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Gray photorefractive polymeric optical spatial solitons

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ABSTRACT

We show that gray spatial optical solitons are possible in biased photorefractive polymers under steady-state conditions. We find that for a given material parameter the absolute value of a gray photorefractive polymeric soliton's phase decreases with an increase in the beam's grayness, whereas it increases with the material parameter for a given beam's grayness and that the full width half maximum (FWHM) of the gray soliton beam's intensity increases with the beam's grayness when the normalized background intensity and the material parameter are fixed and decreases with an increase in the normalized background intensity when the material parameter is fixed. On the other hand, we also show that N coupled beam evolution equations in biased photorefractive polymers can exhibit multicomponent gray solitons. These multicomponent gray solitons can be obtained provided that the N coupled beams share the same polarization, wavelength, and are incoherent with one another. The characteristics and stability properties of these multicomponent gray solitons are also discussed in detail.

Since their first experimental observation [1], photorefractive spatial solitons have attracted substantial research interest [2–20]. Many branches of photorefractive spatial solitons have been suggested, including quasi-steady-state solitons [1–3], screening solitons [4–7], photovoltaic solitons [8–10], screening-photovoltaic solitons [11–14], solitons in centrosymmetric photorefractive crystals [15], and solitons in photorefractive semiconductors [16]. Among these photorefractive solitons, screening solitons, photovoltaic solitons, and screening-photovoltaic solitons are those most thoroughly studied, all of which occur in steady state. To date, bright, dark, and gray solitons [5,7], bright–bright, dark–dark, and bright–dark soliton pairs [17], and multicomponent bright, multicomponent dark, and multicomponent bright–dark solitons [18] have been predicted under steady-state conditions. Recently, bright and dark solitons are addressed in biased photorefractive polymers, which are known as bright and dark photorefractive polymeric solitons [19,20]. Photorefractive polymers can provide many advantages over the traditional photorefractive inorganic crystals. These advantages include flexibility, cheapness, and ease of processing. However, gray solitons, gray–gray soliton pairs, and multicomponent gray solitons in biased photorefractive polymers have not been investigated yet.

In this paper, we show that gray spatial optical solitons are possible in biased photorefractive polymers under steady-state conditions. Our analysis indicates that the absolute value of a gray photorefractive polymeric soliton's phase decreases with an increase in the beam's grayness for a given material parameter and increases with the material parameter for a given beam's grayness and that the full width half maximum (FWHM) of the gray-soliton beam's intensity increases with the beam's grayness when the normalized background intensity and the material parameter are fixed and decreases with an increase in the normalized background intensity when the material parameter is fixed. Moreover, we also show that N coupled beam evolution equations in biased photorefractive polymers can exhibit multicomponent gray solitons. These multicomponent gray solitons can be obtained provided that the N coupled beams share the same polarization, wavelength, and are incoherent with one another. The functional form and characteristics of these multicomponent gray solitons are discussed and their stability properties are also considered.

To start, let us first consider an optical beam that propagates in a film of photorefractive polymer along the z axis and is allowed to diffract only along the x direction. Moreover, let us assume that the thickness of the photorefractive polymer thin film is oriented along the x coordinate and is

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about tens to hundreds of micrometers and that the external bias electric field is applied in the x direction. The electric field component $\mathbf{E}$ of the optical beam satisfies the Helmholtz equation

$$\nabla^2\mathbf{E} + (k_0 n_b')^2\mathbf{E} = 0, \tag{1}$$

where $k_0 = 2\pi/\lambda_0$ is the free-space wave vector, λ_0 is the common free-space wavelength, and n_b' is the nonlinear index of refraction. By expressing the optical field $\mathbf{E}$ in terms of slowly varying envelope ϕ, i.e., $\mathbf{E} = \mathbf{i}\phi(x,z)\exp(ikz)$, where $k = k_0 n_b$ is the propagation constant, n_b is the unperturbed refractive index, and $\mathbf{i}$ is the unit vector pointing to the x direction, we find that Eq. (1) leads to the following evolution equation

$$i\phi_z + \frac{1}{2k}\phi_{xx} + \frac{k_0\Delta\left(n_b'^2\right)}{2n_b}\phi = 0, \tag{2}$$

where $\Delta\left(n_b'^2\right) = n_b'^2 - n_b^2$, $\phi_z = \partial\phi/\partial z$, etc. For typical photorefractive polymers, the index changes for x- and y-polarized lights are approximately given by [19]

$$\Delta\left(n_b'^2\right)_x = (C_{BR} + C_{EO})E^2, \tag{3}$$

$$\Delta\left(n_b'^2\right)_y = (-C_{BR}/2 + C_{EO}/3)E^2, \tag{4}$$

where $C_{BR} = (2/45)(4\pi N_{ch})\Delta\alpha(\mu_D/k_B T_a)^2$, N_{ch} is the number density of the chromophores, $\Delta\alpha = \alpha_{//} - \alpha_{\perp}$, α is the molecular optical polarizability, μ_D is the molecular permanent dipole moment, k_B is the Boltzmann constant, T_a is the absolute temperature, $C_{EO} = (1/5)(4\pi N_{ch})\beta_{333}(\mu_D/k_B T_a)$, β_{333} is the effective molecular optical hyperpolarizability tensor, and E is the electric field. Moreover, the electric field can be obtained from the model equations [21] and it is given by [19]

$$E^{m+1} = E_\infty^{m+1}\frac{I_\infty + I_b}{I + I_b}, \tag{5}$$

where $I = I(x,z)$ is the power density of the optical beam and it is related to the slowly varying envelope ϕ through Poynting's theorem, i.e., $I = (n_b/2\eta_0)|\phi|^2$. In Eq. (5), m is a material parameter ranging from less than 1.0 to greater than 3.0, I_b is the background illumination, E_∞ and I_∞ are, respectively, the constant electric field and the constant power density, away from the center of the optical beam. Substitution of Eq. (5) into Eqs. (3) and (4) yields the following relation:

$$\Delta\left(n_b'^2\right) = C_{x,y}E_\infty^2\left(\frac{I_\infty + I_b}{I + I_b}\right)^{2/(m+1)}, \tag{6}$$

where $C_x = C_{BR} + C_{EO}$ and $C_y = -C_{BR}/2 + C_{EO}/3$. For convenience, let us adopt the following dimensionless variables and coordinates: $\phi = (2\eta_0 I_b/n_b)^{1/2}U$, $\xi = z/\left(kx_0^2\right)$, and $s = x/x_0$, where x_0 is an arbitrary spatial width. By employing these latter transformations and by substituting Eq. (6) into Eq. (2), the normalized envelope U is found to satisfy

$$iU_\xi + \frac{1}{2}U_{ss} + \frac{(k_0x_0)^2C_{x,y}E_\infty^2}{2}\left(\frac{\rho + 1}{1 + |U|^2}\right)^{2/(m+1)}U = 0, \tag{7}$$

where $\rho = I_\infty/I_d$ is the normalized background intensity. Notice that $C_{x,y}>0$ corresponds to dark solitons, whereas $C_{x,y}<0$ corresponds to bright solitons [19]. In the limit $C_{x,y}>0$ and choosing the characteristic length $x_0 = \sqrt{2}/\left(k_0E_\infty\sqrt{C_{x,y}}\right)$, we rewrite Eq. (7) as

$$iU_\xi + \frac{1}{2}U_{ss} + \left(\frac{\rho + 1}{1 + |U|^2}\right)^{2/(m+1)}U = 0. \tag{8}$$

In what follows, we will discuss the possible gray soliton solutions of Eq. (8).

Let us first express the normalized envelope U in the following fashion [5]:

$$U = \rho^{1/2}y(s)\exp\left[i\left(\nu\xi + \int_0^s\frac{\Gamma ds'}{y^2(s')}\right)\right], \tag{9}$$

where ν is a nonlinear shift of the propagation constant, $y(s)$ is an even function of s, and Γ is a real constant to be determined. For gray solitons one requires the boundary conditions $y(s\to\pm\infty) = 1$, $y'(s=0) = 0$, $y^2(s=0) = \delta$ $(0<\delta<1)$, $y'(s\to\pm\infty) = 0$, and $y''(s\to\pm\infty) = 0$. Notice that the parameter δ describes the soliton grayness. Substitution of Eq. (9) into Eq. (8) leads to

$$y'' - 2\nu y - \frac{\Gamma^2}{y^3} + 2\left(\frac{\rho + 1}{\rho y^2 + 1}\right)^{2/(m+1)}y = 0, \tag{10}$$