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UNIVERSAL THEORY OF STEADY-STATE ONE-DIMENSIONAL PHOTOREFRACTIVE SOLITONS*

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A universal theory of steady-state one-dimensional photorefractive spatial solitons is developed which applies to the steady-state one-dimensional photorefractive solitons under various realizations, including the screening solitons in a biased photorefractive medium, the photovoltaic solitons in open- and closed-circuit photovoltaic–photorefractive media and the screening-photovoltaic solitons in biased photovoltaic–photorefractive media. Previous theories advanced individually elsewhere for these solitons can be obtained by simplifying the universal theory under the appropriate conditions.

Keywords: nonlinear optics, spatial optical solitons, photorefractive effects
PACC: 4265J, 7820, 7240

I. INTRODUCTION

In the last decade there has been a growing interest in optical spatial solitons in photorefractive media.[1−12] At present, three types of steady-state photorefractive solitons (screening solitons,[1−6] open- and closed-circuit photovoltaic solitons[7−9] and screening-photovoltaic (SP) solitons[10−12]) have been predicted, and the first two have been found experimentally.

Screening solitons in the steady state are possible when an external bias voltage is appropriately applied to a non-photovoltaic–photorefractive crystal.[1−6]. These screening solitons result from non-uniform screening of the bias field. Photovoltaic solitons in the steady state are possible in open- or closed-circuit photovoltaic–photorefractive crystals without a bias field. These photovoltaic solitons result from the photovoltaic effect.[7−9] Recently, it has been predicted theoretically that the SP solitons in the steady state are possible when an external electric field is applied to a photovoltaic–photorefractive crystal.[10−13] These SP solitons result from both the photovoltaic effect and spatially non-uniform screening of the applied field.

The theories of the three types of steady-state photorefractive solitons have been advanced individually. For example, Christodoulides *et al.*[4] established the theory of screening solitons in a biased photorefractive crystal without a resistor in the external circuit; Valley *et al.*[8] established the theory of open-circuit photovoltaic solitons in a photovoltaic–photorefractive crystal; Segev *et al.*[7] established the theory of both open- and closed-circuit photovoltaic solitons in a photovoltaic–photorefractive crystal with a resistor in the external circuit; Liu *et al.*[11] established the theory of SP solitons in a biased photovoltaic–photorefractive crystal without a resistor in the external circuit. However, a universal theory has not been developed that can describe the three types of the steady-state one-dimensional photorefractive solitons under various realizations. Although the theory of SP solitons established in Ref.[11] can also be used to describe the closed-circuit photovoltaic solitons and screening solitons, it is incomplete because it cannot describe the open-circuit photovoltaic solitons as well as closed-circuit photovoltaic, screening and SP solitons under the realization that a resistor is loaded on the external circuit.

In this paper, we reconsider the problem of one-dimensional bright and dark photorefractive solitons and analyse their formation in biased photorefractive as well as biased and unbiased photovoltaic–photorefractive media under open- and the closed-circuit realizations with a resistor in the external circuit. A universal theory of steady-state one-dimensional photorefractive spatial solitons is developed that describes the three types of steady-state

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one-dimensional spatial solitons including: the screening solitons in a biased photorefractive medium with a resistor in the external circuit; the photovoltaic solitons in an open-circuit photovoltaic–photorefractive medium; the photovoltaic solitons in a closed-circuit unbiased photovoltaic–photorefractive medium with a resistor in the external circuit and the SP solitons in a biased photovoltaic–photorefractive medium with a resistor in the external circuit. Previous theories advanced individually elsewhere for these solitons can be obtained by simplifying the universal theory under the appropriate conditions.

II. THEORETICAL ANALYSIS

Figure 1 illustrates the configuration discussed in the paper. The electrical circuit consists of a photorefractive or photovoltaic–photorefractive crystal, an external electric field with voltage bias $V_{\rm a}$ and an external resistor with resistance R. Let V_0 and E_0 denote the potential and the electric field strength measured between the crystal's electrodes at a separation W, respectively. If the spatial extent of the optical wave is much less than W, we have the following approximate expression: $E_0 = V_0/W$. Letting J denote the current density in the circuit and V_R denote the potential applied to the resistor, we have $V_R = JSR$, where S is the surface area of the crystal's electrodes. Because $V_{\rm a} = V_0 + V_R$, we find that

$$E_0 = \frac{1}{W}(V_{\rm a} - JSR) \tag{1}$$

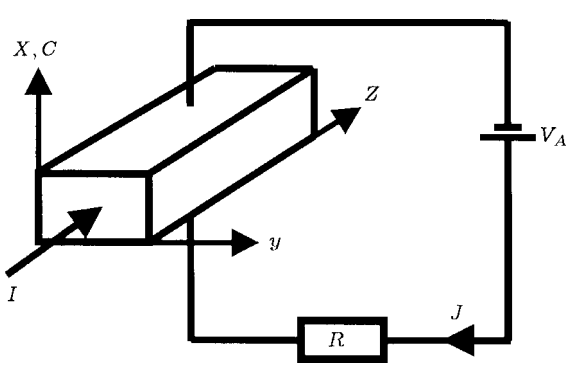


Fig.1. Illustration of the electrical circuit consisting of a photorefractive or photovoltaic–photorefractive crystal, an external electric field with voltage bias $V_{\rm a}$ and an external resistor with resistance R.

Let us consider an optical beam that propagates in the crystal along the z-axis and is permitted to diffract only along the x-direction. The crystal's optical c-axis is oriented along the x-coordinate. Moreover, let us assume that the optical beam is linearly polarized along x and the external electric field is applied in the same direction. Under these conditions the perturbed extraordinary refractive index $\hat{n}_{\rm e}$ (along the c-axis) is given by[14] $(\hat{n}_{\rm e})^2 = n_{\rm e}^2 - n_{\rm e}^4 r_{33} E_{\rm sc}$, where r_{33} is the electro-optic coefficient, $n_{\rm e}$ is the unperturbed extraordinary index of refraction, and $E_{\rm sc}$ is the induced space-charge field. On the other hand, the electric field component E of the optical beam satisfies the Helmholtz equation: $\nabla^2 E + (k_0 \hat{n}_{\rm e})^2 E = 0$, where $k_0 = 2\pi/\lambda_0$ and λ_0 is the free-space wavelength of the lightwave employed. By expressing E in terms of a slowly varying envelope ϕ, i.e. $E = \hat{x}\phi(x,z)\exp(ikz)$, where $k = k_0 n_{\rm e}$, one can find that the Helmholtz equation leads to the following paraxial equation of diffraction

$$i\phi_z + \frac{1}{2k}\phi_{xx} - \frac{k_0}{2}(n_{\rm e}^3 r_{\rm eff} E_{\rm sc})\phi = 0, \tag{2}$$

where $\phi_z = \partial\phi/\partial z$ and $\phi_{xx} = \partial^2\phi/\partial x^2$.

In turn, the induced space-charge field $E_{\rm sc}$ can be obtained from the standard set of rate and continuity equations and Gauss's law, which describe the photorefractive effect in a medium in which the photovoltaic current is nonzero and the electrons are the sole charge carriers. In the steady state and one dimension these equations are[7,11]

$$\gamma_{\rm r} n N_{\rm d}^+ = S_i (I + I_{\rm d})(N_{\rm d} - N_{\rm d}^+), \tag{3}$$

$$\frac{\partial E_{\rm sc}}{\partial x} = \frac{e}{\varepsilon_0 \varepsilon}(N_{\rm d}^+ - N_{\rm a} - n), \tag{4}$$

$$J = e\mu n E_{\rm sc} + k_{\rm B} T \mu \frac{\partial n}{\partial x} + k_{\rm p} S_i (N_{\rm d} - N_{\rm d}^+) I, \tag{5}$$

$$\frac{\partial J}{\partial x} = 0 \text{ or } J = \text{constant}, \tag{6}$$

where $N_{\rm d}^+$ and $N_{\rm d}$ are the ionized donor density and donor density, respectively, $N_{\rm a}$ is the acceptor density, n is the electron density, S_i is the photoexcitation cross section, $\gamma_{\rm r}$ is the carrier recombination rate, μ and e are, respectively, the electron mobility and the charge, $k_{\rm p}$ is photovoltaic constant, $k_{\rm B}$ is Boltzmann's constant, T is the absolute temperature, ε_0 is the free space permittivity, $\varepsilon_{\rm r}$ is the relative static dielectric constant, and $I_{\rm d}$ is the so-called dark irradiance. $I = I(x,z)$ is the power density profile of the optical beam. Moreover, in Eqs.(3)–(6) we have ignored any z spatial dependence by assuming that the variables involved vary much more rapidly in the x-direction.

Even though the space-charge field $E_{\rm sc}$ can be obtained in principle from Eqs.(3)–(6), this task is

considerably involved. However, we can use a similar method to that in Refs.[4] and [11] to greatly simplify Eqs.(3)–(6) by keeping in mind that the following inequalities hold true in typical photovoltaic–photorefractive media: $N_{\rm d}^{+} \gg n$, $N_{\rm d} \gg n$ and $N_{\rm a} \gg n$. In this case, Eqs.(3)–(4) yield the following results:

$$N_{\rm d}^{+} = N_{\rm a}\left(1 + \frac{\varepsilon_0\varepsilon_{\rm r}}{eN_{\rm a}}\frac{\partial E_{\rm sc}}{\partial x}\right), \tag{7}$$

$$n = \frac{S_i(N_{\rm d} - N_{\rm d}^{+})}{\gamma_{\rm r}N_{\rm d}^{+}}(I + I_{\rm d})\left(1 + \frac{\varepsilon_0\varepsilon_{\rm r}}{eN_{\rm a}}\frac{\partial E_{\rm sc}}{\partial x}\right)^{-1}. \tag{8}$$

At this point, let us also assume that the power density $I = I(x,z)$ attains asymptotically a constant value at $x \to \pm\infty$, that is $I(x \to \pm\infty, z) = I_{\infty}$. In these regions of constant illumination, Eqs.(3)–(6) require that the space-charge field $E_{\rm sc}$ is independent of x, i.e. $E_{\rm sc}(x \to \pm\infty, z) = E_0$. Therefore, from Eq.(8) the electron density n in the regions $(x \to \pm\infty)$, denoted by n_{∞}, can be subsequently determined and is given by

$$n_{\infty} = \frac{S_i(N_{\rm d} - N_{\rm a})}{\gamma_{\rm r}N_{\rm a}}(I_{\infty} + I_{\rm d}). \tag{9}$$

On the other hand, from Eq.(5), the current density J in the regions $(x \to \pm\infty)$ can be given by

$$J_{\infty} = e\mu n_{\infty}E_0 + k_{\rm p}S_i(N_{\rm d} - N_{\rm a})I_{\infty}, \tag{10}$$

where $J_{\infty} = J(x \to \pm\infty, z)$. Eq.(6) implies that the current density J is constant everywhere, that is, $J_{\infty} = J(x,z)$. Substituting Eqs.(1) and (9) into Eq.(10), we have

$$J_{\infty} = e\mu n_{\infty}\frac{E_{\rm a} + E_{\rm p}\dfrac{I_{\infty}}{I_{\infty} + I_{\rm d}}}{1 + pR(I_{\infty} + I_{\rm d})}, \tag{11}$$

where $E_{\rm p} = k_{\rm p}\gamma_{\rm r}N_{\rm a}/(e\mu)$ is the photovoltaic field constant, $p = S_i(N_{\rm d} - N_{\rm a})e\mu/r_{\rm r}N_{\rm a}W$, $E_{\rm a} = V_{\rm a}/W$.

In the region of $I(x,z)$ varying with x, from Eqs.(3), (5) and (7), we have

$$J = e\mu n\left[E_{\rm sc} + \frac{k_{\rm B}T}{e}\frac{\partial \ln n}{\partial x} + E_{\rm p}\frac{I}{I + I_{\rm d}}\left(1 + \frac{\varepsilon_0\varepsilon_r}{eN_{\rm a}}\frac{\partial E_{\rm sc}}{\partial x}\right)\right]. \tag{12}$$

Because of $J_{\infty} = J(x,z)$, from Eqs.(11) and (12), we have

$$n_{\infty}\frac{E_{\rm a} + E_{\rm p}\dfrac{I_{\infty}}{I_{\infty} + I_{\rm d}}}{1 + pSR(I_{\infty} + I_{\rm d})} = n\left[E_{\rm sc} + \frac{k_{\rm B}T}{e}\frac{\partial \ln n}{\partial x} + E_{\rm p}\frac{I}{I + I_{\rm d}}\left(1 + \frac{\varepsilon_0\varepsilon_r}{eN_{\rm a}}\frac{\partial E_{\rm sc}}{\partial x}\right)\right]. \tag{13}$$

If the power density $I(x,z)$ of the optical beam varies slowly with respect to x, then in typical photovoltaic–photorefractive media the dimensionless term $|(\varepsilon_0\varepsilon_{\rm r}/eN_{\rm a})(\partial E_{\rm sc}/\partial x)|$ is much less than unity.[4] Under this condition the space-charge field can be determined from Eqs.(8), (9) and (13) and is approximately given by

$$E_{\rm sc} = gE_{\rm a}\frac{I_{\infty} + I_{\rm d}}{I + I_{\rm d}} + E_{\rm p}\frac{gI_{\infty} - I}{I + I_{\rm d}} - \frac{k_{\rm B}T}{e}\frac{1}{I + I_{\rm d}}\frac{\partial I}{\partial x}, \tag{14}$$

where

$$g = \frac{1}{1 + pSR(I_{\infty} + I_{\rm d})}. \tag{15}$$

In general, $0 < g < 1$, which implies that only part of the bias field $E_{\rm a}$ can be applied to the crystal. For the short-circuit condition, R=0, then g=1, which implies that $E_{\rm a}$ can be totally applied to the crystal. For the open-circuit condition, $R \to \infty$, then g=0, which implies that on bias field is applied to the crystal.

The previous expressions of the space-charge field determined individually elsewhere could be obtained from Eq.(14) under appropriate conditions. For a SP soliton in a biased photovoltaic–photorefractive crystal without a resistor in the external circuit, the expression of the space-charge field was determined in Ref.[11]. By taking R=0, then g=1 and $E_{\rm a} = E_0$, Eq.(14) can give the same expression of $E_{\rm sc}$ as Eq.(16) in Ref.[11]. For a screening soliton in a biased photorefractive crystal without a resistor in the external circuit, by taking R=0 and $E_{\rm p}$=0 in Eq.(14) and neglecting the diffusion term, we can obtain the same expression of $E_{\rm sc}$ as Eq.(12) in Ref.[4]. The expression of $E_{\rm sc}$ in the open-circuit photovoltaic medium can be obtained form Eq.(14) by taking $R \to \infty(g$=0) and neglecting the diffusion term, which has the same form as Eq.(6) in Ref.[8]. By taking $E_{\rm a}$=0 and neglecting the diffusion term in Eq (14), we can obtain an equivalent expression of $E_{\rm sc}$ to Eq.(13) in Ref.[7] for a closed-circuit photovoltaic medium with a resistor in the external circuit.

The envelope evolution equation can now be established by the insertion of Eq.(14) into Eq.(2). It proves more convenient, however, to study this equation in a normalized fashion. In doing so, let us adopt the following dimensionless coordinates and variables, i.e., $\xi = z/(kx_0^2)$, $s = x/x_0$ and $\phi = (2\eta_0 I_{\rm d}/n_{\rm e})^{1/2}U$. Here x_0 is an arbitrary spatial width. The power

density profile of the optical beam $I = I(x,z)$ can be also expressed in terms of the envelope ϕ by use of Poynting's theorem, i.e. $I = (n_e/2\eta_0)|\phi|^2$, where $\eta_0 = (\mu_0/\varepsilon_0)^{1/2}$. As a result, we have $I = I_d|U|^2$. Using Eqs.(2) and (15), we can then show that the normalized envelope U obeys the following dynamical evolution equation:

$$iU_\xi + \frac{1}{2}U_{ss} - g\beta(\rho+1)\frac{U}{1+|U|^2} - \alpha\frac{(g\rho-|U|^2)U}{1+|U|^2} + \gamma\frac{(|U|^2)_s U}{1+|U|^2} = 0, \quad (16)$$

where $\rho = I_\infty/I_d$, $\beta = (k_0x_0)^2(n_e^4r_{33}/2)E_a$, $\alpha = (k_0x_0)^2(n_e^4r/2)E_p$ and $\gamma = (k_0^2x_0n_e^4r_{33})k_BT/(2e)$.

The bright and dark soliton solutions can be determined from Eq.(16) by entirely neglecting the diffusion effect, i.e. by taking γ=0 and by expressing the beam envelope U in the usual fashion: $U = \rho^{1/2}y(s)\exp(i\nu\xi)$ for dark solitons and $U = r^{1/2}y(s)\exp(i\nu\xi)$ for bright solitons, where ν represents a nonlinear shift of the propagation constant, $y(s)$ is a normalized real function bounded between $0 \le (y(s)) \le 1$ and the positive quantity r is defined as $r = I(0)/I_d$. For the dark spatial solitons, we require that $y(0)$=0, $\dot{y}(\infty)$=0, $\ddot{y}(\infty)$=0 and $y(s \to \pm\infty)$=1. Substitution of this latter form of U for dark solitons into Eq.(16) (with γ=0) yields

$$\ddot{y} - 2\nu y - 2g\beta(\rho+1)\frac{y}{1+\rho y^2} - 2\alpha\rho\frac{g-y^2}{1+\rho y^2}y = 0, \quad (17)$$

where $\ddot{y} = d^2y/ds^2$. By employing the y-boundary conditions in Eq.(17), we find that $\nu = -g\beta - \alpha\rho(g-1)/(1+\rho)$. When R=0, i.e. g=1, $\nu = -\beta$, that has the same form as Eq.(25) in Ref.[11] for dark SP solitons. However, the SP solitons result from both the photovoltaic effect and spatially non-uniform screening of the applied field and, as a result, the photovoltaic term α should be included in the expression of ν. Therefore, the expression of ν in Ref.[11] is incomplete. It is only suitable for the configuration without a resistor in the external circuit.

By integrating Eq.(17) once and employing the y-boundary conditions, we find that

$$(\dot{y})^2 = -2\frac{g\beta(1+\rho)+\alpha(g\rho+1)}{1+\rho} \cdot \left[(y^2-1) - \frac{1+\rho}{\rho}\ln\left(\frac{1+\rho y^2}{1+\rho}\right)\right]. \quad (18)$$

For integration of Eq.(18), we obtain that the normalized dark-field profile $y(s)$ can be determined from the following equation:

$$\left[-2\frac{g\beta(1+\rho)+\alpha(g\rho+1)}{1+\rho}\right]^{1/2} S = \pm\int_{y(s)}^{0} \frac{d\hat{y}}{\left[(\hat{y}^2-1) - \frac{1+\rho}{\rho}\ln\left(\frac{1+\rho\hat{y}^2}{1+\rho}\right)\right]^{1/2}}. \quad (19)$$

It can be readily shown that the quantity in the square bracket of Eq.(18) remains positive for all values of $y^2 \le 1$, and thus $[g\beta(1+\rho)+\alpha(g\rho+1)]$ must be negative so that $\dot{y}^2 > 0$. In this case, these dark spatial solitons will arise in the photorefractive crystal.

For the bright soliton states, the optical beam intensity is expected to vanish at infinity ($S \to \pm\infty$), thus $\rho = I_\infty/I_d$=0. The boundary conditions for bright solitons is $y(0)$=1, $\dot{y}(0)$=0 and $y(s \to \pm\infty)$=0. Substitution of $U = r^{1/2}y(s)\exp(i\nu\xi)$ into Eq.(16) (with γ=0 and ρ=0) yields

$$\ddot{y} - 2\nu y - 2g\beta\frac{y}{1+ry^2} + 2\alpha\frac{ry^3}{1+ry^2} = 0. \quad (20)$$

By employing the y-boundary conditions, Eq.(20) can be integrated once and leads to $\nu = -[(g\beta+\alpha)/r]\ln(1+r)+\alpha$ and

$$(\dot{y})^2 = \frac{2(g\beta+\alpha)}{r}[\ln(1+ry^2) - y^2\ln(1+r)]. \quad (21)$$

For integration of Eq.(21), we obtain that the normalized bright-field profile $y(s)$ can be determined from the following equation:

$$[2(g\beta+\alpha)]^{1/2} S = \pm\int_{y(s)}^{1} \frac{r^{1/2}d\hat{y}}{[\ln(1+r\hat{y}^2) - \hat{y}^2\ln(1+r)]^{1/2}}. \quad (22)$$

It is straightforward to show that the quantity in the square bracket of Eq.(21) is always positive for all values of y^2 between $0 \le y^2 \le 1$. Therefore $(g\beta+\alpha)$ must be positive so that $\dot{y}^2 > 0$. In this case, these bright spatial solitons will arise in the photorefractive crystal.

Ⅲ. DISCUSSION

The previous theories advanced individually elsewhere for steady-state one-dimensional photorefractive solitons can be obtained from Eqs.(17)–(22). Eqs.(21) and (28) in Ref.[4] for bright and dark screening solitons in a biased photorefractive medium without a resistor in the external circuit can be obtained

from Eqs.(21) and (18) by taking g=1 and α=0, respectively. By setting g=1 in Eqs.(21) and (18), we can obtain the same expressions of bright and dark SP solitons as Eqs.(22) and (26) in Ref.[11], respectively. In Ref.[11], the SP solitons were discussed in a biased photovoltaic–photorefractive crystal without a resistor in the external circuit. The bright solitary equation in an open-circuit photovoltaic medium can be determined form Eq.(21) by taking g=0, $y = r^{-1/2}u$ and $\alpha = \delta/2$, which has the same form as Eq.(18) (lower sign) in Ref.[8], whereas the dark one can be also determined from Eq.(18) by taking g=0, $y = r^{-1/2}u$ and $\alpha = -\delta/2$, which has the same form as Eq.(18) (upper sign) in Ref.[8]. In the meantime, the expressions of closed-circuit photovoltaic solitons can also be obtained. Let $\alpha = -(J+1)/[2(g\rho+1)]$, $y = \rho^{-1/2}u$ and β=0, Eq.(18) has the same form as Eq.(26) in Ref.[7] in which the closed-circuit photovoltaic solitons were discussed in a unbiased photovoltaic–photorefractive crystal with a resistor in the external circuit. Letting $\alpha = r(J+1)/2$, $y = r^{-1/2}u$ and β=0, Eq.(21) has the same form as Eq.(29) in Ref.[7].

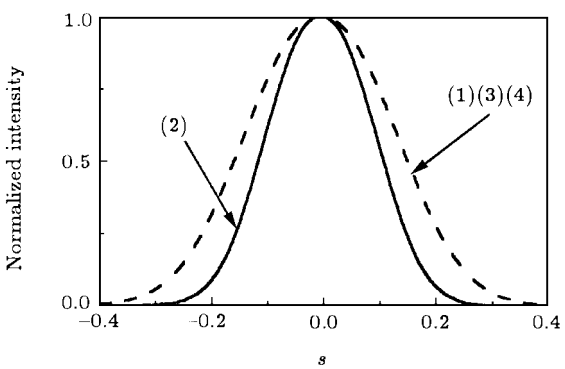


Fig.2. Normalized intensity profile of bright screening, SP, open- and closed-circuit photovoltaic solitons with r=10. (1) Bright screening soliton, g=1, α=0, β=100. (2) Bright SP soliton, g=1, α=100, β=100. (3) Bright open-circuit photovoltaic soliton, g=0, α=100, β=0. (4) Bright closed-circuit photovoltaic soliton, g=1, α =100, β=0.

By use of a simple numerical integration procedure, one can obtain the normalized bright- and dark-field profiles $y(s)$ from Eqs.(22) and (19), respectively. The results calculated for normalized bright- and dark-intensity profile $y^2(s)$ of screening, SP, open- and closed-circuit photovoltaic solitons are shown in Figs.2 and 3, respectively. The results show that the field or intensity profiles of the three types of the steady-state one-dimensional photorefractive bright (or dark) solitons in various realizations can be calculated by use of a universal formula with some appropriate parameters. The dynamical evolution, stability and self-deflection for the three types of steady-state one-dimensional photorefractive solitons can be analysed by numerically solving a universal dynamical evolution equation, i.e. Eq.(16), with some appropriate parameters.

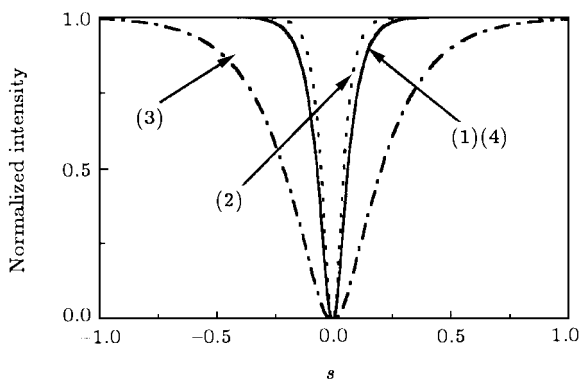


Fig.3. Normalized intensity profile of dark screening, SP, open- and closed-circuit photovoltaic solitons with ρ=10. (1) Dark screening soliton, g=1, α=0, β=–100. (2) Dark SP soliton, g=1, α=–100, β=–100. (3) Dark open-circuit photovoltaic soliton, g=0, α=–100, β=0. (4) Dark closed-circuit photovoltaic soliton, g=1, α = –100, β=0.

IV. CONCLUSION

In conclusion, a universal theory has been developed that is suitable for steady-state one-dimensional photorefractive solitons under various realizations, including the screening solitons in a biased photorefractive medium, the photovoltaic solitons in open- and closed-circuit photovoltaic–photorefractive media and the screening-photovoltaic solitons in biased photovoltaic–photorefractive media. Previous theories advanced individually elsewhere for these solitons could be obtained by simplifying the universal theory under the appropriate conditions.

References

[1] Shih M F, Segev M, Valley G C, Salamo G, Crosignani B and Di Porto P 1995 *Electron. Lett.* **31** 826

[2] Chen Z G, Mitchell M, Shih M F, Segev M, Garrett M H, Valley G C 1996 *Opt. Lett.* **21** 629

[3] Montemezzani C and Gunter P 1997 *Opt. Lett.* **22** 451

[4] Christodoulides D N and Carvalho M I 1995 *J. Opt. Soc. Am.* B **12** 1628

[5] Segev M, Valley G C, Crosignani B, Diporto P and Yariv A 1994 *Phys. Rev. Lett.* **73** 3211

[6] Singh S R and Christodoulides D N 1995 *Opt. Commun.* **118** 569

[7] Segev M, Valley G C, Bashaw M C, Taya M and Fejer M M 1997 *J. Opt. Soc. Am.* B **14** 1772

[8] Valley G C, Segev M, Bruno Crosignani, Amnon Yariv, Fejer M M and Bashaw M C 1994 *Phys. Rev.* A **50** R4457

[9] Taya M, Bashaw M, Fejer M M, Segev M and Vally G C 1995 *Phys. Rev.* A **52** 3095

[10] Liu J S, Lu K Q, Xu J and Hao Z H 1998 *Proc. SPIE* **3554** 81

[11] Liu J S and Lu K Q 1999 *J. Opt. Soc. Am.* B **16** 550

[12] Liu J S and Zhang D Y 2000 *Chin. Phys.* **9** 667

[13] Liu J S and Lu K Q 1998 *Acta Phys. Sin.* **47** 1509 (in Chinese)

[14] Gunter P and Huignard J P (ed) 1988 *Photorefractive Materials and Their Applications I and II* (Berlin: Springer-Verlag);

Yeh P 1993 *Photorefractive Nonlinear Optics* (New York: Wiley)