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# Photorefractive Response Time: Dependence of Grating Spacing and Light Intensity

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**ABSTRACT:** We present a theoretical analysis of the photorefractive response time as a function of applied electric field in different types of photorefractive materials on the basis of Kukhtarev rate equations. We study the variation of photorefractive response time with grating spacing and light intensity. We also study the photorefractive response time with grating spacing in absence of the applied electric field for KNbO<sub>3</sub>:Fe crystal and compared the results with the experimental results. Agreement between theoretical and the experimental results are found to be reasonably good.

**KEYWORDS:** Photorefractive response time; photorefractive sensitivity; grating spacing and light intensity.

## I. INTRODUCTION

Photorefractive crystals [1-3] are the most widely used optical materials because of their large nonlinear optical effects even at low laser powers (mW/cm<sup>2</sup>) combined with excellent optical qualities. In recent years a number of applications, like self-focusing and defocusing effects [4], optical phase conjugation [5], photorefractive resonators [6, 7], holographic storage [8], beam cleanup [9], image amplification [10], programmable optical interconnections [11], neural network simulation [12] etc. have been proposed and demonstrated in laboratory. Zhou et al. [13], presented an analytical solution of the response time of two-wave coupling at large modulation depths using the empirical correction function introduced by Kwak et al. [14]. It was shown that the response time depends on both the material and experimental parameters. Zhang et al. [15], measured the photorefractive response time of KNbO<sub>3</sub>:Mn:Rb and KNbO<sub>3</sub>:Fe:Rb and compared with KNbO<sub>3</sub>:Mn and KNbO<sub>3</sub>:Fe, respectively. As a result, it was found that the photorefractive response time in KNbO<sub>3</sub>:Mn:Rb is 3-10 times shorter than that in KNbO<sub>3</sub>:Mn and in KNbO<sub>3</sub>:Fe:Rb 6 times faster than that in KNbO<sub>3</sub>:Fe. Raita et al. [16], measured the response time of sillenite material Bi<sub>12</sub>SiO<sub>20</sub> (BSO) at 810 and 980 nm of wavelengths by applying the polarization self-modulation effect. The response time was found to be 130 ms at 810 nm and 540 ms at 980 nm with incident intensities of 110 and 200 mW/cm<sup>2</sup>, respectively. Chen et al. [17] investigated the influence of stoichiometry and MgO dopant on the photorefractive sensitivity and response time of LiNbO<sub>3</sub>:Fe crystals. Kong et al. [18] investigated photorefractive properties of LiNbO<sub>3</sub>:Fe, Zr and compared these with LiNbO<sub>3</sub>:Fe, Hf, the concentration of Fe<sup>2+</sup> ions is strongly increased in LiNbO<sub>3</sub>:Fe, Zr. It was found that the photorefractive response time of these as-grown crystals is only 2s and the sensitivity is larger than 12 cm/J, which is desirable for volume holographic storage.

Effects of grating spacing on photorefractive response time have been investigated theoretically only for BSO and BaTiO<sub>3</sub> with and without applied electric field [19]. In the present work, the effect of grating spacing and light intensity on the photorefractive response time in absence and presence of the applied electric field for different classes of photorefractive materials, LiNbO<sub>3</sub>, KNbO<sub>3</sub>:Fe, KNSBN, SPS, BGO and GaAs, has been investigated thoroughly. Photorefractive response time with grating spacing in absence of the applied electric field for KNbO<sub>3</sub>:Fe crystal have also been studied and compared the theoretical results with the experimental results reported by Ewart [20].

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## II. THEORETICAL DESCRIPTION

When two monochromatic light beams of intensities interact in a photorefractive medium, an interference pattern is formed which creates refractive index grating via photorefractive effect. The refractive index grating moves if the two beams have differing frequencies by very small amount and remains stationary if the two beams have the same frequency. Assuming the slowly varying amplitude approximation and neglecting the second-order time derivatives for space charge field (SCF), we get the following differential equation for the transient SCF [21],

$$A(t)\frac{\partial E_{sc}}{\partial t} + B(t)E_{sc} = mC(t) \quad (1)$$

$$A(t) = \frac{e\mu n_0}{\epsilon_0 \epsilon} - \frac{1}{E_0 + iE_D} \frac{\partial E_0}{\partial t} - i\mu k_g (E_0 + iE_D) + \gamma_R N \quad (2)$$

$$B(t) = \frac{e\mu n_0 \gamma_R N}{\epsilon_0 \epsilon} - \frac{e\mu n_0}{\epsilon_0 \epsilon} \frac{1}{E_0 + iE_D} \frac{\partial E_0}{\partial t} - i\mu k_g \gamma_R N (E_0 + iE_D) \quad (3)$$

$$C(t) = \frac{e\mu n_0 \gamma_R N}{\epsilon_0 \epsilon} (E_0 + iE_D) \quad (4)$$

where,  $e$  is the electronic charge,  $\mu$  is the mobility,  $\epsilon_0$  is the free space permittivity,  $\epsilon_r$  is the relative static dielectric constant,  $E_0$  is the applied electric field,  $E_D = k_B T k_g / e$  is the diffusion field,  $k_B T$  is the thermal energy which is the product of the Boltzmann's constant  $k_B$  and absolute temperature  $T$ ,  $k_g = \frac{2\pi}{\Lambda}$  is the spatial grating frequency with the grating spacing  $\Lambda$ ,  $\gamma_R$  is the carrier ionized trap recombination rate,  $N = N_A + n_0$ ,  $N_D$  and  $N_A$  stand for the densities of neutral donor atoms, and neutral acceptor atoms, respectively. The Eq. (1) could be rewritten in the following form as [21, 22],

$$\frac{\partial E_{sc}}{\partial t} + \beta E_{sc} = m\zeta \quad (5)$$

$$\beta = \frac{1}{\alpha \tau_{di}} \left[ 1 - \frac{\tau}{E_0 + iE_D} \frac{\partial E_0}{\partial t} - \frac{iE_0}{E_q} + \frac{E_D}{E_q} \right] \quad (6)$$

$$\zeta = \frac{1}{\alpha \tau_{di}} [(E_0 + iE_D)] \quad (7)$$

$$\alpha = \left[ 1 - \frac{\tau}{E_0 + iE_D} \frac{\partial E_0}{\partial t} - \frac{iE_0}{E_M} + \frac{E_D}{E_M} \right] \quad (8)$$

In presence of applied DC electric field  $\left( \frac{\partial E_0}{\partial t} = 0 \right)$ , Eq. (8) reduced in the real and imaginary part is given by,

$$\alpha = \frac{(E_M + E_D) - iE_0}{E_M} \quad (9)$$

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where,  $\tau_{di} = \frac{e\mu n_0}{\epsilon_0 \epsilon}$  is the dielectric relaxation time,  $n_0 = \tau_R s I_0 N_D$  is the average electron density,  $s$  is the photo-ionization cross section,  $I_0$  is the intensity of the light,  $\tau_R = \frac{1}{\gamma_r N_A}$  is the recombination life time,  $E_q = \frac{eN_A}{\epsilon_r \epsilon_0 k_g}$  is the limiting SCF, and  $E_M = \frac{\gamma_r N_A}{\mu k_g}$  is drift field.

Integrating the Eq. (5), transient solution of the SCF is given by [22]

$$E_{sc}(t) = m \frac{\zeta}{\beta} E_{sc} [1 - \exp(-\beta t)] \quad (10)$$

with  $m = \frac{2\sqrt{I_p I_s}}{I_s + I_s}$  is the modulation depth,  $I_p$  and  $I_s$  are the pump and signal beam intensities respectively.

Substituting the value of  $\alpha$  from Eq. (9) in the Eq. (6), the parameter  $\beta$  can be written in the following form as,

$$\beta = \frac{1}{\tau_{di}} \frac{\left\{ \left(1 + \frac{E_D}{E_q}\right) \left(1 + \frac{E_D}{E_M}\right) + \frac{E_0^2}{E_q E_M} \right\} - i \left\{ \frac{E_0}{E_q} \left(1 + \frac{E_D}{E_M}\right) - \frac{E_0}{E_M} \left(1 + \frac{E_D}{E_q}\right) \right\}}{\left(1 + \frac{E_D}{E_M}\right)^2 + \left(\frac{E_0}{E_M}\right)^2} = \frac{1}{\tau_{di}} \left( \frac{1}{\tau} - i\omega \right) \quad (11)$$

According to Yeh [14], there is a fundamental limit for grating formation given by the time known as photorefractive response time, and the response time is required to generate the space-charge density that builds-up the steady-state space-charge field across one grating.

where, real part in the Eq. (11) is the photorefractive response time  $\tau$  given by [21],

$$\tau = \tau_{di} \frac{\left[ \left(1 + \frac{E_D}{E_M}\right)^2 + \left(\frac{E_0}{E_M}\right)^2 \right]}{\left(1 + \frac{E_D}{E_q}\right) \left(1 + \frac{E_D}{E_M}\right) + \frac{E_0}{E_M} \frac{E_0}{E_q}} \quad (12)$$

and imaginary part in the Eq. (11) is the characteristic frequency  $\omega$  given by [21],

$$\omega = \frac{1}{\tau_{di}} \frac{\left( \frac{1}{E_M} - \frac{1}{E_q} \right) E_0}{\left(1 + \frac{E_D}{E_M}\right)^2 + \left(\frac{E_0}{E_M}\right)^2} \quad (13)$$

### III. RESULTS AND DISCUSSION

Eq. (11) is used to investigate the effect of the grating spacing and light intensity on the photorefractive response time in the absence and presence of the applied electric field for different photorefractive materials. The required parameters for the present calculations are taken from the work of Serrano et al. for LiNbO<sub>3</sub> [23]; Zhou et al. for KNSBN [24]; Shumelyuk et al. for SPS [25]; Aubrecht et al. for BGO [26]; Brost et al. for GaAs [27], and Montemezzani et al. for KNbO<sub>3</sub>:Fe [28].

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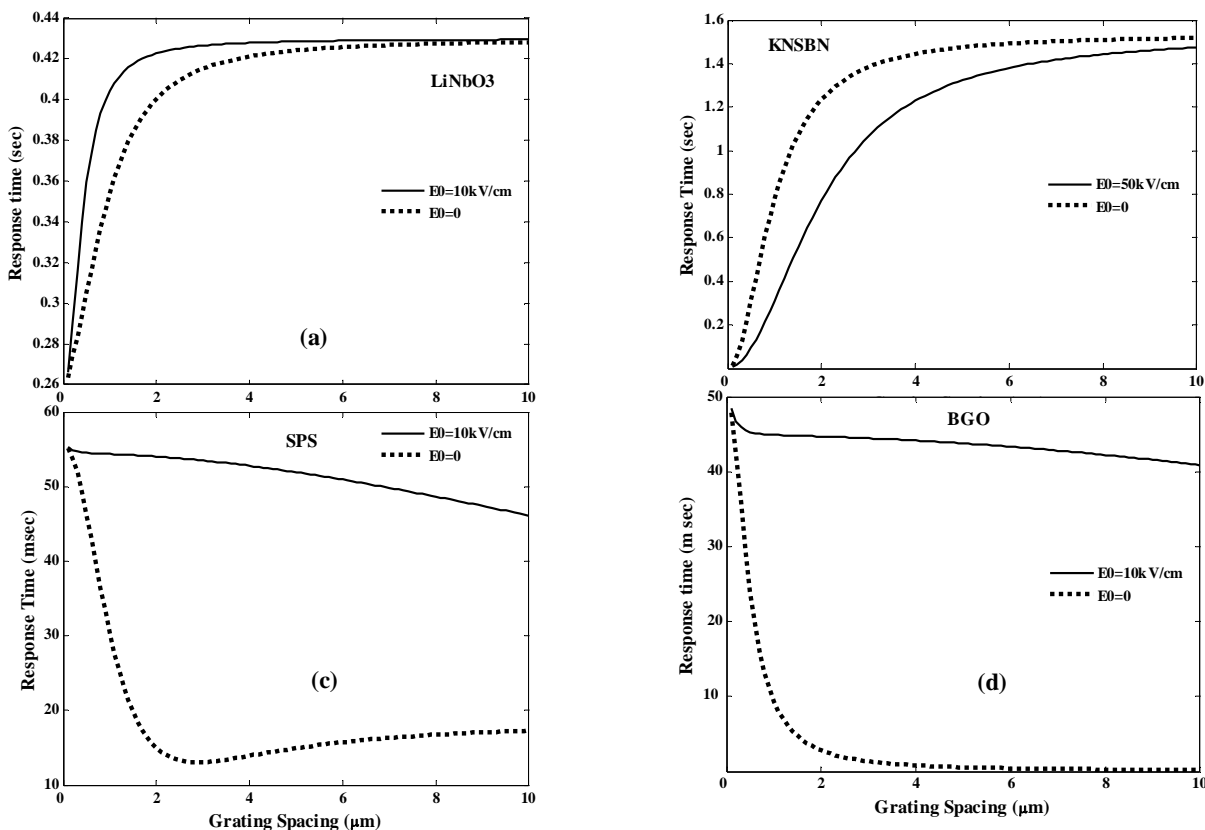
### III. (a). VARIATION OF THE PHOTOREFRACTIVE RESPONSE TIME WITH THE GRATING SPACING

Variation of the photorefractive response time with the grating spacing in the absence and presence of applied electric field for LiNbO<sub>3</sub>, KNSBN, SPS, BGO and GaAs are shown in Figs.-1(a)-(e), respectively. From the Fig.-1(a), it is clear that for LiNbO<sub>3</sub> the photorefractive response time increases up to the saturation value 0.42 sec with the increasing grating spacing and in the presence of applied electric field ( $E_0=10$  kV/cm) as well as in the absence of applied electric field. The value of response time is slightly smaller for all values of grating spacing in the absence of applied electric field.

It could be seen from the Fig.-1(b), that for KNSBN the photorefractive response time increases upto the saturation value 1.5 sec with the increasing grating spacing in the absence of applied electric field. In contrast to LiNbO<sub>3</sub> in this case its value in the presence of applied electric field is smaller than that in the absence of applied electric field for all the values of the grating spacing. Further, its values are higher than that of LiNbO<sub>3</sub> due to its large value of dielectric constant and small value of mobility-life time combination.

From the Figs. 1(c)-(e), it could be seen that the maximum values of photorefractive response time are 55 msec, 50 msec and 12 msec for SPS, BGO and GaAs materials, respectively in the presence of applied electric field as well as in the absence of applied electric field for lower grating spacings. In the absence of applied electric field it decreases slowly with the increasing grating spacing for these materials. In the presence of applied electric field it is evident from the Figs. 1(c)-(e) that the SPS has much smaller value of photorefractive response time than those of BGO and GaAs for lower grating spacing.

The Fig.-1(f) shows the variation of the response time with the grating spacing in the absence of applied electric field for KNbO<sub>3</sub>:Fe crystal. From this Fig., it could be seen that the response time increases linearly with the increasing grating spacing upto  $\Lambda_g = 0.5 \mu\text{m}$  and further, it increases sharply for  $\Lambda_g > 0.5 \mu\text{m}$ . Our calculated results are found to be in good agreement with the experimental results reported by Ewart [20].



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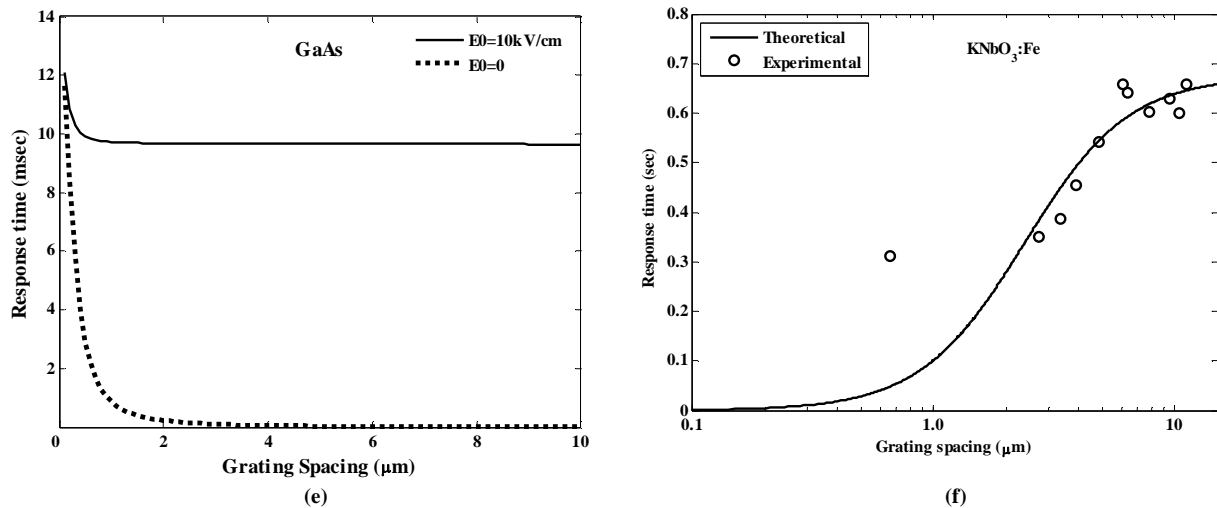
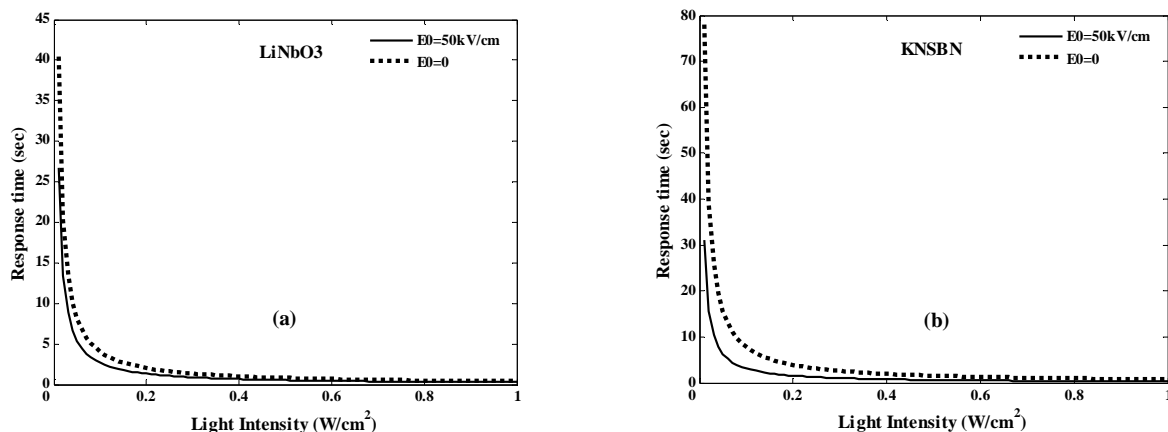


Fig. 1. Variation of response time with grating spacing in absence and presence of applied electric field for (a)  $\text{LiNbO}_3$  (b) KNSBN (c) SPS (d) BGO (e) GaAs (f) variation of response time with grating spacing in absence of applied electric field for  $\text{KNbO}_3:\text{Fe}$ . Theoretical results (solid line) and Experimental results (empty dots).

### III. (b). VARIATION OF PHOTOREFRACTIVE RESPONSE TIME WITH THE LIGHT INTENSITY

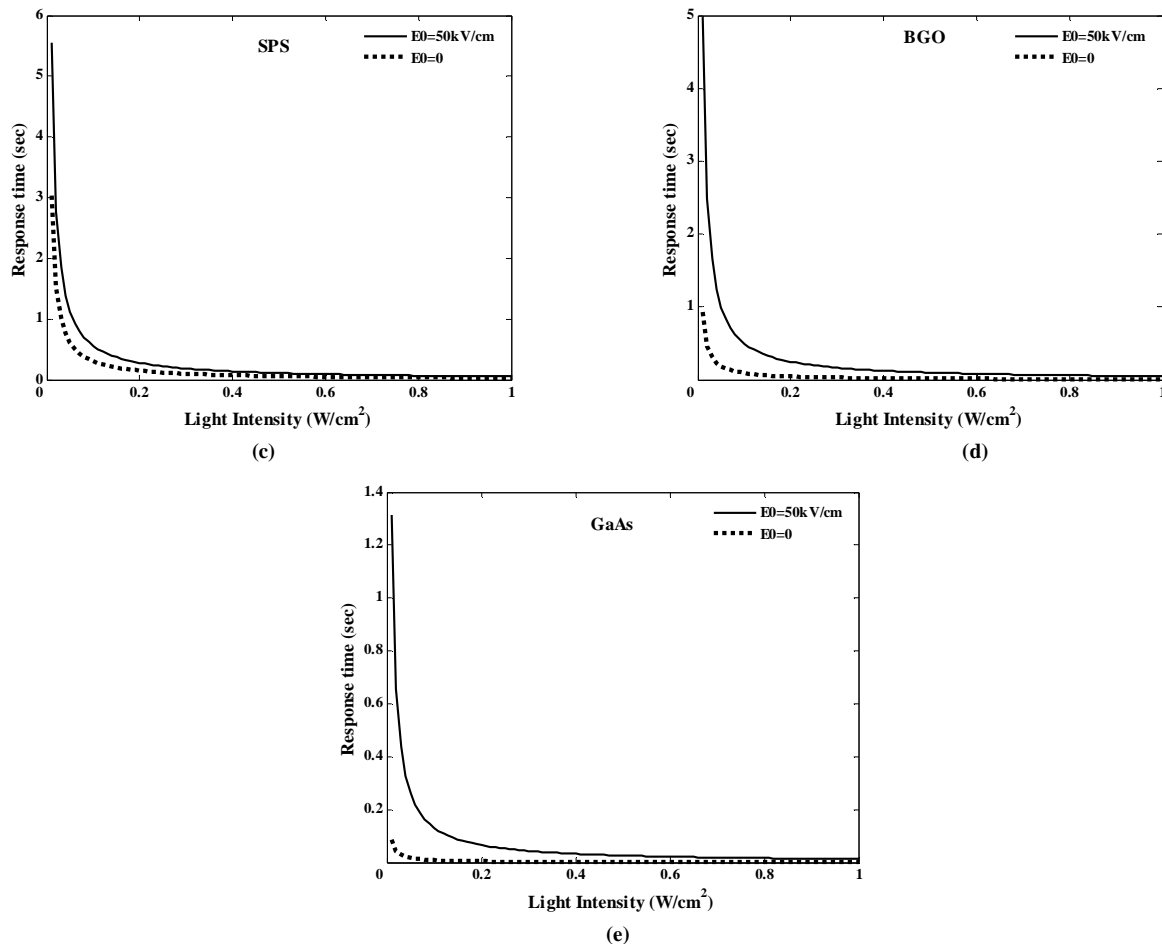
Figs.2(a)-(e), present variation of the photorefractive response time with the light intensity in the presence and absence of the applied electric field for  $\text{LiNbO}_3$ , KNSBN, SPS, BGO and GaAs respectively. It is clear from the Fig.-2(a) that the photorefractive response time decreases abruptly from 40 sec to about 2 sec for the lower light intensity in the absence of applied electric field. In the presence of applied electric field its values is slightly smaller with 27 sec for the lower light intensity. From the Fig.-2(b), it could be seen that in KNSBN for the lower light intensity the behavior is similar to that found in the Fig.-2(a) but the values of the photorefractive response time in the absence of applied electric field and in the presence of applied electric field are 80 sec and 30 sec, respectively. Unlike behavior is observed for SPS, BGO and GaAs as could be seen in Figs.-2(c)-(e) respectively. From these Figs., it is clear that the photorefractive response time decreases with increasing light intensity in the presence of applied electric field as well as in the absence of applied electric field. But in the presence of applied electric field its value is higher than that in the absence of applied electric field for the lower light intensities in contrast to  $\text{LiNbO}_3$  and KNSBN for which its value is lower in the presence of applied electric field.



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**Fig. 2.** Variation of response time with light intensity in absence and presence of applied electric field for (a)  $LiNbO_3$  (b)  $KNSBN$  (c) SPS (d) BGO (e) GaAs

## IV. CONCLUSION

From the present study it could be concluded that for  $LiNbO_3$  and  $KNSBN$ , the response time increases with the increasing grating spacing in the absence as well as presence of applied electric field. For  $LiNbO_3$  and  $KNSBN$ , the response time decreases in the presence of applied electric field. For the SPS, BGO and GaAs materials the response time attains constant values for higher values of grating spacing as compared to that in  $LiNbO_3$  and  $KNSBN$  in both the cases. In the presence of applied electric field, it was found that the GaAs has much smaller value of photorefractive response time than those of SPS and BGO for the lower grating spacing. Response time with grating spacing in absence of the applied electric field for  $KNbO_3:Fe$  crystal has been studied and compared with the experimental results. Agreement between theoretical and the experimental results are found to be reasonably good.

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