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INCOHERENTLY COUPLED SCREENING–PHOTOVOLTAIC SOLITON FAMILIES IN BIASED PHOTOVOLTAIC PHOTOREFRACTIVE CRYSTALS*

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It is shown that the existence of incoherently coupled screening–photovoltaic soliton families is possible in biased photovoltaic photorefractive crystals under steady-state conditions. These screening–photovoltaic soliton families can be established provided the multiple incident beams have the same polarization and wavelength, and are mutually incoherent. Such soliton families reduce to screening–photovoltaic soliton pairs when they contain only two components. Relevant examples are presented where the photovoltaic photorefractive crystal is of the lithium niobate type.

Keywords: optical spatial solitons, photorefractive effect, photovoltaic effect
PACC: 4265, 7820, 7240

I. INTRODUCTION

Photorefractive spatial solitons have been a research topic of growing interest during the past few years.[1−16] Upon illumination, photorefractive materials can set up a space-charge field in the crystal, which will induce nonlinear changes in the refractive index of the materials by means of the electro-optic (Pockels) effect. The latter process is then capable of counteracting the effects of diffraction, and thus the non-diffracting optical beam or photorefractive soliton forms. At present, several different types of scalar photorefractive soliton, i.e., quasi-steady-state solitons[1−3], screening solitons[4−7] and photovoltaic solitons[8−10] have been observed. The quasi-steady-state solitons can exist in biased photorefractive crystals during the finite time in which the externally applied field is slowly being screened by the space-charge field. The screening solitons are possible in the steady state in biased non-photovoltaic photorefractive crystals. They result from non-uniform screening of the bias field. The photovoltaic solitons can exist in the steady state in photovoltaic photorefractive materials. These photovoltaic solitons rely on the photovoltaic effect to create the space-charge field. Very recently, a new type of photorefractive spatial solitons has been predicted in photovoltaic photorefractive crystals to which an external field is applied.[11−14] These solitons have been called screening–photovoltaic solitons, for they stem from both the photovoltaic effect and non-uniform screening of the bias field.

Several years ago, Christodoulides *et al.*[15] considered the coupling between two screening solitons whose carrier beams share the same polarization, wavelength, and are mutually incoherent. They showed that incoherently coupled screening soliton pairs can be formed in biased non-photovoltaic photorefractive crystals under steady-state conditions. Chen *et al.*[16] soon experimentally observed these screening soliton pairs.

In this paper, we predict that the incoherently coupled screening–photovoltaic soliton families can exist in biased photovoltaic photorefractive crystals under steady-state conditions. These screening–photovoltaic soliton families are formed by multiple incident beams which have the same polarization, wavelength, and are mutually incoherent. Such incoherently coupled soliton families can be readily realized in a biased photovoltaic photorefractive crystal in which the mutually incoherent incident optical beams propagate collinearly. Such soliton families will become screening–photovoltaic soliton pairs when they contain only two components. The necessary conditions for the formation of these soliton families are discussed, and relevant examples are also provided where the photovoltaic photorefractive crystal is taken here to be lithium niobate ($LiNbO_3$) to illustrate our results.

II. THE SOLITON COUPLING EQUATION

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To study the incoherently coupled screening–photovoltaic soliton families in biased photovoltaic photorefractive crystal, let us consider N optical beams that propagate collinearly in a photovoltaic photorefractive crystal along the z-axis and are permitted to diffract only along the x-direction. The incident beams have the same polarization, wavelength, and are mutually incoherent. The photovoltaic photorefractive crystal is taken here to be $LiNbO_3$, with its optical c-axis oriented along the x coordinate. Moreover, let us assume that the polarizations of the incident optical beams are all parallel to the c-axis, and the external bias electric field is applied in the same direction. As usual, the optical fields are expressed in terms of slowly varying envelopes ϕ_1, ϕ_2, ... and ϕ_N, i.e., $\boldsymbol{E}_1 = \hat{x}\phi_1(x,z)\exp(ikz)$, $\boldsymbol{E}_2 = \hat{x}\phi_2(x,z)\exp(ikz)$, ... and $\boldsymbol{E}_N = \hat{x}\phi_N(x,z)\exp(ikz)$, where $k = k_0 n_e = (2\pi/\lambda_0)n_e$, n_e is the unperturbed extraordinary index of refraction, and λ_0 is the free-space wavelength. Under these conditions, the N optical beams satisfy the following envelope evolution equations:[6,15]

$$
\begin{aligned}
&i\frac{\mathrm{d}\phi_1}{\mathrm{d}z} + \frac{1}{2k}\frac{\mathrm{d}^2\phi_1}{\mathrm{d}x^2} - \frac{k_0 n_e^3 r_{33} E_{\mathrm{sc}}}{2}\phi_1 = 0,\\
&i\frac{\mathrm{d}\phi_2}{\mathrm{d}z} + \frac{1}{2k}\frac{\mathrm{d}^2\phi_2}{\mathrm{d}x^2} - \frac{k_0 n_e^3 r_{33} E_{\mathrm{sc}}}{2}\phi_2 = 0,\\
&\cdots\cdots\\
&i\frac{\mathrm{d}\phi_N}{\mathrm{d}z} + \frac{1}{2k}\frac{\mathrm{d}^2\phi_N}{\mathrm{d}x^2} - \frac{k_0 n_e^3 r_{33} E_{\mathrm{sc}}}{2}\phi_N = 0, \qquad (1)
\end{aligned}
$$

where r_{33} is the electro-optic coefficient, and $\boldsymbol{E}_{\mathrm{sc}} = E_{\mathrm{sc}}\hat{x}$ is the induced space-charge field. In the case that the diffusion effect is neglected, the space-charge field can be approximately given by[11,12]

$$
E_{\mathrm{sc}} = E_0\frac{I_\infty + I_d}{I + I_d} + E_p\frac{I_\infty - I}{I + I_d}, \qquad (2)
$$

where I_d is the so-called dark irradiance; $I = I(x,z)$ is the total intensity of the N optical beams; I_∞ represents the total intensity in the area far away from the centre of the photovoltaic photorefractive crystal, i.e., $I_\infty = I(x \to \pm\infty, z)$; E_0 is the value of the space-charge electric field also at $x \to \pm\infty$; and E_p is the photovoltaic field constant. If the spatial extent of the optical beams is much less than the x-width W of the photorefractive crystal, E_0 is approximately given by $\pm V/W$, where V is the applied bias voltage.[6] The total intensity of the N mutually incoherent optical beams can be obtained by summing up the N Poynting fluxes; that is, $I = (n_e/2\eta_0)\sum_{j=1}^{N}|\phi_j|^2$, where $\eta_0 = (\mu_0/\varepsilon_0)^{1/2}$. Substituting Eq.(2) into Eqs.(1), and after appropriate normalization, we find that the normalized envelopes U_1, U_2, ..., and U_N of the N optical beams satisfy the following dynamical evolution equations

$$
\begin{aligned}
&i\frac{\mathrm{d}U_1}{\mathrm{d}\xi} + \frac{1}{2}\frac{\mathrm{d}^2U_1}{\mathrm{d}s^2} - \frac{\beta(1+\rho)U_1}{1+\sum_{j=1}^{N}|U_j|^2}\\
&\quad - \frac{\alpha\left(\rho - \sum_{j=1}^{N}|U_j|^2\right)U_1}{1+\sum_{j=1}^{N}|U_j|^2} = 0,\\
&i\frac{\mathrm{d}U_2}{\mathrm{d}\xi} + \frac{1}{2}\frac{\mathrm{d}^2U_2}{\mathrm{d}s^2} - \frac{\beta(1+\rho)U_2}{1+\sum_{j=1}^{N}|U_j|^2}\\
&\quad - \frac{\alpha\left(\rho - \sum_{j=1}^{N}|U_j|^2\right)U_2}{1+\sum_{j=1}^{N}|U_j|^2} = 0,\\
&\cdots\cdots\\
&i\frac{\mathrm{d}U_N}{\mathrm{d}\xi} + \frac{1}{2}\frac{\mathrm{d}^2U_N}{\mathrm{d}s^2} - \frac{\beta(1+\rho)U_N}{1+\sum_{j=1}^{N}|U_j|^2}\\
&\quad - \frac{\alpha\left(\rho - \sum_{j=1}^{N}|U_j|^2\right)U_N}{1+\sum_{j=1}^{N}|U_j|^2} = 0, \qquad (3)
\end{aligned}
$$

where U_j=$[n_e/(2\eta_0 I_d)]^{1/2}\phi_j$; s and ξ are dimensionless coordinates defined as $s = x/x_0$ and $\xi = z/(kx_0^2)$ respectively, through the agency of an arbitrary spatial scale x_0; and $\rho = I_\infty/I_d, \alpha = (k_0x_0)^2(n_e^4 r_{33}/2)E_p, \beta = (k_0x_0)^2(n_3^4 r_{33}/2)E_0$. The intensities of the optical beams have been scaled with respect to the dark irradiance I_d, i.e., $I_j = |U_j|^2 I_d$. In what follows, the soliton family solutions of Eqs.(3) and their characteristics will be discussed in detail.

Ⅲ. THE BRIGHT SOLITON FAMILY

Firstly, we consider the class of bright screening–photovoltaic soliton family. In this case, the intensity is expected to vanish at infinity ($s \to \pm\infty$) and thus

$I_\infty = \rho = 0$. We can obtain the soliton family solutions of Eqs.(3) by expressing the normalized envelope U_j in the form of $U_j = r^{1/2}c_j y(s)\exp(i\mu\xi)$, where μ represents a nonlinear shift of the propagation constant, r stands for the ratio of the peak value of the total intensity of the soliton family to the dark irradiance I_d, $y(s)$ is a normalized real function bounded between $0 \le y(s) \le 1$. The parameter c_j^2 corresponds to the ratio of the intensity of the jth soliton component to the total intensity of the soliton family, i.e., c_j^2 satisfies the conditions of $c_j^2 = I_j \Big/ \sum_{l=1}^{N} I_l$, and $\sum_{j=1}^{N} c_j^2 = 1$. Furthermore, since the optical intensity of the bright solitons attain to maximum at the beam centre (s=0) and vanish at infinity ($s \to \pm\infty$), $y(s)$ is required to satisfy the boundary conditions of $y(0) = 1$, $\dot{y}(0) = 0$, and $y(s \to \pm\infty) = 0$. Substitution of this form of U_j into Eqs.(3) yields the following equation

$$\frac{\mathrm{d}^2 y}{\mathrm{d}s^2} - 2\mu y - 2\beta\frac{y}{1+ry^2} + 2\alpha\frac{ry^3}{1+ry^2} = 0, \qquad (4)$$

which is known to describe the single bright screening–photovoltaic soliton in biased photovoltaic–photorefractive crystal.[11,12] By integrating Eq.(4) and by employing the y-boundary conditions, it can be shown that the bright soliton families will be possible only when $\alpha + \beta$ or $E_p + E_0$ are positive quantities (i.e. $\alpha + \beta > 0$ or $E_p + E_0 > 0$) and $\mu = -[(\alpha + \beta)/r]\ln(1 + r) + \alpha$. Under these conditions the bright-field profile $y(s)$ can be determined by the equation[11,12]

$$s = \pm\int_y^1 \frac{[2(\alpha+\beta)]^{-1/2} r^{1/2}\mathrm{d}\tilde{y}}{[\ln(1+r\tilde{y}^2) - \tilde{y}^2\ln(1+r)]^{1/2}}, \qquad (5)$$

from which $y(s)$ can be easily found by numerical integration. In this case, the soliton family components can then be simply obtained through $U_j = r^{1/2}c_j y(s)\exp(i\mu\xi)$. To illustrate our results, we consider the following physical system where $\lambda_0 = 0.5\mu$m, x_0=40μm, r=10, and $E_0 = 7 \times 10^6$V/m. The $LiNbO_3$ parameters are taken here to be[12] $n_e = 2.2$, $r_{33} = 30 \times 10^{-12}$m/V, and $E_p = 4 \times 10^6$V/m (this photovoltaic field is physically accessible[8]). For this set of values, $|\alpha| = 355$, $\beta = 621$. According to Ref.[12], we take α=–355, and thus $\alpha + \beta$=266. Figure 1 depicts the normalized intensity profiles of the bright screening–photovoltaic soliton family with five components ($c_1^2 = 0.30$, $c_2^2 = 0.25$, $c_3^2 = 0.20$, $c_4^2 = 0.15$, $c_5^2 = 0.10$) in an $LiNbO_3$ crystal when $r = 10$ and $\alpha + \beta = 266$. Under these conditions, the intensity full width at half maximum (FWHM) of the components is found to be 7.4μm. According to Eq.(5), it can be seen that the FWHM of the soliton components of the bright soliton family is inversely proportional to the square root of the absolute value of the sum of the externally applied electric field and the photovoltaic field.

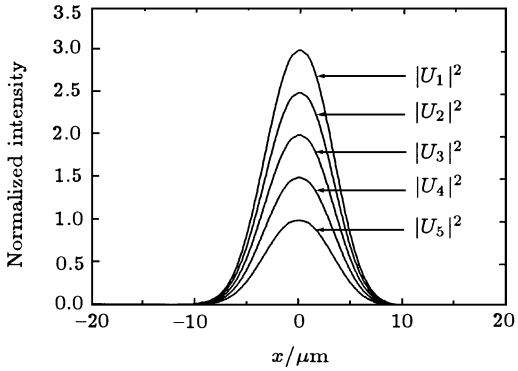


Fig.1. Soliton profiles for a bright screening–photovoltaic soliton family with five components ($c_1^2 = 0.30$, $c_2^2 = 0.25$, $c_3^2 = 0.20$, c_4^2= 0.15, c_5^2=0.10) in an $LiNbO_3$ crystal when $r = 10$ and $\alpha+\beta$=266.

IV. THE DARK SOLITON FAMILY

The dark screening–photovoltaic soliton families can be analysed in a similar way. These dark beams exhibit an anti-symmetric field profile (with respect to x) and, moreover, they are embedded in a constant intensity background; that is, I_∞ and ρ are finite quantities. To get the dark family, we put $U_j = \rho^{1/2}c_j y(s)\exp(i\mu\xi)$, where $y(s)$ is a normalized odd function of s and satisfies the following boundary conditions: $y(0) = 0$, $y(s \to \pm\infty) = \pm 1$, and all the derivatives of $y(s)$ vanish at infinity. Substitution of this form of U_j in Eqs.(3) leads to the following equation

$$\frac{\mathrm{d}^2 y}{\mathrm{d}s^2} - 2\mu y - 2\beta(1+\rho)\frac{y}{1+\rho y^2} - 2\alpha\rho\frac{1-y^2}{1+\rho y^2}y = 0, \qquad (6)$$

and the single dark soliton solutions have been discussed in detail in Refs.[11] and [12]. By integrating Eq.(6) and by using the y-boundary conditions, one can show that the dark soliton families will be possible only when $\alpha+\beta$ or E_p+E_0 are negative quantities (i.e. $\alpha + \beta < 0$ or $E_p + E_0 < 0$) and $\mu = -\beta$. Under these conditions the dark-field profile $y(s)$ can be determined by the equation[11,12]

$$s = \pm\int_y^0 \frac{[-2(\alpha+\beta)]^{-1/2}\mathrm{d}\tilde{y}}{\left[(\tilde{y}^2-1) - \dfrac{\rho+1}{\rho}\ln\left(\dfrac{1+\rho\tilde{y}^2}{1+\rho}\right)\right]^{1/2}}, \qquad (7)$$

from which $y(s)$ can be easily obtained by numerical integration, and thus the soliton family components can then be presented by $U_j{=}\rho^{1/2}c_j y(s)\exp(i\mu\xi)$. The dark screening–photovoltaic soliton family with five components ($c_1^2 = 0.30$, $c_2^2 = 0.25$, $c_3^2 = 0.20$, $c_4^2{=}$ 0.15, $c_5^2 = 0.10$) at $\rho = 10$, $\alpha + \beta = -89$ or $E_p + E_0{=}$ -1×10^6V/m in an $LiNbO_3$ crystal is shown in Fig.2. The intensity FWHM of the N dark beams is found to be 5.2μm. From Eq.(7), it can be shown that the FWHM of the soliton components of the dark soliton family is also inversely proportional to the square root of the absolute value of the sum of the externally applied electric field and the photovoltaic field.

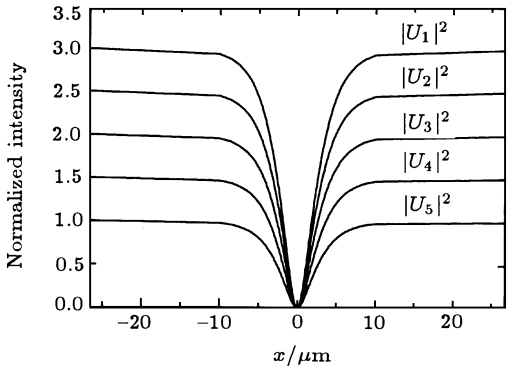


Fig.2. Soliton profiles for a dark screening–photovoltaic soliton family with five components ($c_1^2 = 0.30$, $c_2^2 = 0.25$, $c_3^2 = 0.20$, $c_4^2{=}$ 0.15, $c_5^2 = 0.10$) at $\rho{=}10$, $\alpha + \beta{=}-89$ in an $LiNbO_3$ crystal

V. CONCLUSION

It is shown that incoherently coupled screening–photovoltaic soliton families can exist in biased photovoltaic–photorefractive crystals under steady-state conditions. These screening–photovoltaic soliton families can be established provided that the incident beams have the same polarization, wavelength, and are mutually incoherent. It is found that the bright soliton families will be possible only when $E_p{+}E_0 > 0$, whereas the dark ones require $E_p + E_0 < 0$. It is also shown that the FWHM of the soliton components of the screening–photovoltaic soliton family is inversely proportional to the square root of the absolute value of the sum of the externally applied electric field and the photovoltaic field.

The screening–photovoltaic soliton families can be considered as the united form of the screening soliton families and the closed-circuit photovoltaic soliton families. They will become screening soliton families in the absence of the photovoltaic effect, whereas they degenerate to photovoltaic soliton families in the closed-circuit condition when the bias field is not applied. Moreover, such soliton families reduce to screening–photovoltaic soliton pairs when they contain only two components.

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