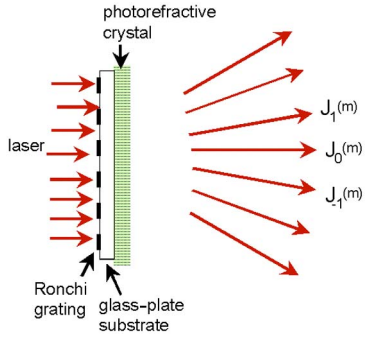

Fig. 1. (Color online) Schematic representation of the laser diffraction through the Ronchi-grating–photorefractive-crystal ensemble, showing the 1.5 mm thick Ronchi grating glass-plate substrate in between.

$$\eta_N = |A + Be^{i\phi} J_N(m(t))|^2, m(t) = m_0(1 - e^{-t/\tau_{sc}}), \quad (2)$$

where A is the amplitude diffracted by the fixed amplitude Ronchi grating, B is a parameter related to the amplitude of the photorefractive grating, with ϕ representing the phase shift between the Ronchi and the photorefractive grating, and m_0 represents the maximum photorefractive modulation m of the sample in actual experimental conditions.

Iron-doped $LiNbO_3$:Fe (LN:Fe) with nominal molar concentration [Fe] $\approx 2 \times 10^{19}$ cm^{-3}, a cerium-doped strontium barium niobate $Sr_{1-x}Ba_xNb_2O_6$ with 0.1% weight Ce (SBN:Ce), and a nominally undoped titanosillenite $Bi_{12}TiO_{20}$ (BTO) photorefractive crystal samples were measured using this technique, under an attenuated (to slow down the response time to facilitate measurement) direct unexpanded $\lambda = 633$ nm wavelength laser beam. The LN:Fe and the SBN:Ce crystals were fixed to the Ronchi grating with their c axes parallel to the grating vector $\rightarrow K$, whereas the BTO crystal was fixed with its [001] axis perpendicular to $\rightarrow K$ and its (110) plane parallel to the Ronchi glass-plate surface. To average out the interference fringes, due to multiple reflections in the crystal–glass-plate ensemble interfaces, we collected (with a lens) the whole light of the selected diffracted beam to be measured and focused it into a linear photodetector, and the time evolution of this signal was recorded, as shown for LN:Fe with extraordinarily polarized light in Fig. 2. Data fitted using Eq. (2) allowed computing $\tau_{sc} \approx \tau_M$, with a precision estimated to be better than 5%, as shown in Fig. 2, with all three samples (LN:Fe, SBN:Ce, and BTO) in this Letter behaving similarly. Evolution curves for orders +1 and −1 showed nonsymmetric curves but lead to the same value for τ_{sc}, as expected. The reciprocal value $1/\tau_{sc}$, on its turn, was plotted in Fig. 3, as a function of the intensity I_0 of the recording/measurement beam, and fitted with

$$1/\tau_{sc} = aI_0^b, \quad (3)$$

using $b = 1$, thus verifying the well-known inverse relation between τ_{sc} and the irradiance, as already reported

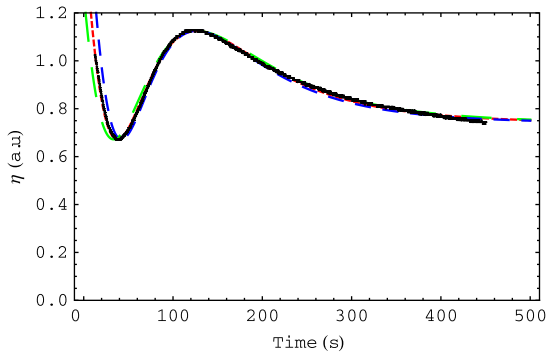

Fig. 2. (Color online) Evolution of the zero diffraction order for LN:Fe under an extraordinarily polarized 633 nm recording laser beam with $I = 0.51$ au, and corresponding theoretical fitting (dashed curve) leading to $A = 1.27$, $B = 1.65$, $\phi = 2.44$ rad, $m_0 = 1.035$, and $\tau_{sc} = 106.15$ s. The additional dashed curves, clearly not matching data, were plotted using $\tau_{sc} = 106.15 \pm 5\%$ s; all other parameters were unchanged.

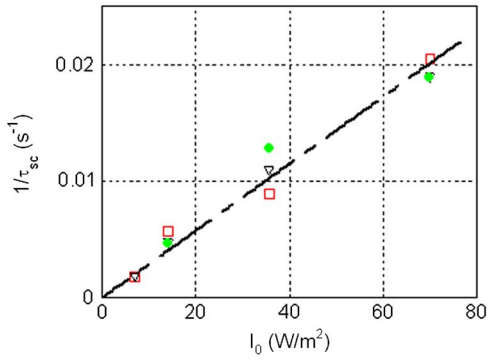

Fig. 3. (Color online) Computed $1/\tau_{sc}$ for Fe-doped $LiNbO_3$ crystal as a function of the irradiance I_0 of the $\lambda = 633$ nm recording nonexpanded beam. The solid green circles represent zero diffraction order data under ordinarily polarized light, whereas the open red squares and open black triangles represent the first diffraction orders (from one side and the other referred to the zeroth order, respectively) data with extraordinarily polarized light. The dashed line is the best fitting with Eq. (3) using $b = 1$.

in the literature [7]. Similar procedures were followed for BTO and for SBN:Ce and the corresponding $1/\tau_{sc}$ versus I_0 plottings and data fitting are reported on Fig. 4. The linear relation between $1/\tau_{sc}$ and I_0 was also verified for BTO as for the case of LN:Fe. For SBN:Ce instead, a sublinear relation with a $b \approx 0.31$ exponential value for the irradiance was verified, in agreement with nonlinear relations already reported before [8] for SBN, as well as for other materials [9]. All irradiances noted as I_0 in this Letter are the estimated peak values of the Gaussian distribution of the nonexpanded direct laser beam, at the input plane, outside the crystal. The effect of light absorption on τ_{sc} [10] has not been taken into account because all our samples are rather thin and exhibit moderately low absorption at the 633 nm wavelength light.

To assess the reliability of the present technique, besides the τ_{sc} versus I_0 already discussed above, we also compared the presently computed quantity $\tau_M \times I_0 \approx 5700$ sW/m^2 for BTO from Fig. 4 to the similar value (≈4500 sW/m^2) computed from the slow (holographic)

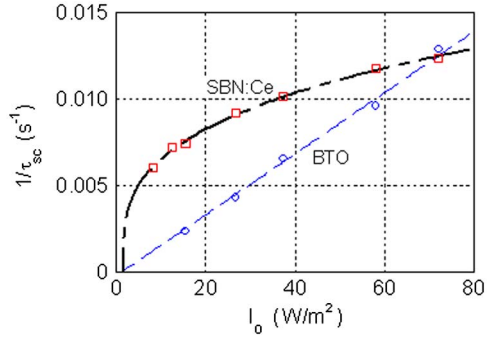

Fig. 4. (Color online) Computed $1/\tau_{sc}$ plotted as a function of the irradiance I_0 of the $\lambda = 633$ nm recording nonexpanded beam for the zero diffraction order for SBN:Ce (open red squares) and for BTO (open blue circles). The best fitting (dashed curves) of data with Eq. (3) leads to $b = 1$ for BTO and to $b \approx 0.31$ for SBN:Ce.

relaxation time constant τ_{sc}^{s} ($\tau_M = \tau_{sc}^{s}(1 + K^2 l_s^2)/(1 + K^2 L_D^2)$ with $L_D \approx 0.15\ \mu$m and $l_s \approx 0.06\ \mu$m) at 15 mW/cm^2 (75 W/m^2 erasure irradiance), as reported in Table 5 in [11], published in 2007, for another BTO (20% thicker) sample produced at the same laboratory. Reference [11] showed that, for the low irradiance limit (as the one presently involved), there are no longer two (fast and slow) exponential relaxation time constant terms, but just a single term (in agreement with our present results) remains: the slow one. Also, LN:Fe was reported [12] to exhibit a monoexponential behavior, as experimentally verified in this Letter.

In conclusion, we have reported on a simple optical technique for the measurement of the recording time in photorefractive materials that does not require holographic recording at all. The current technique was tried on different materials and the results are in agreement with already published data. Other photosensitive materials, not necessarily photorefractives, may be measured using this technique, too.

We acknowledge the Conselho Nacional de Desenvolvimento Científico (CNPq), the Coordenação para o Aperfeiçoamento do Pessoal de nível Superior (CAPES), the Fundação de Amparo à Pesquisa do Estado de São Paulo (FAPESP), and the Fundo de Apoio ao Ensino, Pesquisa e Extensão (FUNCAMP-FAEPEX-PAPDIC), all from Brazil, for financial support.

References

1. S. Stepanov and M. Petrov, in *Photorefractive Materials and Their Applications I*, Vol. **61** of Topics in Applied Physics, P. Günter and J.-P. Huignard, eds. (Springer-Verlag, 1988), Chap. 9, pp. 263–289.
2. K. Buse, Appl. Phys. B **64**, 273 (1997).
3. J. Frejlich, *Photorefractive Materials: Fundamental Concepts, Holographic Recording, and Materials Characterization* (Wiley-Interscience, 2006), p. 61.
4. H. Kogelnik, Bell Syst. Tech. J. **48**, 2909 (1969).
5. L. Solymar and D. Cooke, *Volume Holography and Volume Gratings* (Academic, 1981), pp. 41–44.
6. J. W. Goodman, *Introduction to Fourier Optics* (McGraw-Hill, 1968), pp. 69–70.
7. K. Peithmann, A. Wiebrock, and K. Buse, Appl. Phys. B **68**, 777 (1999).
8. K. Buse, U. van Stevendaal, R. Pankrath, and E. Krätzig, J. Opt. Soc. Am. B **13**, 1461 (1996).
9. G. A. Brost and R. A. Motes, Opt. Lett. **15**, 1194 (1990).
10. I. de Oliveira and J. Frejlich, Opt. Commun. **178**, 251 (2000).
11. P. V. dos Santos, J. F. Carvalho, and J. Frejlich, Opt. Mater. **29**, 462 (2007).
12. K. Buse, Appl. Phys. B **64**, 391 (1997).