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The photorefractive sensitivity and the effective electron transport length in two-centre holographic recording*

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In this paper the photorefractive sensitivity defined for single-centre holographic recording is modified to adapt two-centre holographic recording. Based on the time analytic solution of Kukhtarev equations for doubly doped crystals, the analytical expression of photorefractive sensitivity is given. For comparison with single-centre holographic recording and summing the electron competition effects between the deeper and shallower traps, an effective electron transport length is proposed, which varies with the intensity ratios of recording light to sensitive light. According to analyses in this paper, the lower photorefractive sensitivity in two-centre holographic recording is mainly due to the lower concentration of unionized dopants in the shallower centre and the lower effective electron transport length.

Keywords: photorefractive, sensitivity, electron transport length, two-centre holographic recording
PACC: 4270Y, 7240, 7820W, 4240E

1. Introduction

The two-centre holographic recording method has attracted attention because of its ability to record persistent holograms.[1] Because UV light can be used to fix selectively a small-volume hologram out of the whole recorded hologram, it is possible to integrate a miniaturized optical three-dimensional system into a substrate.[2] However, their sensitivity and depth of space-charge field are very low in comparison with single-centre recordings.[3,4] Though the Kukhtarev equations modified for doubly doped crystals can be used for describing the time evolution of them, an intuitional explanation in physics is absent. The analyses of the electron transport lengths make good explanations on holographic grating formation in single-centre recordings,[5,6] but it cannot be used for the two-centre holographic recording directly. Figure 1 shows the energy-band diagrams for $LiNbO_3$:Fe:Mn crystal used in two-centre holographic recording. In the two-centre holographic recording method the deep centre and the shallow centre share the same conduction band and the same free electrons, thus the excitation, recombination and transport of carriers should have different behaviour with single-centre recording method. Furthermore, the deeper centres and shallower centres involve in the grating formation simultaneously and the contribution of high-frequency sensitizing light to the grating formation cannot be neglected in the analyses of photorefractive sensitivity. All of these analyses must be based on analytic solutions for Kukhtarev equations modified for the two-centre holographic recording.

The photorefractive sensitivity is defined as the changes of diffraction efficiencies per unit absorbed energy and volume or per incident energy density for unit crystal length, respectively, at the initial stage of hologram formation.[7] In Ref.[4], Adibi *et al* modified the sensitivity expression by multiplying a coefficient β on account of the effect of partial erasure during readout in two-centre holographic recording. Only in single-centre recording the dynamics of grating formation is a monoexponential function of time and thus the sensitivity has a direct relation with the final diffraction efficiency, but for the two-centre holographic recording the dynamics of grating formation is a double-exponential function of time and thus the modification in Ref.[4] is irrational. In Ref.[8], Montahan and Adibi give an analytical solution of photorefractive sensitivity based on Kukhtarev equations

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modified for the two-centre holographic recording but neglect the initial first-order density of free electrons in the conduction band, which leads to neglect of the influences of diffuse field and external electrical field on photorefractive sensitivity. Furthermore, above two references neglect the contribution of high-frequency sensitizing light to grating formation.

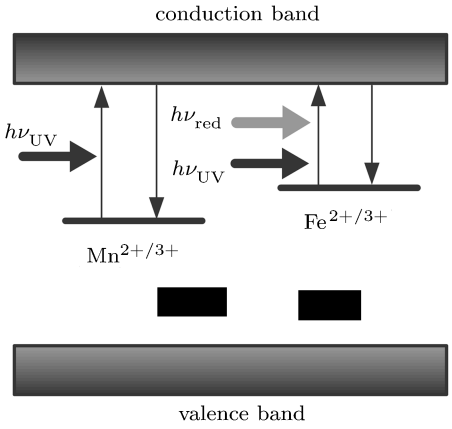


Fig.1. Energy-band diagrams for a typical $LiNbO_3$ crystal doped with Fe and Mn.

In this paper we modify the definition of photorefractive sensitivity for single-centre holographic by taking the sensitizing light into account. Based on the time analytic solution of Kukhtarev equations for two-centre holographic recording, in Section 2 we give the analytic expression of the photorefractive sensitivity and describe it with the electron transport lengths. In Section 3, we propose an effective electron transport length which can be used to describe the electron competition between the deeper and shallower traps and to compare with single-centre holographic recording.

2. The photorefractive sensitivity in two-centre holographic recording

In general, the photorefractive sensitivity for characterizing the holographic recording potential of a material has been defined as the changes of diffraction efficiencies per incident energy density for unit crystal length at the initial stage of hologram formation. The expression is[7]

$$S_1 = \frac{(\mathrm{d}\sqrt{\eta}/\mathrm{d}t)|_{t=0}}{I \cdot L}. \tag{1}$$

In Eq.(1), η, t, and L are diffraction efficiency, time, and crystal thickness, respectively. For single-centre holographic recording, the I is the total recording intensity (sum of the intensities of two recording beams). However, for two-centre holographic recording, the lower-frequency recording beams and the higher-frequency sensitizing beam illuminate the crystals simultaneously and the deeper centres and shallower centres involve in the grating formation simultaneously. Though the intensity distribution of sensitizing beam is homogeneous, the concentration of unionized donor is modified by recording beams and then the corresponding photovoltaic currents is modified, which contribute to $I_{\rm H}$ the holographic formation. Furthermore, the intensity ratios between the recording light and the sensitizing light control the concentration of unionized shallower centre and determine the saturation space-charge field. Thus in two-centre holographic recording the I is the sum of the intensity of lower-frequency recording light ($I_{\rm L0}$) and the intensity of higher-frequency sensitizing light ($I_{\rm H}$). Then Eq.(1) is modified as

$$S_{1\rm tc} = \frac{(\mathrm{d}\sqrt{\eta}/\mathrm{d}t)|_{t=0}}{(I_{\rm L0} + I_{\rm H}) \cdot L}. \tag{2}$$

For a phase hologram with a sinusoidal index variation of amplitude Δn and noninteracting beams, the diffraction efficiency η is given by[9]

$$\eta = \mathrm{e}^{(-\alpha L/\cos\theta_0)} \sin^2\Big(\pi\Delta n \frac{L}{\lambda\cos\theta_0}\Big), \tag{3}$$

where θ_0 is the Bragg angle corresponding to the incident wavelength λ.

According to the electro-optic effect, the magnitude of the refractive index changes Δn can be calculated in a good approximation as[7]

$$\Delta n(t) = -\frac{1}{2} n_{\rm o}^3 r_{\rm eff} E_{\rm sc}(t), \tag{4}$$

where $n_{\rm o}$, $r_{\rm eff}$, and $E_{\rm sc}$ are the ordinary index of refraction, the effective electro-optic coefficient, and the space-charge field, respectively.

Substituting Eqs.(3) and (4) into Eq.(2) and neglecting the absorption term for sufficiently thin crystals, we have

$$S_{1\rm tc} = \frac{\pi n_{\rm o}^3 r_{\rm eff}}{2(I_{\rm L0} + I_{\rm H})\lambda\cos\theta_0} \frac{\mathrm{d}E_{\rm sc}(t)}{\mathrm{d}t}\Big|_{t=0}. \tag{5}$$

In Ref.[10] we give the analytical solution of time evolution of space-charge field for two-centre holographic recording which is a double-exponential function of time. By taking the space-charge field with time into Eq.(5) we have

$$S_{1\mathrm{tc}} = m\frac{\pi n_{\mathrm{o}}^3 r_{\mathrm{eff}}}{2(I_{\mathrm{L0}}+I_{\mathrm{H}})\varepsilon\lambda\cos\theta_0}\frac{eS_{\mathrm{SL}}I_{\mathrm{L0}}(KD-\mathrm{i}\mu E_0)-\mathrm{i}k_{\mathrm{SL1}}I_{\mathrm{L0}}(\gamma_{\mathrm{S}}N_{\mathrm{S0}}^{+}+\gamma_{\mathrm{D}}N_{\mathrm{D0}}^{+})}{\gamma_{\mathrm{S}}N_{\mathrm{S0}}^{+}+\gamma_{\mathrm{D}}N_{\mathrm{D0}}^{+}+K^2D-\mathrm{i}K\mu E_0}(N_{\mathrm{S}}-N_{\mathrm{S0}}^{+}), \tag{6}$$

where

$$N_{\mathrm{S0}}^{+} = \frac{S_{\mathrm{SL}}I_{\mathrm{L0}}+S_{\mathrm{SH}}I_{\mathrm{H}}}{S_{\mathrm{SL}}I_{\mathrm{L0}}+S_{\mathrm{SH}}I_{\mathrm{H}}+\gamma_{\mathrm{S}}n_0}N_{\mathrm{S}}, \tag{7}$$

$$N_{\mathrm{D0}}^{+} = \frac{S_{\mathrm{DH}}I_{\mathrm{H}}}{S_{\mathrm{DH}}I_{\mathrm{H}}+\gamma_{\mathrm{D}}n_0}N_{\mathrm{D}}, \tag{8}$$

$$n_0 = \frac{1}{2N_{\mathrm{A}}}\Big\{\sqrt{[\Gamma_{\mathrm{D}}(N_{\mathrm{A}}-N_{\mathrm{D}})+\Gamma_{\mathrm{S}}(N_{\mathrm{A}}-N_{\mathrm{S}})]^2+4N_{\mathrm{A}}\Gamma_{\mathrm{S}}\Gamma_{\mathrm{D}}(N_{\mathrm{S}}+N_{\mathrm{D}}-N_{\mathrm{A}})} - [\Gamma_{\mathrm{D}}(N_{\mathrm{A}}-N_{\mathrm{D}})+\Gamma_{\mathrm{S}}(N_{\mathrm{A}}-N_{\mathrm{S}})]\Big\}, \tag{9}$$

where N_{D}, N_{D0}^{+}, N_{S}, N_{S0}^{+}, N_{A}, and n_0 are the concentrations of deeper traps, the ionized zero-order deeper traps, the shallower traps, the ionized zero-order shallower traps, acceptors, and the conducting electrons, respectively. S_{DH},S_{SH}, andS_{SL} are the photo excitation coefficients of the deeper and shallower traps for higher-frequency light and the shallower traps for lower-frequency light respectively. γ_{D} and γ_{S} are the recombination constants of the deep and shallower traps respectively. D and μ are the diffusion coefficient and the electron mobility coefficient in conduct band respectively. E, e, ε, K and m is the external electrical field, the elementary charge, the static permittivity, the grating vector, and the modulation depth, respectively. $\Gamma_{\mathrm{S}} = (S_{\mathrm{SL}}I_{\mathrm{L0}}+S_{\mathrm{SH}}I_{\mathrm{H}})/\gamma_{\mathrm{S}}$, and $\Gamma_{\mathrm{D}} = S_{\mathrm{DH}}I_{\mathrm{H}}/\gamma_{\mathrm{D}}$. k_{SL1} are the first-order photovoltaic coefficients corresponding to lower-frequency light from shallower traps, which have relation with zero-order photovoltaic coefficients k_{SL0} as[5]

$$k_{\mathrm{SL1}} = \frac{k_{\mathrm{SL0}}}{\sqrt{1+(KL_{\mathrm{ph}})^2}}\mathrm{e}^{-\mathrm{i}\varphi_{\mathrm{ph}}}, \tag{10}$$

where L_{ph} is the photovoltaic transport length corresponding to lower-frequency light from shallower traps, and $\varphi_{\mathrm{ph}} = \tan^{-1}(KL_{\mathrm{ph}})$. When the polarizations of two recording beams are parallel and the photovoltaic transport length is far more short than grating space, i.e. $KL_{\mathrm{ph}} << 1$, $k_{\mathrm{SL1}} = k_{\mathrm{SL0}} = k_{\mathrm{SL}}$.

According to Refs.[11, 12], we get the photovoltaic current

$$J_{\mathrm{phSL}} = k_{\mathrm{SL0}}I_{\mathrm{L0}}(N_{\mathrm{S}}-N_{\mathrm{S0}}^{+}) = eq_{\mathrm{SL}}(\alpha_{\mathrm{SL}}I_{\mathrm{L0}}/h\nu\mathrm{L})L_{\mathrm{ph}}, \tag{11}$$

where q_{SL} is the quantum efficiency defined as the probability that an electron is ejected when a lower-frequency photon is absorbed by shallower traps, ν_{L} is the frequency of recording light and α_{SL} is the absorption coefficient of the shallower traps for lower-frequency light and is defined as[13]

$$\alpha_{\mathrm{SL}} = s_{\mathrm{csSL}}h\nu_{\mathrm{L}}(N_{\mathrm{S}}-N_{\mathrm{S0}}^{+}), \tag{12}$$

where s_{csSL} is the photon absorption cross section of shallower-traps for lower-frequency light and $S_{\mathrm{SL}} = q_{\mathrm{SL}}s_{\mathrm{cSL}}$.

Then we have relations between κ_{SL0}, S_{SL}, and L_{ph} as

$$L_{\mathrm{ph}} = \frac{\kappa_{\mathrm{SL0}}}{e\cdot S_{\mathrm{SL}}}, \tag{13}$$

$$k_{\mathrm{SL0}} = eS_{\mathrm{SL}}L_{\mathrm{ph}}. \tag{14}$$

According to Ref.[3], for 633 nm recording light, $\kappa_{\mathrm{SL0}} = 7\times10^{-34}$, and $S_{\mathrm{SL}} = 3.3\times10^{-6}$ in $LiNbO_3$:Fe:Mn crystals, we have $L_{\mathrm{ph}} = 1.32$ nm which is far lower than grating space in small recording angle, thus $k_{\mathrm{SL1}} \approx k_{\mathrm{SL0}} = k_{\mathrm{SL}}$.

The diffusion transport length L_{D} and the drift transport length L_{E} can be given as[6]

$$L_{\mathrm{D}} = \sqrt{D\tau_{\mathrm{e}}}, \tag{15}$$

$$L_{\mathrm{E}} = \mu\tau_{\mathrm{e}}E_0, \tag{16}$$

where τ_{e} is the free-electron lifetime. In two-centre holographic recording, the free-electrons in conduction band can be recombined with either deeper traps or shallower traps. The free-electron lifetime can be deduced from zero-order free-electrons rate equation in Kukhtarev equations modified for the two-centre holographic recording.

$$\frac{\mathrm{d}n}{\mathrm{d}t} = S_{\mathrm{DH}}I_{\mathrm{H}}(N_{\mathrm{D}}-N_{\mathrm{D0}}^{+}) + (S_{\mathrm{SL}}I_{\mathrm{L0}}+S_{\mathrm{SH}}I_{\mathrm{H}}) \times (N_{\mathrm{S}}-N_{\mathrm{S0}}^{+}) - (\gamma_{\mathrm{S}}N_{\mathrm{S0}}^{+}+\gamma_{\mathrm{D}}N_{\mathrm{D0}}^{+})n. \tag{17}$$

The free-electron lifetime is thus given as

$$\tau_{\mathrm{e}} = \frac{1}{\gamma_{\mathrm{S}} N_{\mathrm{S0}}^{+} + \gamma_{\mathrm{D}} N_{\mathrm{D0}}^{+}}. \tag{18}$$

Substituting Eqs.(10)–(18) into Eq.(6), we can reformulate the photorefractive sensitivity as

$$\begin{aligned} S_{1\mathrm{tc}} = m & \frac{e S_{\mathrm{SL}} \pi n_{\mathrm{o}}^{3} r_{\mathrm{eff}}}{2\varepsilon\lambda\cos\theta_0} \\ & \times \frac{K L_{\mathrm{D}}^{2} - \mathrm{i} L_{\mathrm{E}} - \mathrm{i} L_{\mathrm{ph}} \mathrm{e}^{-\mathrm{i}\varphi_{\mathrm{ph}}} / \sqrt{1 + K^{2} L_{\mathrm{ph}}^{2}}}{1 + K^{2} L_{\mathrm{D}}^{2} - \mathrm{i} K L_{\mathrm{E}}} \\ & \times \frac{I_{\mathrm{L0}}}{I_{\mathrm{L0}} + I_{\mathrm{H}}} (N_{\mathrm{S}} - N_{\mathrm{S0}}^{+}). \end{aligned} \tag{19}$$

For two-centre holographic recording in congruently melting double-doped $LiNbO_3$ crystals using transmission geometry, the bulk photovoltaic current is dominant and the diffusion current density can be neglected,[14] when we neglect the external electrical field meanwhile, Eq.(19) can be simplified to

$$\begin{aligned} S'_{1\mathrm{tc}} &= m \frac{\pi n_{\mathrm{o}}^{3} r_{\mathrm{eff}}}{2\varepsilon\lambda\cos\theta_0} \frac{k_{\mathrm{SL}}}{1 + I_{\mathrm{H}}/I_{\mathrm{L0}}} (N_{\mathrm{S}} - N_{\mathrm{S0}}^{+}) \\ &= m \frac{\pi n_{\mathrm{o}}^{3} r_{\mathrm{eff}}}{2\varepsilon\lambda\cos\theta_0} \frac{e S_{\mathrm{SL}} L_{\mathrm{ph}}}{1 + I_{\mathrm{H}}/I_{\mathrm{L0}}} (N_{\mathrm{S}} - N_{\mathrm{S0}}^{+}). \end{aligned} \tag{20}$$

From Eqs.(7)–(9), the concentrations of the ionized zero-order deeper traps, the ionized zero-order shallower traps, and the density of free electrons are the function of intensity ratio of recording light to sensitizing light, thus the photorefractive sensitivity of two-centre holographic recording is also the function of intensity ratio of recording light to sensitizing light. Figure 2 shows the time evolutions of space-charge field with intensity ratios of recording light to sensitizing light in recording time, here we take the parameters in Ref.[3] and maintain the sum of intensity of recording light and sensitizing light invariable. It can be seen that the slope of space-charge field, which represents the photorefractive sensitivity, will first arise and subsequently down with the increase of intensity ratios in initial recording phase. Figure 3 simulates the variation of the photorefractive sensitivity of two-centre holographic recording with the intensity ratios, we can see that the modified expression Eq.(6) exactly describes the variation of photorefractive sensitivity with the intensity ratios. When the intensity ratios increase the two expressions Eqs.(1) and (2) have the same results.

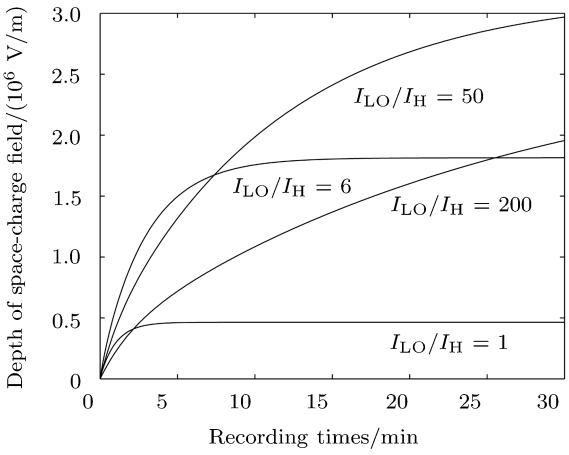


Fig.2. The time evolutions of space-charge field with intensity ratios of recording beam to sensitizing beam in recording phase.

In doubly-doped $LiNbO_3$ crystals for nonvolatile holographic recording, the crystal needs to be annealed properly to ensure that initially all shallower traps and a portion of the deeper traps are empty. During two-centre holographic recording, the sensitizing light transfers a portion of electrons trapped in deeper traps into shallower traps via conduction band and recording light transfers the electrons in shallower traps back into deeper traps via conduction band; the free electrons in conduction band can be trapped by either deeper centres or shallower centres, but the recording light only excites electrons trapped in the shallower centres to conduction band. According to Eq.(20), all the above effects are included in the concentration of the unionized shallower traps and cause the photorefractive sensitivity of two-centre holographic recording relatively lower than the single-centre holographic recording. Typical sensitivities obtained in normal holographic recording in $LiNbO_3$:Fe crystals in transmission geometry with ordinary polarization are $S \approx 0.01 - 0.1$ cm/J for recording with red light (633 nm),[4] and typical sensitivity obtained in two-centre holographic recording experiments in $LiNbO_3$:Fe:Mn crystals is 0.0047 cm/J. According to Eq.(20), lower intensity ratio (but greater than 6) will increase the photorefractive sensitivity by increasing the concentration of unionized shallower traps. But lower intensity ratio will cause the dynamic range of two-centre holographic recording to decrease according to the analysis in Ref.[3]. According to Eq.(19), positive external electrical field applied to crystal in recording phase will enhance the sensitivity harm-

lessly, which proves the experimental results[15] in theory.

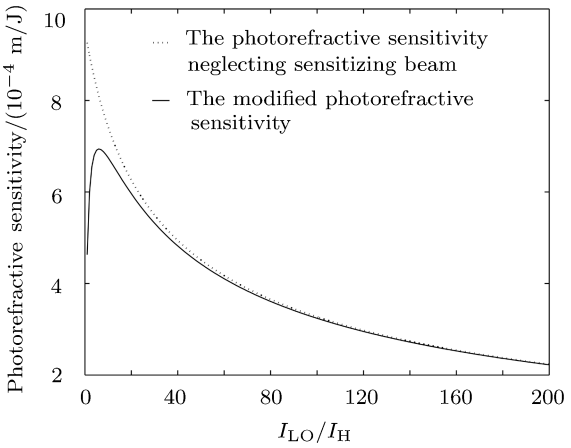


Fig.3. The variation of the photorefractive sensitivity of two-centre holographic recording with the intensity ratios.

3. The effective electron transport length in two-centre holographic recording

It can be seen from the analyses of the above section, according to the definition of photorefractive sensitivity given in Eq.(1), that the photorefractive sensitivity varies with the concentration of unionized donors (thus the annealing state) even doped in the same host crystal. For comparing the photorefractive sensitivities of the photorefractive crystals with different absorption coefficients, another sensitivity definition, which we call the relative photorefractive sensitivity, has been defined as: the changes of diffraction efficiencies per unit absorbed energy and volume at the initial stage of hologram formation.[7] For two-centre holographic recording, the expression is

$$S_{2\mathrm{tc}} = \frac{(\mathrm{d}\sqrt{\eta}/\mathrm{d}t)|_{t=0}}{[\alpha_{\mathrm{SL}} I_{\mathrm{L0}} + (\alpha_{\mathrm{SH}} + \alpha_{\mathrm{DH}}) I_{\mathrm{H}}] \cdot L}, \tag{21}$$

where α_{SH} and α_{DH} are the absorption coefficients of the shallower traps and the deeper traps for higher-frequency sensitizing light respectively, and are defined as

$$\alpha_{\mathrm{SH}} = s_{\mathrm{csSH}} h\nu_{\mathrm{H}} (N_{\mathrm{S}} - N_{\mathrm{S0}}^{+}), \tag{22}$$

$$\alpha_{\mathrm{DH}} = s_{\mathrm{csDH}} h\nu_{\mathrm{H}} (N_{\mathrm{D}} - N_{\mathrm{D0}}^{+}), \tag{23}$$

where ν_{H} is the frequency of sensitizing light, s_{csSH} and s_{csDH} are the photon absorption cross sections of shallower traps and deeper traps for higher-frequency sensitizing light, respectively. And $S_{\mathrm{SH}} = q_{\mathrm{SH}} s_{cSH}, S_{\mathrm{DH}} = q_{\mathrm{DH}} s_{\mathrm{DSH}}$, where q_{SH} and q_{DH} are the quantum efficiency defined as the probability that an electron is ejected when a higher-frequency photon is absorbed by shallower traps and deeper traps respectively.

Substituting Eqs.(6), (14), (22), (23) into Eq.(21) and neglecting the diffusion field and external electrical field, in doubly-doped $LiNbO_3$ crystals with transmission geometry, we have

$$S'_{2tc} = em \frac{\pi n_{\mathrm{o}}^3 r_{\mathrm{eff}}}{2\varepsilon\lambda\cos\theta_0} \frac{q_{\mathrm{SL}} s_{\mathrm{csSL}} I_{\mathrm{L0}} (N_{\mathrm{S}} - N_{\mathrm{S0}}^{+}) L_{\mathrm{ph}}}{(s_{\mathrm{csSL}} h\nu_{\mathrm{L}} I_{\mathrm{L0}} + s_{\mathrm{csSH}} h\nu_{\mathrm{H}} I_{\mathrm{H}})(N_{\mathrm{S}} - N_{\mathrm{S0}}^{+}) + s_{\mathrm{csDH}} h\nu_{\mathrm{H}} I_{\mathrm{H}} (N_{\mathrm{D}} - N_{\mathrm{D0}}^{+})}. \tag{24}$$

In Ref.[7], the effective electron transport length was used to evaluate the photorefractive sensitivity of the materials, and the longer the effective electron transport length is, the higher the photorefractive sensitivity is. For photovoltaic effect dominant photorefractive holographic recording and short photovoltaic transport length, the effective electron transport length is equal to the photovoltaic transport length. For two-centre holographic recording, the free-electrons in conduction band can be recombined with either deeper traps or shallower traps, thus the effective electron transport length is no longer equal to the photovoltaic transport length of shallower traps illuminated by lower-frequency recording light. The effective electron transport length in the two-centre holographic recording is

$$L_{\mathrm{eff}} = \mu\tau_{\mathrm{e}} E_{\mathrm{phSL}}, \tag{25}$$

where E_{phSL} is the shallow-centre lower-frequency photovoltaic field, which in Ref.[10] we gave as

$$E_{\mathrm{phSL}} = \frac{I_{\mathrm{L0}} k_{\mathrm{SL}}}{e n_0 \mu} (N_{\mathrm{S}} - N_{\mathrm{S0}}^{+}). \tag{26}$$

For normal holographic recording in single-centre crystals, the effective electron transport length deduced from Eq.(25) is equal to the photovoltaic transport length.

Substituting Eqs.(25), (26) into Eq.(24), we can transform Eq.(24) to

$$S'_{2\mathrm{tc}} = em\frac{\pi n_{\mathrm{o}}^3 r_{\mathrm{eff}}}{2\varepsilon\lambda\cos\theta_0}\frac{(s_{\mathrm{csSL}}q_{\mathrm{SL}}I_{\mathrm{L0}} + s_{\mathrm{csSH}}q_{\mathrm{SH}}I_{\mathrm{H}})(N_{\mathrm{S}} - N_{\mathrm{S0}}^+) + s_{\mathrm{csDH}}q_{\mathrm{DH}}I_{\mathrm{H}}(N_{\mathrm{D}} - N_{\mathrm{D0}}^+)}{(s_{\mathrm{csSL}}h\nu_{\mathrm{L}}I_{\mathrm{L0}} + s_{\mathrm{csSH}}h\nu_{\mathrm{H}}I_{\mathrm{H}})(N_{\mathrm{S}} - N_{\mathrm{S0}}^+) + s_{\mathrm{csDH}}h\nu_{\mathrm{H}}I_{\mathrm{H}}(N_{\mathrm{D}} - N_{\mathrm{D0}}^+)}L_{\mathrm{eff}}. \tag{27}$$

Figure 4 simulates the variation of the relative photorefractive sensitivity defined as Eq.(21) of two-centre holographic recording with the intensity ratios. It can be seen that the relative photorefractive sensitivity defined as Eq.(21) increases with the increase of the intensity ratios of recording light to sensitizing light. Figure 5 simulates the variation of the effective electron transport length in $LiNbO_3$:Fe:Mn crystals with the intensity ratios. It can be seen that the effective electron transport length in the two-centre holographic recording increases with the increase of intensity ratios of recording light to sensitizing light but is always lower than photovoltaic transport length. This means that the relative photorefractive sensitivity of the two-centre holographic recording is always lower than normal holographic recording in single-centre crystals with the same host material, the same shallower dopant, and the same recording condition.

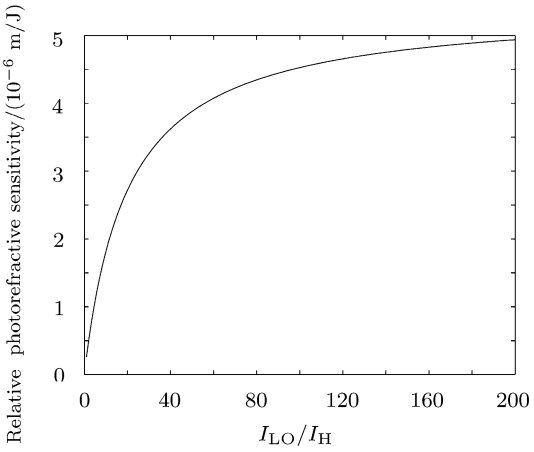


Fig.4. The variation of the relative photorefractive sensitivity of two-centre holographic recording with the intensity ratios.

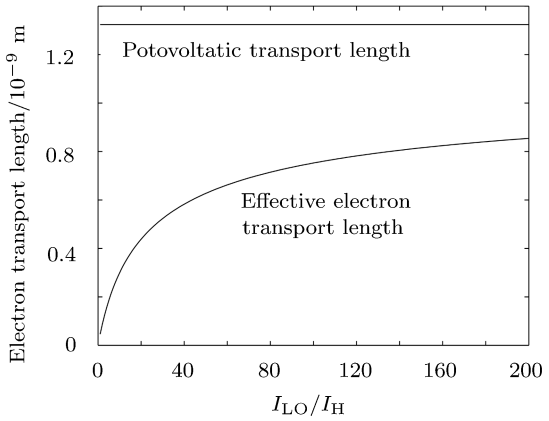


Fig.5. The variation of the effective electron transport length in $LiNbO_3$:Fe:Mn crystals with the intensity ratios.

4. Conclusions

In this paper the photorefractive sensitivity defined for single-centre holographic recording is modified to adapt the two-centre holographic recording by accounting for the contributions of sensitizing light. Based on the time analytic solution of Kukhtarev equations for doubly doped crystals, the analytic expression of photorefractive sensitivity is given. The photorefractive sensitivity first increases and subsequently decreases with the increase of intensity ratios of recording light to sensitizing light. Furthermore, the photorefractive sensitivity is directly proportional to the concentration of unionized shallower traps which decreases with the increase of the intensity ratio. For comparing with single-centre holographic recording and summing the electron competition between the deeper and shallower traps, an effective electron transport length is proposed which increases with the increase of the intensity ratio and is always lower

than photovoltaic transport length. Though the effective electron transport length increases with the increase of the intensity ratio, the concentration of unionized shallower traps decreases more fast, which causes the photorefractive sensitivity of the two-centre holographic recording eventually decrease with the increase of the intensity ratio. According to our analyses the lower photorefractive sensitivity in two-centre holographic recording is mainly due to the lower concentration of unionized dopants in shallower centre and the lower effective electron transport length.

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