

Contribution of photovoltaic effect in photorefractive grating formation under the influence of applied electric field

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Contribution of photovoltaic effect in photorefractive grating formation due to presence of an externally applied electric field in photorefractive materials have been calculated by solving the Kukhtarev's material rate of equations. The influence of photovoltaic field, diffusion field and carrier concentration ratio on the space-charge field (SCF) and the relative spatial phase-shift of the index grating with respect to the light interference pattern in the absence of the externally applied electric field have also been studied in details. It has been found that in the absence of applied dc electric field ($E_{ON} = 0$) and without photovoltaic effect (i.e., zero photovoltaic field ($E_{phN} = 0$), the magnitude of the space-charge field in the photovoltaic-photorefractive materials can be enhanced by increasing the diffusion field ($E_{DN} > 40$).

Introduction

Refractive index of the photorefractive material varies with illumination due to spatial variation in light intensity is of great interest because of its potential application in optoelectronic devices [1-5]. However, an incredible improvement of the performance of electronic devices has been achieved in the last thirty years and there was no necessity for extensive usage of photorefractive crystals. Now the limits of, e.g., electronic data transmissions are reached and further advances require all-optical networks [2-4]. Photorefractive materials enable several advantages and unique opportunities for technical optics [4]. Some examples: Self-pumped phase conjugation [5] can be used for efficient coupling of light from a multimode into a single-mode fiber [6] or for efficient injection-locking of a weak master laser beam into a high power diode laser array yielding a coherent and nearly diffraction limited output [7-9]. Holographic gratings are excellent for the production of outstanding interference filters and wavelength demultiplexers because of the very pronounced Bragg condition [10-12]; first products are available. The Bragg condition enables superposition of thousands of holograms at a single crystal position [13] which can be used for the construction of volume holographic memories.

The photorefractive effect consists of several steps: Inhomogeneous illumination excites charge carriers, and spatially modulated currents appear. A charge density pattern builds-up and space charge fields arise. These fields modulate the refractive index via the electro-optic effect [2-4]. Reproducible production of crystals and tailoring of their properties for special applications require a detailed knowledge about the light-induced charge transport processes which are essential for the photorefractive effect. In the last years the understanding of these processes and of many related phenomena increased substantially [1-5]. The band transport model [5, 7, 11] has become the general explanation for such photorefractive. In this model, diffusion

mechanism acts as a main role and in some cases drift mechanism (under applied field) as well as the photovoltaic effect (under uniform illumination) were added [7, 10, 11]. However, experiments and theoretical analysis have shown that the photovoltaic effect should always be considered; in the case of ferroelectrics, e.g., LiNbO_3 , this effect often exceeds the diffusion and thus dominates [3, 5, 7, 10, 11].

The role of defects in the photorefractive effect is known in principle: their photoionization in the brighter regions of a photorefractive crystal, illuminated by an inhomogeneous light pattern, causes quasifree charge carriers. These are separated from their home sites by diffusion, by the bulk photovoltaic effect, or by drift in an external electric field [7, 10, 11]. Eventually they are trapped at empty levels of defects in the darker regions, and a space charge field is created. Crystals with a linear electrooptic effect transform this into a refractive index pattern [10, 11].

The discovery of a new bulk photovoltaic effect characteristic for pyroelectrics additionally stimulated the investigation of light-induced charge transport in these crystals. Already rather early photoinduced currents and voltages were observed in the absence of external fields in noncentrosymmetric crystals [5, 11]. Glass et al. [8] pointed out in 1974 that a new bulk photovoltaic effect is involved that cannot be explained by conventional photovoltaic processes in crystals containing macroscopic inhomogeneities (pn junctions) [7, 10].

In the present paper, the influence of photovoltaic field, diffusion field and carrier concentration ratio on the space-charge field (SCF) and the relative spatial phase-shift of the index grating in the absence of the externally applied electric field have been studied in details.

Theoretical description

Photorefractive due to photovoltaic effect

The response of the photorefractive material to the light input may be described by the differential equations of Kukhtarev et al. [3, 5, 10, 11] as follows:

$$\frac{\partial n}{\partial t} = \frac{\partial N_D^+}{\partial t} + \frac{1}{e} \vec{\nabla} \cdot \vec{J} \quad (1)$$

$$\frac{\partial N_D^+}{\partial t} = (N_D - N_D^+) (\beta_e + sI) + \gamma_R N_D^+ n \quad (2)$$

$$\vec{J} = k_B T \vec{\nabla} n + \mu e n \vec{E} + k s I (N_D - N_D^+) c \quad (3)$$

$$\vec{\nabla} \cdot (\epsilon_0 \epsilon_r \vec{E}) = e (N_D^+ - N_A - n) \quad (4)$$

where n is electron density, N_D is density donors, N_D^+ is density of donors, N_A is the density of acceptors, N_D^+ is the density of ionized donors, J is the current density, E is the static electric field made of the applied field E_0 and of the space charge field created by the charge imbalance, I is the optical intensity in the crystal, e is the electronic charge, β_e is the rate of thermal generation, γ_r is the carrier recombination constant, μ is the mobility of the electrons, k_B is the Boltzmann's constant, T is temperature, ϵ_0 is free space permittivity, ϵ_r is the relative static dielectric constant. The third term on the R.H.S. of the Eq. (3) is known as photovoltaic term, which depends on the non-ionized trap density because the photovoltaic current is proportional to the photo-absorption constant which in turn depends on the non-ionized trap density [3, 10, 11]. In order to obtain analytic solutions for the SCFs Kukhtarev et al. introduced the method of Fourier development of all spatially dependent quantities [3, 5, 7, 10, 11]

$$I(z) = I_0 \left(1 + \frac{M}{2} \exp(iKz) + c.c \right) \quad (5)$$

This sinusoidally modulated intensity pattern can be easily created by interference of two plane waves in a photorefractive crystal.

Where $\vec{I}_0 = \vec{I}_1 + \vec{I}_2$, M is the modulation index $K = K_1 - K_2$ is the grating wave vector parallel to c-axis. The response of material to the light intensity distribution can be limited to only including the spatial Fourier's zeroth and first components, so the solution of the Eqs. (1), (2) and (4) can be written as

$$n(z) = n_0 \left(1 + \frac{a}{2} \exp(iKz) + c.c \right) \quad (6)$$

$$N_D^+(z) = N_{D0}^+ \left(1 + \frac{A}{2} \exp(iKz) + c.c \right) \approx N_A \left(1 + \frac{A}{2} \exp(iKz) + c.c \right) \quad (7)$$

$$\vec{E}(z, t) = \vec{E}_0 + \frac{\vec{E}_{sc}}{2} \exp(iKz) + c.c \quad (8)$$

where n_0, N_{D0}^+, \vec{E}_0 , and $n_0, a, N_{D0}^+, A, \vec{E}_{sc}$ are spatial Fourier's zeroth and first components respectively. In the case when there is an externally applied dc electric field ($E_0 \neq 0$), the complex amplitude of steady-state space charge field (E_{sc}^t) is given by Eq. (8)

$$E_{sc}^t(E_{ph}) = -m \left[\frac{(E_0 + E_{ph} + iE_D)}{1 + \left(\frac{r}{r-1}\right) \frac{E_D}{E_q} - i \left[\left(\frac{r}{r-1}\right) \frac{E_0}{E_q} + \left(\frac{1}{r-1}\right) \frac{E_{ph}}{E_q} \right]} \right] \quad (9)$$

and also the phase-shift (ϕ) of the steady-state space charge field (E_{sc}^t) with respect to the light intensity interference pattern is given by the relation as,

$$\phi = \pi + \tan^{-1} \left[\frac{E_D \left(E_q + \left(\frac{r}{r-1}\right) E_D \right) + (E_0 + E_{ph}) \left[\left(\frac{r}{r-1}\right) E_0 + \left(\frac{1}{r-1}\right) E_{ph} \right]}{E_q (E_0 + E_{ph}) + E_D E_{ph}} \right] \quad (10)$$

In the absence of the external field ($E_0 = 0$) and for the photovoltaic-photorefractive crystals and therefore using Eq. (9) one has,

$$E_{sc}^t(E_{ph}) = -m \left[\frac{E_{ph} + iE_D}{1 + \left(\frac{r}{r-1}\right) \frac{E_D}{E_q} - i \left(\frac{1}{r-1}\right) \frac{E_{ph}}{E_q}} \right] \quad (11)$$

and

$$\phi = \pi + \tan^{-1} \left[\frac{E_D \left(E_q + \left(\frac{r}{r-1}\right) E_D \right) + \left(\frac{1}{r-1}\right) E_{ph}^2}{E_{ph} (E_q + E_D)} \right] \quad (12)$$

The photovoltaic dependence factor normalized to low photovoltaic field is obtained after dividing Eq. (9) by Eq. (11), i.e.,

$$\frac{\text{Im} E_{sc}^t(E_{ph})}{\text{Im} E_{sc}^t(E_{ph}=0)} = \frac{1 + 2 \left(\frac{r}{r-1}\right) \frac{E_D}{E_q} + \left(\frac{1}{r-1}\right) \frac{E_{ph}^2}{E_q E_D} + \left(\frac{r}{r-1}\right)^2 \left(\frac{E_D}{E_q}\right)^2 + r \left(\frac{1}{r-1}\right)^2 \left(\frac{E_{ph}}{E_q}\right)^2}{\left(1 + \left(\frac{r}{r-1}\right) \frac{E_D}{E_q} \right)^2 + \left(\frac{1}{r-1}\right)^2 \frac{E_{ph}^2}{E_q^2}} \quad (13)$$

The Eq. (13) represents an expression for the normalized photovoltaic field dependent space-charge field (SCF) with

respect to the saturation field (E_q) in the absence of external applied dc electric field ($E_0 = 0$) in photovoltaic-photorefractive materials.

Results and discussion

Figure 1 depicts variation of the space-charge field (η') against the dimensionless photovoltaic field (E_{phN}) for various normalized diffusion field (E_{DN}) with respect to the saturation field (E_q) at constant $r = 100$ in the absence of applied dc electric field, respectively. In the absence of externally applied dc electric field ($E_{ON} = 0$) it is obvious from the Fig.-1 that the space-charge field (imaginary part of the Eq. (13) increases linearly with the increasing the photovoltaic field. However, for a given value of E_{phN} , the magnitude of the space-charge field in photovoltaic-photorefractive materials is found to be higher for higher value of the diffusion field ($E_{DN} > 40$). One can also be seen from the Fig.-1 that in the absence of applied dc electric field ($E_{ON} = 0$) and without photovoltaic effect (i.e., zero photovoltaic field ($E_{phN} = 0$)), the magnitude of the space-charge field in the photovoltaic-photorefractive materials can be enhanced by increasing the diffusion field ($E_{DN} > 40$).

Figure 2 shows the variation of the space-charge field as a function of the photovoltaic field (E_{phN}) for different values of carrier concentration ratio at constant $E_{DN} = 10$ in the absence of the externally applied dc electric field, respectively. In the absence of externally applied dc electric field it is evident from the Fig.-2 that the magnitude of the space-charge field increases with the increasing the photovoltaic field. However, it is interesting to note that for a given value of E_{phN} , the magnitude of the space-charge field in photovoltaic-photorefractive materials is found to be higher for higher value of carrier concentration ratio ($r > 100$). This means that for a fixed value of photovoltaic field, the magnitude of the space-charge field can be enhanced to the higher degree by increasing the carrier concentration ratio ($r > 100$) in the absence of externally applied dc field.

Figure 3 presents variation of the relative spatial phase-shift (ϕ) of the index grating with the normalized photovoltaic field (E_{phN}) for the different values of the normalized diffusion field (E_{DN}) at constant carrier concentration ratio ($r = 100$) in the absence of applied dc electric field, respectively. In the absence of externally applied dc electric field ($E_{ON} = 0$), the magnitude of the spatial phase-shift (ϕ) of the index grating relative to the interference pattern increases with the increasing the photovoltaic field and finally attains saturation value in the optimum photovoltaic field range of $E_{phN} = 40-100$ with increasing the photovoltaic field (Fig.-3). It is interesting to note that the saturation value of ϕ decreases with increasing the diffusion field (E_{DN}). Thus, from the Fig.-3 one may conclude that in the absence of external applied dc electric field the magnitude of the spatial phase-shift of the index grating relative to the interference pattern is found to be higher for a photovoltaic-photorefractive material having lower value of the diffusion field ($E_{DN} < 10$). Such a higher magnitude of the relative spatial phase-shift of the index grating enhances the possibility of the non-reciprocal steady-state transfer of energy between the two light beams interfering in a photovoltaic-

photorefractive medium, which greatly improves the performance of photorefractive effect in these materials and related phenomena [3, 5, 10, 11].

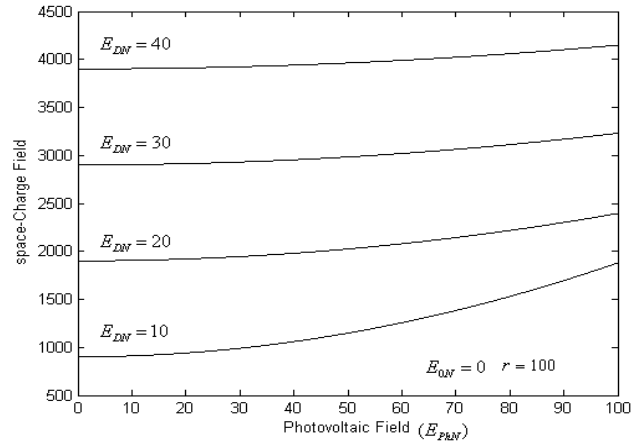


Fig. 1 Variation of the space-charge field with photovoltaic field for different values of diffusion field in the absence of the applied dc electric field.

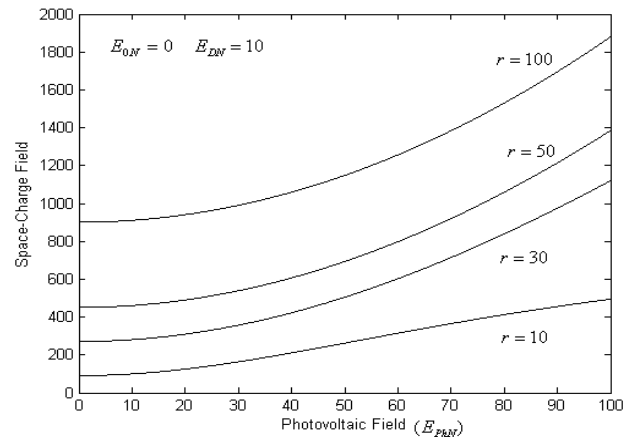


Fig. 2. Dependence of the space-charge field on photovoltaic field for different values of the concentration ratio in the absence of the applied dc electric field.

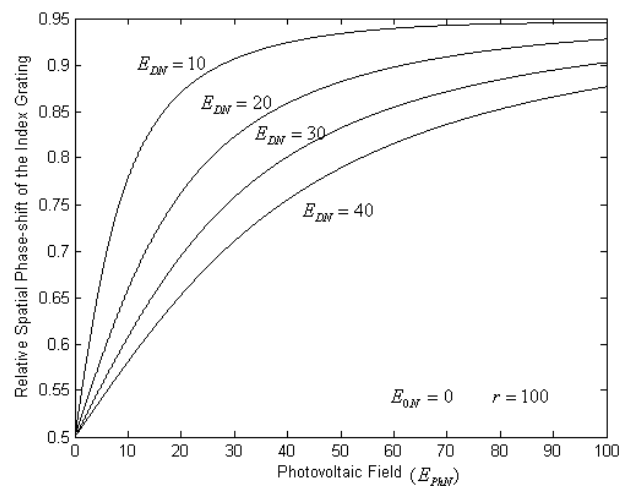


Fig. 3. Variation of the relative spatial phase-shift of the index grating as a function of photovoltaic field for different values of diffusion field in the absence of the applied dc electric field.

Figure 4. shows the variation of the relative spatial phase-shift (ϕ) of the index grating with respect to the light interference pattern as a function of the photovoltaic field (E_{PhN}) for different values of carrier concentration ratio (r) at constant $E_{DN} = 10$ in the absence of the externally applied dc electric field, respectively. In the absence of externally applied dc electric field ($E_{ON} = 0$), the magnitude of the relative spatial phase-shift (ϕ) of the index grating increases with the increasing the photovoltaic field initially, reaches a maximum value and decreases afterwards (Fig.-4). This maximum value of the relative spatial phase-shift of the index grating is different for different value of the carrier concentration ratio (r) and shifted towards the higher value of the photovoltaic field (E_{PhN}) for the higher carrier concentration ratio (r). However, for a given values of E_{PhN} and E_{DN} , the magnitude of the spatial phase-shift of the index grating relative to the light interference pattern in the absence of the applied dc electric field ($E_{ON} = 0$) can be increased by increasing the carrier concentration ratio ($r > 100$) in photovoltaic-photorefractive medium. This means that for a fixed value of photovoltaic field (E_{PhN}) and the diffusion field (E_{DN}), the transfer of energy between the two light beams interfering in a photovoltaic-photorefractive medium can be enhanced significantly by increasing the carrier concentration ratio in these materials in the absence of the applied electric field ($E_{ON} = 0$). This enhancement of the energy transfer between two light beams interfering in a photovoltaic-photorefractive medium is responsible for the strongest beam coupling in photovoltaic-photorefractive materials.

Conclusion

In conclusion, contribution of photovoltaic effect in refractive index grating due to presence of an external applied electric field in photorefractive materials has been studied in details. It is found that for a given values of E_{PhN} and E_{DN} , the magnitude of the SCF in photovoltaic-photorefractive materials can be enhanced greatly by applying the lower external dc electric field ($E_{ON} \ll 10$) across the photovoltaic-photorefractive crystal and higher value of the carrier concentration ratio ($r > 100$). Such a higher value of the space-charge field is responsible for large change in the index of refraction via the linear electro-optic effect, which greatly improved the photorefractive effect and its related phenomena [3, 5, 10, 11].

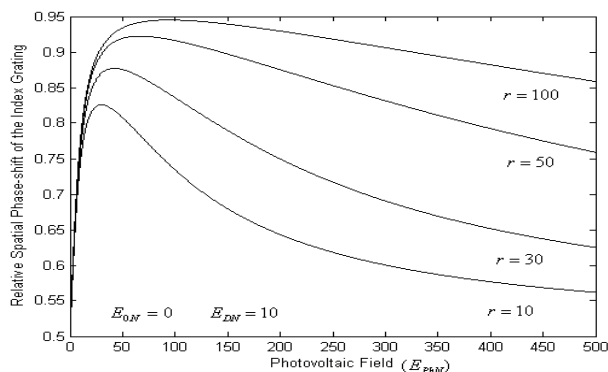


Fig. 4. Dependence of the relative spatial phase-shift of the index grating on the photovoltaic field for different values of the concentration ratio in the absence of applied dc field.

Notes and References

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