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Grey screening-photovoltaic soliton-induced waveguides*

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This paper shows that waveguides induced by grey screening-photovoltaic solitons are always single mode for all intensity ratios, which are the ratio between the peak intensity of the soliton and the dark irradiance. It finds that the confined energy near the centre of the grey soliton and the propagation constant of the guided mode increase monotonically with increasing intensity ratio. On the other hand, when the soliton greyness increases, the confined energy near the centre of the grey soliton and the propagation constant of the guided mode reduce monotonically. When the bulk photovoltaic effect is neglected for short circuits, these waveguides become waveguides induced by grey screening solitons. When the external bias field is absent, these waveguides become waveguides induced by grey photovoltaic solitons.

Keywords: soliton waveguide, photorefractive effect, nonlinear optics
PACC: 4280, 7240, 4265

1. Introduction

Photorefractive (PR) spatial solitons have attracted a great deal of attention because of their possible applications for optical switching and routing.[1−18] At present, two generic types of steady state soliton are known: screening solitons[7] and photovoltaic (PV) solitons,[8,9] all of which exist in bright, dark, and grey forms. Very recently, we have shown theoretically that the application of an external field enables steady-state screening-PV solitons in PR–PV crystals,[10−12] which were demonstrated experimentally.[13] These solitons can propagate in bright, dark, and grey configurations.[12] In particular, screening-PV solitons change into screening solitons when the bulk PV effect is neglected for short circuits, and PV solitons when the external field is absent.[10] However, PR spatial solitons induce waveguides that offer potential applications, some of which are truly unique[8,14]: three-dimensional optical circuitry,[14] reconfigurable near-field interconnects,[15] nonlinear frequency conversion,[8] directional coupling,[16] and beam steering.[17] Waveguides induced by bright and dark screening solitons have been demonstrated.[18] Another interesting class of solitary waves is grey solitons, which are by nature more complicated. Evidently, it would be of interest to know if such grey solitons induce waveguides.

In this paper, we show that a waveguide induced by a grey screening-PV soliton has a single guiding mode, of which the confined energy increases monotonically with the intensity ratio between the peak intensity of the soliton and the dark irradiance, and the propagation constant of the guided mode of the waveguide induced by the grey screening-PV soliton is monotonically increasing with intensity ratio. We find that when the soliton greyness is increased, the confined energy near the centre of the grey soliton and the propagation constant of the guided mode reduce monotonically. Our analysis indicates that these waveguides are waveguides induced by grey screening solitons when the bulk PV effect is neglected for short circuits and predict waveguides induced by grey PV solitons when the external bias field is absent.

2. Theory and results

To study waveguides induced by grey screening-PV solitons, let us first consider an optical beam that propagates in a PR–PV material along the z axis and

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is allowed to diffract only along the x direction. Moreover, let us assume that the optical beam is linearly polarized along the x coordinate and the external bias electric field is applied in the same direction. In this case, the perturbed extraordinary refractive index $n'_{\rm e}$ (along the c-axis) is given by $n'^2_{\rm e} = n^2_{\rm e} - n^4_{\rm e} r_{33} E_{\rm sc}$,[7] where $n_{\rm e}$ is the unperturbed extraordinary index of refraction, r_{33} is the electro-optic coefficient, and $\boldsymbol{E}_{\rm sc} = \boldsymbol{i} E_{\rm sc}$ is the space-charge field induced in this PR-PV material, $\boldsymbol{i}$ is the unit vector pointing to the x direction. The electric-field component $\boldsymbol{E}$ of the optical beam is then expressed in terms of slowly varying envelope φ, i.e., $\boldsymbol{E} = \boldsymbol{i}\varphi(x,z)\exp(\mathrm{i}kz)$, where $k = k_0 n_{\rm e} = (2\pi/\lambda_0)\, n_{\rm e}$ is the propagation constant and λ_0 is the common free-space wavelength. Under these conditions, it can be readily shown that the envelope φ obeys the following evolution equation:[7]

$$\mathrm{i}\varphi_z + \frac{1}{2k}\varphi_{xx} - \frac{k_0\left(n^3_{\rm e} r_{33} E_{\rm sc}\right)}{2}\varphi = 0, \tag{1}$$

where $\varphi_z = \partial\varphi/\partial z$, etc. On the other hand, under steady-state conditions and for typical PR crystals, the induced space-charge field can be directly obtained from the Vinetskii–Kukhtarev transport model and is given by[2,10,12]

$$E_{\rm sc} = E_0 \frac{I_\infty + I_{\rm d}}{I + I_{\rm d}} + E_{\rm p}\frac{I_\infty - I}{I + I_{\rm d}}, \tag{2}$$

where $I = I(x,z)$ is the power density of the optical beam, $I_{\rm d}$ is the so-called dark irradiance, $I_\infty = I(x \to \pm\infty, z)$, $E_{\rm p} = \kappa\gamma N_{\rm A}/(q\mu)$ is the PV field constant, $N_{\rm A}$ is the number density of negatively charged acceptors, γ is the recombination rate, κ is the PV constant, μ is the electron mobility, and q is the electron charge. The constant field E_0 can be determined from the potential condition $\oint E_{\rm sc}\cdot \mathrm{d}l = 0$ and is given by[2,12] $E_0 = -(V_0\eta + E_{\rm p}\sigma\eta - RJS\eta)$, where $\eta = 1/\int_{-l/2}^{l/2}(I_\infty + I_{\rm d})(I + I_{\rm d})^{-1}\mathrm{d}x$, $\sigma = \int_{-l/2}^{l/2}(I_\infty - I)(I + I_{\rm d})^{-1}\,\mathrm{d}x$, R is the external resistance, S is the surface area of the electrodes, $\boldsymbol{J} = J\boldsymbol{i}$ is the electric current density, and V_0 is the external voltage applied to the crystal between electrodes separated by distance l. The beam power density I can be expressed in terms of the envelope φ by use of Poynting's theorem, i.e. $I = (n_{\rm e}/2\eta_0)\,|\varphi|^2$, where $\eta_0 = (\mu_0/\varepsilon_0)^{1/2}$ is the vacuum intrinsic impedance. For convenience, let us adopt the following dimensionless coordinates and variables: $\varphi = (2\eta_0 I_{\rm d}/n_{\rm e})^{1/2} U$, $\xi = z/(kx_0^2)$, and $s = x/x_0$, where x_0 is an arbitrary spatial width. By employing these latter transformations and by substituting Eq.(2) into Eq.(1), we find that the normalized envelope U satisfies

$$\mathrm{i}U_\xi + \frac{1}{2}U_{\rm ss} + (\beta + \alpha - \tau)(\rho + 1)\frac{U}{1 + |U|^2} - \delta\frac{\left(\rho - |U|^2\right)U}{1 + |U|^2} = 0, \tag{3}$$

where $\rho = I_\infty/I_{\rm d}$, $\beta = (k_0x_0)^2(n^4_{\rm e}r_{33}\eta/2)V_0$, $\alpha = (k_0x_0)^2(n^4_{\rm e}r_{33}\eta\sigma/2)E_{\rm p}$, $\tau = (k_0x_0)^2(n^4_{\rm e}r_{33}\eta/2)RJS$, and $\delta = (k_0x_0)^2(n^4_{\rm e}r_{33}/2)E_{\rm P}$. To obtain the grey screening-PV soliton solutions of Eq.(3), let us express U in the following fashion:[7]

$$U = \rho^{1/2}\phi(s)\exp\left[\mathrm{i}\left(\nu\xi + \int_0^s \frac{\Gamma\mathrm{d}s'}{\phi^2(s')}\right)\right], \tag{4}$$

where ν is a nonlinear shift of the propagation constant, $\phi(s)$ is a normalized function bounded between $0 \le \phi(s) \le 1$, and Γ is a real constant to be determined. Substitution of Eq.(4) into Eq.(3) leads to

$$\phi'' - 2\nu\phi - \frac{\Gamma^2}{\phi^3} + 2(\beta + \alpha - \tau)(\rho + 1)\frac{\phi}{1 + \rho\phi^2} - 2\delta\rho\frac{(1 - \phi^2)\phi}{1 + \rho\phi^2} = 0, \tag{5}$$

where $\phi'' = \mathrm{d}^2\phi/\mathrm{d}s^2$, etc. For grey solitons one requires the boundary conditions: $\phi(0) = \sqrt{m}$, $\phi(s \to \pm\infty) = 1$, $\phi'(0) = 0$, and $\phi'(s \to \pm\infty) = \phi''(s \to \pm\infty) = 0$. The m parameter $(0 < m < 1)$ describes the soliton greyness. Substituting the boundary conditions $\phi(s \to \infty) = 1$, $\phi''(s \to \infty) = 0$, and $s \to \infty$ into Eq.(5) we get

$$\Gamma^2 = -2[\nu - (\beta + \alpha - \tau)]. \tag{6}$$

By integrating Eq.(5) and by employing the boundary conditions $\phi(s \to \infty) = 1$, $\phi'(s \to \infty) = 0$, $\phi'(0) = 0$, and $\phi^2(0) = m$, we find that

$$\nu = \frac{\delta m}{m - 1} - \frac{1}{(m-1)^2}\left[m(\delta - \beta - \alpha + \tau)\frac{\rho + 1}{\rho}\ln\left(\frac{1 + \rho m}{1 + \rho}\right) - (\beta + \alpha - \tau)(1 - m)\right], \tag{7}$$

$$(\phi')^2 = 2(\nu - \delta)\left(\phi^2 - 1\right) + 2(\nu - \beta - \alpha + \tau)\left(\frac{1 - \phi^2}{\phi^2}\right) + 2(\delta - \beta - \alpha + \tau)\frac{\rho + 1}{\rho}\ln\left(\frac{1 + \rho\phi^2}{1 + \rho}\right), \tag{8}$$

from which the grey envelope $\phi(s)$ can be obtained by numerical integration. After the grey screening-PV soliton has formed, the space-charge field is presented in the PR material, which gives rise to a change in the refractive index. Let us consider a probe beam propagating in this soliton-induced waveguide. The optical field $\bar{\boldsymbol{E}}_{\rm opt}$ of the probe beam is then expressed in terms of a slowly varying envelope ψ, i.e., $\bar{\boldsymbol{E}}_{\rm opt}(x,z,t) = \boldsymbol{i}\psi(x)\exp\left(\mathrm{i}\bar{\beta}z - \mathrm{i}\bar{\varpi}t\right)$, where $\bar{\varpi}$ is the frequency of the probe beam and $\bar{\beta}$ is the propagation constant. In this case, the refractive index $\bar{n}$ for paraxial approximation is given by $\bar{n}^2 = \bar{n}_{\rm e}^2 - \bar{n}_{\rm e}^4\bar{r}_{33}E_{\rm sc}$,[18] where $\bar{n}_{\rm e}$ and $\bar{r}_{33}$ are the values of unperturbed refractive index and the electro-optic coefficient at the new frequency $\bar{\varpi}$ respectively. The wave equation for the slowly varying amplitude $\psi(x)$ is

$$\frac{\mathrm{d}^2\psi}{\mathrm{d}x^2} + \left[\bar{k}_0^2\bar{n}^2(x) - \bar{\beta}^2\right]\psi = 0, \tag{9}$$

where $\bar{k}_0 = 2\pi/\bar{\lambda}_0$ is the wave vector in vacuum, $\bar{\lambda}_0$ is the common free-space wavelength used. Substituting $\bar{n}^2 = \bar{n}_{\rm e}^2 - \bar{n}_{\rm e}^4\bar{r}_{33}E_{\rm sc}$ and Eq.(2) into Eq.(9) we get

$$\frac{\mathrm{d}^2\psi}{\mathrm{d}\bar{s}^2} = \left\{\bar{\tau} - \frac{(\beta+\alpha-\tau)(\rho+1)}{1+\rho\phi^2\left(\bar{s}/\sqrt{2}\sigma_1\sigma_2\right)} - \frac{\delta\rho\left[\phi^2\left(\bar{s}/\sqrt{2}\sigma_1\sigma_2\right)-1\right]}{1+\rho\phi^2\left(\bar{s}/\sqrt{2}\sigma_1\sigma_2\right)}\right\}\psi, \tag{10}$$

where the normalized propagation constant $\bar{\tau}$, the new normalized length $\bar{s}$, and normalization factors σ_1 and σ_2 are defined as

$$\bar{\tau} = \frac{\bar{\beta}^2 - \sigma_1^2k^2}{2\sigma_1^2\sigma_2^2/x_0}, \tag{11}$$

$$\bar{s} = \sqrt{2}\sigma_1\sigma_2 s, \tag{12}$$

$$\sigma_1 = \frac{\bar{n}_{\rm e}}{n_{\rm e}}\frac{\lambda}{\bar{\lambda}}, \tag{13}$$

$$\sigma_2 = \frac{\bar{n}_{\rm e}}{n_{\rm e}}\sqrt{\frac{\bar{r}_{33}}{r_{33}}}. \tag{14}$$

In the above equations, $\bar{\tau}$ must be in the range between $(\beta+\alpha-\tau)$ and $\dfrac{(\beta+\alpha-\tau)(1+\rho)+\delta\rho(m-1)}{1+m\rho}$ to fulfill the condition that the propagation constant of a guided mode, $\bar{\beta}$, lies between the maximum and the minimum values of the refractive index $\bar{n}_{\rm e}(x)$ times the wave vector $\bar{k}_0$.[18] We now wish to find the modes of the waveguide, $\psi(\bar{s})$, in a waveguide induced by the grey soliton $\phi(s)$. First, let us solve Eq.(8) numerically for various values of ρ and find the soliton wave forms $\phi(s)$. We then solve Eq.(10) for $\psi(\bar{s})$ by the shooting method. As an example, let us consider the $LiNbO_3$ crystal with the following parameters: $n_{\rm e} = 2.2$, $r_{33} = 30\times10^{-12}\,\mathrm{m/V}$, and $E_{\rm p} = 40\,\mathrm{kV/cm}$. Let us also assume that $\lambda_0 = 0.5\,\mu\mathrm{m}$, $l = 1\,\mathrm{cm}$, $R = 0$, and $x_0 = 40\,\mu\mathrm{m}$. Notice that $R = 0$ signifies that the potential difference produced by the external resistance may be neglected in $\oint \boldsymbol{E}_{\rm sc}\cdot\mathrm{d}l = 0$. Figure 1 shows the normalized envelope of the grey screening-PV soliton ϕ and the normalized envelope of the single guided mode ψ for three different values of ρ when $V_0 = 20000\,\mathrm{V}$, $m = 0.2$, and $\alpha_1\alpha_2 = 0.697$. This figure demonstrates that the bigger ρ, the more confined is the optical energy near the centre of the grey screening-PV soliton. Figure 2 depicts the normalized envelope of the grey screening-PV soliton ϕ and the normalized envelope of the single guided mode ψ for three different values of m when $V_0 = 10000\,\mathrm{V}$, $\rho = 5$, and $\alpha_1\alpha_2 = 0.697$. Evidently, the confined energy near the centre of the grey screening-PV soliton reduces when m increases. Figure 3 plots the propagation constant as a function of ρ for $\alpha_1\alpha_2 = 0.697$ and $V_0 = 10000\,\mathrm{V}$, where $m = 0.1$, 0.3 and 0.5. The number of guided modes at each ρ is given by the number of intersections of the dash-dot vertical line with the curve of the propagation constant in Fig.3.[18] The dash-dot line corresponds to $\rho = 5$ (the examples given in Fig.2). It reveals that waveguides induced by grey screening-PV solitons are always single mode for all intensity ratios. From Fig.3 it is also apparent that the propagation constant increases monotonically with increasing ρ. On the other hand, in Fig.3 we show that when the soliton greyness is increased, the propagation constant reduces monotonically.

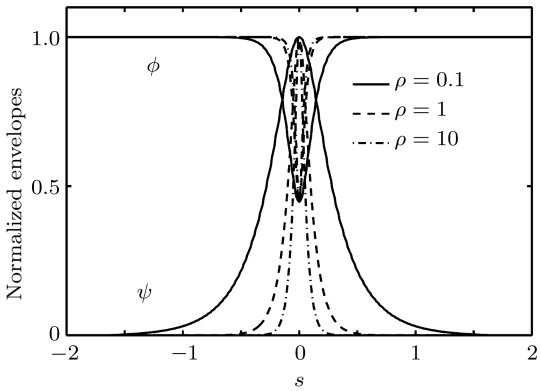


Fig.1. Normalized field profiles of the grey screening-photovoltaic soliton (solid, dashed, and dash-dot curves) and the single guided mode (solid, dashed, and dash-dot curves) of the soliton-induced waveguide at $\rho = 0.1$, 1, and 10 when $V_0 = 20000\,\mathrm{V}$, $m = 0.2$, and $\alpha_1\alpha_2 = 0.697$. $\psi(s)$ is normalized to the maximum of $\psi(s)$.

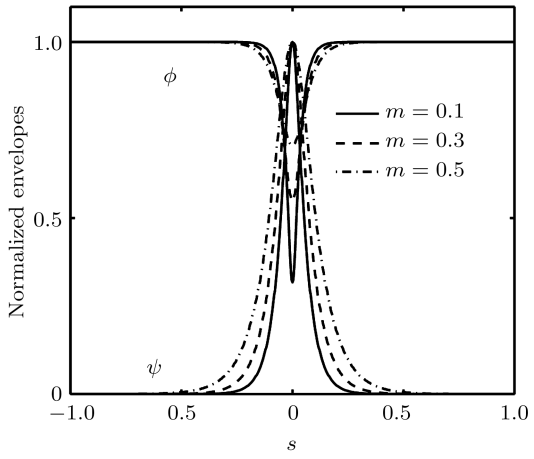


Fig.2. Normalized field profiles of the grey screening-photovoltaic soliton (solid, dashed, and dash-dot curves) and the single guided mode (solid, dashed, and dash-dot curves) of the soliton-induced waveguide at $m = 0.1$, 0.3 and 0.5 when $V_0 = 10000\,\mathrm{V}$, $\rho = 5$, and $\alpha_1\alpha_2 = 0.697$. $\psi(s)$ is normalized to the maximum of $\psi(s)$.

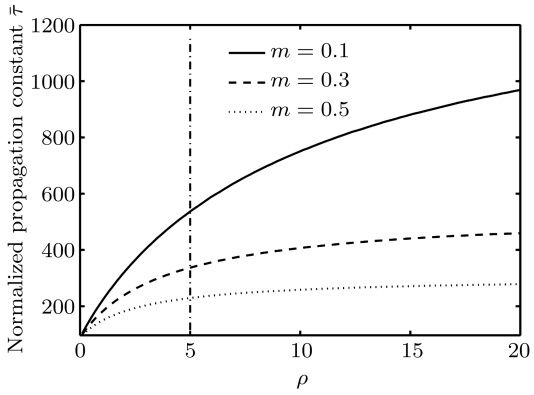


Fig.3. Propagation constants of the guided modes of the waveguide induced by the grey screening-photovoltaic soliton at $m = 0.1$, 0.3, and 0.5 when $V_0 = 10000\,\mathrm{V}$, $\rho = 5$, and $\alpha_1\alpha_2 = 0.697$.

3. Discussion

The properties of waveguides induced by grey screening-PV solitons will now be discussed. First of all, when the bulk PV effect is neglected for short circuits ($R = 0$), i.e., $\delta = \alpha = \tau = 0$, our physical system becomes the physical system of waveguides induced by grey screening solitons and grey screening-PV solitons become grey screening solitons, i.e., Eqs.(3)–(8) have the same dimensionless parameters and form as Eqs.(25) and (30)–(34) in Ref.[7]. In this case, Eqs.(7), (8) and (10) yield

$$\nu = \frac{\left(-\hat{\beta}\right)}{(m-1)^2}\left[\frac{m(\rho+1)}{\rho}\ln\left(\frac{1+\rho m}{1+\rho}\right) + (1-m)\right], \tag{15}$$

$$(\phi')^2 = 2\nu\left(\phi^2-1\right) + 2\left(\nu+\hat{\beta}\right)\left(\frac{1-\phi^2}{\phi^2}\right) + \frac{2\hat{\beta}}{\rho}(\rho+1)\ln\left(\frac{1+\rho\phi^2}{1+\rho}\right), \tag{16}$$

$$\frac{\mathrm{d}^2\psi}{\mathrm{d}\bar{s}^2} = \left\{\bar{\tau} + \frac{\hat{\beta}(\rho+1)}{1+\rho\phi^2\left(\bar{s}/\sqrt{2}\sigma_1\sigma_2\right)}\right\}\psi, \tag{17}$$

where $\hat{\beta} = (k_0x_0)^2(n_\mathrm{e}^4 r_{33}/2)E_0 = -\beta$. The above equations show that waveguides induced by grey screening solitons are possible. As an example, let us assume that the SBN crystal, of which parameters are taken to be $n_\mathrm{e} = 2.33$ and $r_{33} = 224\times10^{-12}\,\mathrm{m/V}$ at a wavelength $\lambda_0 = 0.5\mu\,\mathrm{m}$, is biased by $V_0 = 1000$, 3000, and 5000 V. Let us also assume that $\rho = 10$, $m = 0.3$, and $\alpha_1\alpha_2 = 0.697$. Figure 4 shows the normalized envelope of the grey screening-PV soliton ϕ and the normalized envelope of the single guided mode ψ obtained under these conditions. If the external bias field is absent, i.e., $\beta = 0$, our physical system becomes the physical system of waveguides induced by grey PV solitons. The absence of the external bias field signifies the two cases: an open circuit ($J = 0$) and a closed circuit ($J \neq 0$). Here, the electric current density J is given by[10,12]

$$\hat{J} = \frac{I_\infty + \eta(RSJ/E_\mathrm{P} - \sigma)(I_\infty + I_\mathrm{d})}{I_\mathrm{d}}, \tag{18}$$

where $\hat{J} = J/(\hat{s}I_\mathrm{d}N_\mathrm{D}\kappa)$, N_D is the total donor density, and $\hat{s}$ is the photoexcitation cross section. Thus, when $\beta = 0$, waveguides induced by grey screening-PV solitons become waveguides induced by grey PV solitons for either closed-circuit or open-circuit conditions. Substituting $\beta = 0$ and Eq.(18) into Eqs.(7), (8) and (10) we get

$$\nu = \frac{\delta m}{m-1} - \frac{\delta}{(m-1)^2}\left[m\left(1+\frac{\hat{J}-\rho}{\rho+1}\right)\frac{\rho+1}{\rho}\ln\left(\frac{1+\rho m}{1+\rho}\right) + \frac{\left(\hat{J}-\rho\right)(1-m)}{\rho+1}\right], \tag{19}$$

$$(\phi')^2 = 2(\nu-\delta)\left(\phi^2-1\right) + 2\left[\nu + \frac{\delta\left(\hat{J}-\rho\right)}{\rho+1}\right]\left(\frac{1-\phi^2}{\phi^2}\right) + 2\delta\left(1+\frac{\hat{J}-\rho}{\rho+1}\right)\frac{\rho+1}{\rho}\ln\left(\frac{1+\rho\phi^2}{1+\rho}\right), \quad (20)$$

$$\frac{\mathrm{d}^2\psi}{\mathrm{d}\bar{s}^2} = \left\{\bar{\tau} + \frac{\delta\left[\hat{J}-\rho\phi^2\left(\bar{s}/\sqrt{2}\sigma_1\sigma_2\right)\right]}{1+\rho\phi^2\left(\bar{s}/\sqrt{2}\sigma_1\sigma_2\right)}\right\}\psi, \quad (21)$$

which predict waveguides induced by grey PV solitons for closed and open circuits. On the other hand, some PV materials (for example, $BaTiO_3$) possess PV constants κ (i.e., E_p) which change sign under polarization rotation.[9] Let us assume that the PV field constant of the $LiNbO_3$ crystal can change by rotating the polarization of the light. The normalized envelope of the grey PV soliton ϕ and the normalized envelope of the single guided mode ψ obtained at $R=0$, $\rho=10$, $m=0.5$, and $\alpha_1\alpha_2=0.697$ for three different values of E_p are shown in Fig.5. A close examination of Fig.4 (5) reveals that the confined energy near the centre of the grey screening (PV) soliton increases with increasing external voltage V_0 (PV field constant E_p). Similar plots are obtained also for grey screening-PV solitons, which indicate that the confined energy near the centre of the grey screening-PV soliton increases with increasing external voltage V_0 or increasing PV field constant E_p. On the other hand, similar Figs.1 and 2 can be obtained for grey screening solitons and grey PV solitons. We conclude that the confined energy near the centre of the PR steady-state grey soliton (screening solitons, PV solitons, and screening-PV solitons) increases monotonically with increasing intensity ratio and reduce monotonically with increasing soliton greyness.

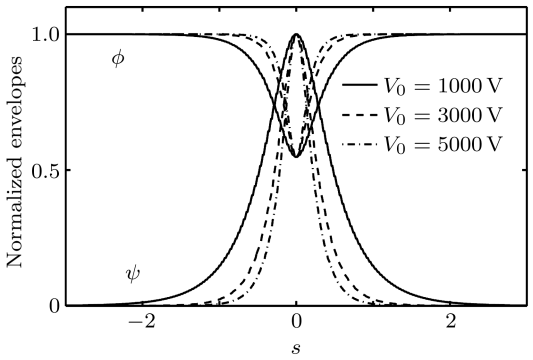


Fig.4. Normalized field profiles of the grey screening soliton (solid, dashed, and dash–dot curves) and the single guided mode (solid, dashed, and dash–dot curves) of the soliton-induced waveguide at $V_0 = 1000$, 3000, and 5000 V when $m=0.3$, $\rho=10$ and $\alpha_1\alpha_2=0.697$. $\psi(s)$ is normalized to the maximum of $\psi(s)$.

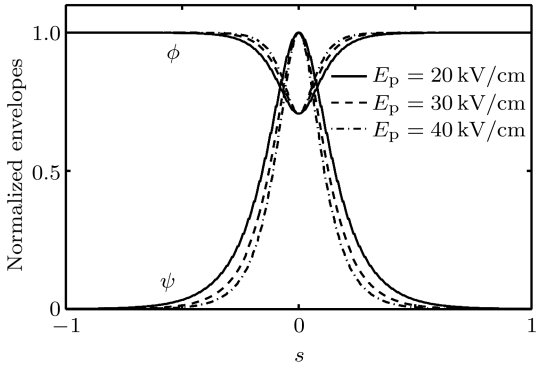


Fig.5. Normalized field profiles of the grey photovoltaic soliton (solid, dashed, and dash-dot curves) and the single guided mode (solid, dashed, and dash-dot curves) of the soliton-induced waveguide at $E_\mathrm{p} = 20$, 30, and 40 kV/cm for short circuits when $R=0$, $m=0.5$ $\rho=10$, and $\alpha_1\alpha_2=0.697$. $\psi(s)$ is normalized to the maximum of $\psi(s)$.

4. Conclusion

In conclusion, we have shown that waveguides induced by grey screening-PV solitons are always single mode for all intensity ratios. We have found that the confined energy near the centre of the grey soliton and the propagation constant of the guided mode increase monotonically with intensity ratio and reduce monotonically with increasing soliton greyness. Our analysis indicates that under appropriate conditions, these waveguides are waveguides induced by grey screening solitons and by grey PV solitons.

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