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Grey–grey incoherently coupled spatial soliton pairs in guest–host photorefractive polymers*

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We show that incoherently coupled grey–grey spatial soliton pairs can be established in guest–host photorefractive polymers under steady-state conditions, provided that their carrier beams have the same polarization, wavelength, and are mutually incoherent. The properties of these soliton pairs, such as their width and polarization, are discussed in detail.

Keywords: photorefractive effect, spatial solitons, photorefractive materials, photorefractive polymers

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In the last decade, optical spatial solitons in photorefractive materials have been actively investigated because of the fact that they can be formed at low light intensity. Up to the present, several generic types of photorefractive spatial solitons have been known: quasi-steady-state solitons,[1−4] screening solitons,[5−8] photovoltaic solitons,[9−14] screening-photovoltaic solitons,[15−22] spatial solitons in centrosymmetric photorefractive media,[23,24] and resonant self-trapping which occur in photorefractive semiconductors.[25,26] The quasi-steady-state solitons can exist in a biased photorefractive crystal over a time interval during which the externally applied field is slowly being screened by the space charge field.[1,2] Moreover, the quasi-steady-state solitons can also be induced by another laser beam.[3,4] The screening solitons are possible in steady state in a biased non-photovoltaic photorefractive crystal. They result from non-uniform screening of the bias field. The photovoltaic solitons can be established in steady state in photorefractive materials with a strong photovoltaic effect. These photovoltaic solitons rely on the photovoltaic effect to create the space charge field. The screening-photovoltaic solitons were shown to be able to exist in biased photovoltaic photorefractive crystal, they stem from both photovoltaic effect and non-uniform screening of the bias field.

All of the above-mentioned solitons can exist in inorganic photorefractive materials. Recently, a new type of dark, bright,[27] and grey[28] photorefractive spatial soliton was predicted in biased guest–host photorefractive polymers. Of all photorefractive polymers, guest–host photorefractive polymers which are made from photoconducting polymer hosts and doped with high levels of chromophores, are one of the most successful types of photorefractive polymers. Upon illumination, the photosensitizer in the guest–host photorefractive polymer contributes mobile charges, which redistribute following the spatial dependence of the optical intensity under the action of diffusion or externally applied field, and yield a space charge field. The space charge field then gives rise to the index change by means of orientational enhancement and electro-optic effect. The latter process is capable of counteracting the effect of diffraction, and thus the non-diffracting optical beam or polymeric soliton forms.

In 1996, Christodoulides *et al*[28,29] studied the incoherent coupling between two screening solitons. They showed theoretically that bright–bright, dark–

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dark, and bright–dark incoherently coupled soliton pairs can be established in biased non-photovoltaic photorefractive crystals, provided the two mutually incoherent incident beams have the same polarization and wavelength, and propagate collinearly. Soon afterwards, Chen *et al*[30−32] observed these incoherently coupled soliton pairs in biased strontium barium niobate (SBN) crystal in experiments. Very recently, we predicted that incoherently coupled soliton pairs can also be formed in biased photovoltaic photorefractive crystals[33−35] and in biased centrosymmetric photorefractive media.[36] In addition, we have found that incoherently coupled dark–dark and bright–bright soliton pairs can exist in the guest–host photorefractive polymer.[37] In this paper, we will show that incoherently coupled grey–grey spatial soliton pairs can also be supported in guest–host photorefractive polymer.

To investigate the incoherently coupled grey–grey soliton pairs in guest–host photorefractive polymer, let us consider two mutually incoherent optical beams (with the same wavelength and polarization) that propagate collinearly in a biased guest–host photorefractive polymer along the z-axis and permitted to diffract only along the x-direction. Moreover, the external bias field $E_{\rm ext}$ is assumed to be applied along the x-direction. The electric field components of the two optical beams are expressed in terms of slowly varying envelopes φ and ψ, i.e. $E_1 = \varphi(x,z)\exp(\mathrm{i}k_0 n_{\rm b} z)\sqrt{I_{\rm b}}$ and $E_2 = \psi(x,z)\exp(\mathrm{i}k_0 n_{\rm b} z)\sqrt{I_{\rm b}}$, where φ and ψ are the amplitudes of the slowly varying envelopes normalized by $\sqrt{I_{\rm b}}$, $I_{\rm b}$ is a uniform background illumination, $k = k_0 n_{\rm b}$, $k_0 = 2\pi/\lambda$, $n_{\rm b}$ is the unperturbed index of the polymer, and λ is the free-space wavelength of the light. Under the above conditions and using the dimensionless variables $\zeta = z/2kx_0^2$, $s = x/x_0$, where x_0 is an arbitrary spatial width, we obtain the following equations:[37]

$$\mathrm{i}\varphi_\zeta + \varphi_{ss} + \beta\left(\frac{\gamma+1}{|\varphi|^2+|\psi|^2+1}\right)^{2/(m+1)}\varphi = 0, \quad (1a)$$

$$\mathrm{i}\psi_\zeta + \psi_{ss} + \beta\left(\frac{\gamma+1}{|\varphi|^2+|\psi|^2+1}\right)^{2/(m+1)}\psi = 0, \quad (1b)$$

where $\varphi_\zeta = \partial\varphi/\partial\zeta$, $\varphi_{ss} = \partial^2\varphi/\partial s^2$, etc.; m is a material parameter that ranges from less than 1.0 to greater than 3.0, $\gamma = I_0/I_{\rm b}$, and

$$\beta = \beta_{x,y} = k_0^2 x_0^2 C_{x,y} E_0^2. \quad (2)$$

Here E_0 and I_0 are, respectively, the electric field and soliton intensity far away from the soliton centre, i.e. $E_0 = E(x \to \pm\infty, z)$, $I_0 = I(x \to \pm\infty, z)$. If the spatial extent of the optical beams is much less than the x-width of the photorefractive polymer, E_0 is approximately equal to $E_{\rm ext}$. The parameter $C_{x,y}$ in Eq.(2) is dependent on the polarization of the incident optical beam, which can be expressed as[25]

$$C_x = 0.54 N_{\rm ch}\Delta\alpha(\mu_{\rm D}/k_{\rm B}T_a)^2 \quad (3a)$$

and

$$C_y = -C_x/2 = -0.27 N_{\rm ch}\Delta\alpha(\mu_{\rm D}/k_{\rm B}T_a)^2 \quad (3b)$$

for x- and y-polarized light, respectively. In Eqs.(3), $N_{\rm ch}$ is the density of chromophores, $\mu_{\rm D}$ is the permanent dipole moment of the chromophores, $k_{\rm B}$ is the Boltzmann constant, T_a is the ambient temperature. $\Delta\alpha = \alpha_{//} - \alpha_\perp$, where $\alpha_{//}$ and $\alpha_\perp$ denote the polarizabilities of chromophores parallel and perpendicular to its dipole moment, respectively.

When $m = 1$, Eqs.(1a) and (1b) are actually the same as that for the soliton pairs in biased photorefractive crystals, for which the soliton pair solutions have been discussed in detail in Refs.[29, 34]. In what follows, we will give the grey–grey soliton pair solutions of Eqs.(1) for all $m \neq 1$. To get the grey–grey soliton pair solutions of Eqs.(1), we express φ and ψ in the form of[20,28,34]

$$\varphi(s,\zeta) = \gamma^{1/2}\cos\theta\, y(s)\exp\left\{\mathrm{i}\left[v\zeta + \int\frac{J\mathrm{d}s}{y^2(s)} + \Phi_0\right]\right\}, \quad (4a)$$

$$\psi(s,\zeta) = \gamma^{1/2}\sin\theta\, y(s)\exp\left\{\mathrm{i}\left[v\zeta + \int\frac{J\mathrm{d}s}{y^2(s)} + \Phi_0\right]\right\}, \quad (4b)$$

where v represents a nonlinear shift of the propagation constant, J is a real constant to be determined, θ is an arbitrary projection angle, and Φ_0 is an arbitrary phase. $y(s)$ satisfies the boundary conditions $y^2(s=0) = \delta$ $(0 < \delta < 1$, i.e. the intensity is finite at the origin), $\dot{y}(0) = 0$, $y(s \to \pm\infty) = 1$, and all the derivatives of $y(s)$ are also zero at infinity. Substitution of Eqs.(4) into Eqs.(1) yields the following ordinary differential equation:

$$\frac{\mathrm{d}^2 y}{\mathrm{d}s^2} - vy - \frac{J^2}{y^3} + \beta\left(\frac{1+\gamma}{1+\gamma y^2}\right)^{2/(m+1)} y = 0. \quad (5)$$

According to the boundary conditions of $y(s)$ at infinity, we find that

$$J^2 = \beta - v. \quad (6)$$

Equation (5) can be integrated once and leads to

$$\left(\frac{\mathrm{d}y}{\mathrm{d}s}\right)^2 = v(y^2-1)+(v-\beta)\left(\frac{1}{y^2}-1\right) - \frac{\beta(1+\gamma)}{\gamma}\frac{m+1}{m-1} \times\left[\left(\frac{1+\gamma y^2}{1+\gamma}\right)^{(m-1)/(m+1)}-1\right]. \quad (7)$$

Using the boundary conditions of $y(s)$ at zero, we obtain

$$v=\beta\left\{\frac{1}{1-\delta}+\frac{1+\gamma}{\gamma}\frac{\delta}{(1-\delta)^2}\frac{m+1}{m-1} \times\left[\left(\frac{1+\gamma\delta}{1+\gamma}\right)^{(m-1)/(m+1)}-1\right]\right\}. \quad (8)$$

From Eqs.(6) and (8) we know

$$\beta\left\{\frac{1+\gamma}{\gamma}\frac{\delta}{(1-\delta)^2}\frac{m+1}{m-1} \times\left[1-\left(\frac{1+\gamma\delta}{1+\gamma}\right)^{(m-1)/(m+1)}\right]-\frac{\delta}{1-\delta}\right\}>0. \quad (9)$$

By expanding

$$\left(\frac{1+\gamma\delta}{1+\gamma}\right)^{(m-1)/(m+1)} = \left[1-\frac{(1-\delta)\gamma}{1+\gamma}\right]^{(m-1)/(m+1)}$$

into series, we can prove that the quantity in the braces of inequality (9) is positive, so that we have

$$\beta>0, \quad (10)$$

that is, the incident optical beam are required to be x-polarized (y-polarized) for launching a grey–grey polymeric soliton pair for chromophores with its polarizability parallel to its dipole moments larger (smaller) than that perpendicular to it. By further integrating Eq.(7), we arrive at

$$s=\pm\int_{\sqrt{\delta}}^{y}\left\{v\left(\tilde{y}^2+\frac{1}{\tilde{y}^2}-2\right) -\beta\left(\frac{1}{\tilde{y}^2}-1\right)-\frac{\beta(1+\gamma)}{\gamma}\frac{m+1}{m-1} \times\left[\left(\frac{1+\gamma\tilde{y}^2}{1+\gamma}\right)^{(m-1)/(m+1)}-1\right]\right\}^{-1/2}\mathrm{d}\tilde{y}, \quad (11)$$

from which the normalized amplitude $y(s)$ can be easily obtained by numerical integration, and the grey–grey soliton pair components can then be obtained through a θ projection.

To illustrate our result, we set $\gamma = 10$, $m = 2.0$, $x_0 = 10\mu$m, T_a=300K, $E_0 = 70\mathrm{V}/\mu$m, and $\theta = 30°$. The polymer parameters are taken to be[38] $N_{ch} = 1.27\times10^{21}\mathrm{cm}^{-3}$, $\mu_D = 5.5\times10^{-18}$esu $= 1.83\times10^{-29}$C·m, and $\Delta\alpha = 3.9\times10^{-23}\mathrm{cm}^3$ at $\lambda = 690$nm. For this set of values, $\beta = \beta_x = 21.2$. Figure 1 depicts the normalized intensity profiles of a grey–grey polymeric soliton pair when $\beta = 21.2$, $\gamma = 10$, $\delta = 0.3$, $m = 2.0$, and $\theta = 30°$. Under these conditions, the FWHM intensity of the two components is found to be 8.2μm. Figure 2 provides the normalized FWHM of the grey–grey polymeric soliton pair as a function of γ for various values of δ when m=2.0. Figure 3 shows the dependence of the normalized FWHM of the grey–grey polymeric soliton pair on γ for different values of m when δ=0.1.

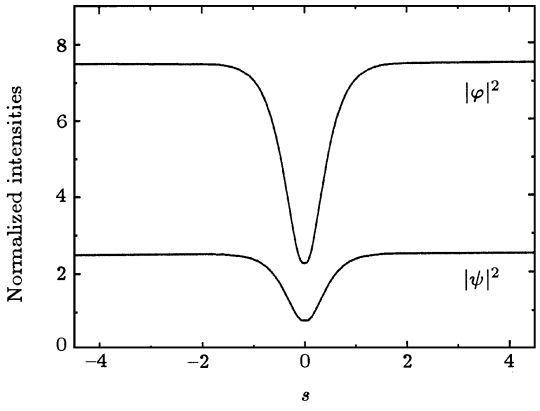


Fig.1. Soliton components, $|\varphi|^2$ and $|\psi|^2$, for a grey–grey polymeric soliton pair when $\beta = 21.2$, $\gamma = 10$, $\delta = 0.3$, $m = 2.0$ and $\theta = 30°$.

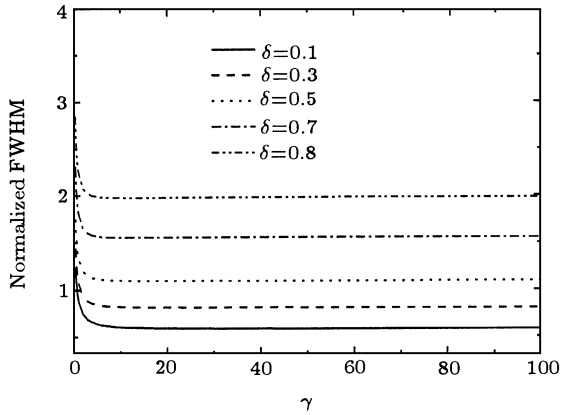


Fig.2. Normalized FWHM of a grey–grey polymeric soliton pair versus γ for various values of δ when $m = 2.0$.

According to Eqs.(2), (8) and (11), we conclude that the FWHM of the grey–grey polymeric soliton pair is inversely proportional to the absolute value of the external bias field. From Fig.2, one can find that for a given intensity ratio γ the FWHM of the grey–grey polymeric soliton pair becomes greater as the greyness parameter δ increases. Based on Fig.3,

we also see that for a given intensity ratio γ the grey–grey polymeric soliton pair tends to widen with the rise of the value of the material parameter m.

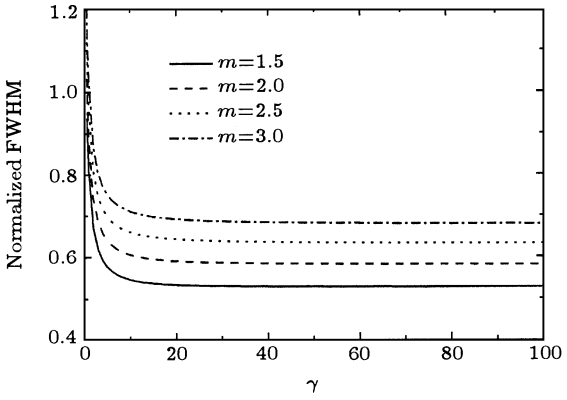


Fig.3. Dependence of the normalized FWHM of a grey–grey polymeric soliton pair on γ for different values of m when $\delta = 0.1$.

In conclusion, it is shown that the photorefractive polymer doped with nonlinear optical chromophores with its polarizability parallel to its dipole moment larger than its perpendicular polarizability can support x-polarized grey–grey incoherently coupled spatial soliton pairs, whereas the photorefractive polymer doped with nonlinear optical chromophores with its polarizability parallel to its dipole moment smaller than its perpendicular polarizability can support y-polarized grey–grey incoherently coupled spatial soliton pairs. These soliton pairs can be established provided that the two collinearly propagating optical beams have the same wavelength, polarization, and are mutually incoherent. It is found that the FWHM of the grey–grey polymeric soliton pair is inversely proportional to the absolute value of the external bias field. The dependences of the FWHM of the grey–grey polymeric soliton pair on the intensity ratio γ, greyness parameter δ, and material parameter m are also presented.

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