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Spatial solitons in biased photovoltaic photorefractive materials with the pyroelectric effect

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ABSTRACT

Spatial solitons in biased photorefractive media due to the photovoltaic effect and the pyroelectric effect are investigated. The pyroelectric field considered is induced due to the heating by the incident beam's energy. These solitons can be called screening photovoltaic pyroelectric solitons. It is shown that the solitons can exist in the bright and dark realizations. The conditions for formation of these solitons are discussed. Relevant example is considered to illustrate the self trapping of such solitons. The external electric field interacts with the photovoltaic field and the pyroelectric field to either support or oppose the self trapping.

1. Introduction

Photorefractive spatial solitons have been at the forefront of current research because of their possible applications for all-optical switching and routing. Till now, three types of steady-state photorefractive spatial solitons have been observed and investigated in detail i.e. screening solitons [1–3], photovoltaic solitons [4–7] and screening–photovoltaic solitons [8,9].

For screening solitons, an external bias field is required, whereas the photovoltaic solitons can exist in unbiased photorefractive-photovoltaic crystals due to the photovoltaic effect. Screening–photovoltaic solitons result from the combination of the external bias field and photovoltaic effect. The photorefractive effect is the phenomenon which causes the self trapping [10]. The photorefractive effect can be explained as a refractive index change through the electro-optic effect driven by the buildup of a space–charge field. The external bias field, photovoltaic field and pyroelectric field can induce a space–charge field [11–14].

In a ferroelectric crystal at equilibrium, the net internal field inside the crystal is zero because the field due to the spontaneous polarization is balanced by the charge distribution on the faces of the crystal. However, a temperature change induces a variation in the spontaneous polarization and hence, an electric field E_{py} is induced. This field is not immediately compensated and consequently, a drift current can be set up as if an external voltage is applied to the crystal. This field is locally screened due to the photorefractive effect which results in a self trapped beam, i.e. a soliton. The pyroelectric field itself is transient but it can induce a space charge field which can persist to form a self trapped beam. Recently, the writing of soliton waveguides due to the photorefractive–pyroelectric effect have been investigated thoroughly [15,16]. The authors in Refs. [15,16] replace the external electric field with the pyroelectric field which is induced due to a controlled heating of the crystal. They report multiple advantages of such a configuration. Also, the pyrolitons, i.e., pyroelectric spatial solitons originating from the pyroelectric field in photorefractive crystals have been predicted and observed [17,18]. A theoretical formulation of spatial solitons in pyroelectric photovoltaic photorefractive media has also been discussed for open circuit crystals [19].

Now, the transient pyroelectric field can be induced by temperature variations that are caused by externally-controlled sources or by absorption of the incident field energy. In all the previous theoretical studies on screening solitons or screening photovoltaic solitons, the effect of pyroelectricity due to the absorption of energy of the beam itself has been neglected, even while considering crystals with an appreciable pyroelectric coefficient. In this letter, we discuss the formation of solitons in biased photovoltaic photorefractive media considering the pyroelectric field induced by the significant absorption of the incident beam's energy.

2. Theoretical model

We consider an optical beam propagating along the z-axis. Since we look for a one dimensional soliton, we assume the diffraction compensation only in x-direction. The soliton beams

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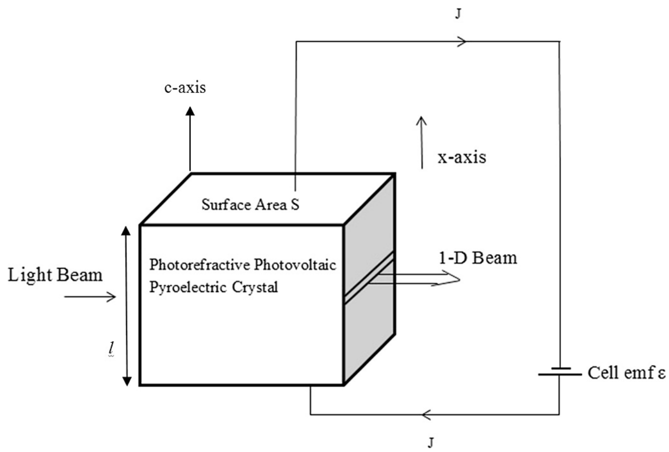

Fig. 1. Illustration of the electrical circuit consisting of a pyroelectric photovoltaic photorefractive crystal biased by a cell of electro-motive force (emf) or Voltage $= \varepsilon$.

are polarized along the positive x-direction and the external electric field is also applied in the same direction. The crystal is kept such that its c-axis coincides with the positive x axis. An external voltage bias ε is applied to the crystal. In addition, a thermally insulating cover is kept on top of the crystal in so as to minimize any temperature gradient due to undesirable external factors and stabilize the temperature. Fig. 1 illustrates the setup schematically.

As usual, the incident beam is expressed as a slowly varying envelope $\boldsymbol{E} = \hat{x}A(x,z)\exp(ikz)$ where $k = k_0 n_e$, n_e is the unperturbed refractive index, n_e' is the refractive index along the c-axis and λ_0 is the free space wavelength. Under the above conditions, $\boldsymbol{E}$ satisfies the Helmholtz equation,

$$\nabla^2 \boldsymbol{E} + \left(k_0 n_e'\right)^2 \boldsymbol{E} = 0 \tag{1}$$

Substituting the form of $\boldsymbol{E}$ in (1), we get [1],

$$\left(i\frac{\partial}{\partial z} + \frac{1}{2k}\frac{\partial^2}{\partial x^2} + \frac{k}{n_e}\Delta n\right)A(x,z) = 0 \tag{2}$$

$$\Delta n = -\frac{1}{2}n_e^3 r_{\text{eff}} E_{\text{sc}} \tag{3}$$

where E_{sc} is the space charge field in the medium resulting from the photovoltaic drift and the pyroelectric field. The parameter r_{eff} is the effective (linear) electro-optic coefficient. We can consider E_{sc} to consist of three parts, the space charge field due to the external bias, the photovoltaic contribution and the pyroelectric space charge field. Hence, the total space charge field can be approximated as [11,12],

$$E_{\text{sc}} = E_1 + E_2 + E_3 \tag{4}$$

The space charge field $(E_1 + E_2)$ results in screening photovoltaic solitons. It has been previously studied in detail [8,9],

$$E_1 + E_2 = E_0\frac{I_\infty + I_d}{I + I_d} + E_p\frac{I_\infty - I}{I + I_d} \tag{5}$$

where I is the intensity of the optical beam and I_d is the dark irradiance. $E_0 = E(x \to \pm\infty)$ is the electric field in regions of constant illumination. The amplitude of E_p is dependent on the light polarization and the sign is determined by the photovoltaic coefficient. E_{pysc} is the space–charge field arising due to the pyroelectric field E_{py} which results transiently from a change in temperature. Pyroelectric effect induced by a pulse of light is similar to that induced by a temperature change [11–14,19]. For a short pulse of light, E_{pysc} can be expressed as, [13,14,19],

$$E_3 = E_{\text{pysc}} = -\frac{1}{\varepsilon_r\varepsilon_0}\frac{\partial P_s}{\partial T}\frac{t_p}{2}\frac{\sigma_{\text{ph}}}{\varepsilon_0\varepsilon_r}\Delta T(t) = -E_{\text{py}}\frac{t_p}{2}\frac{\sigma_{\text{ph}}}{\varepsilon_0\varepsilon_r} \tag{6}$$

We follow the approach of Ref. [19] to approximate the value of E_{pysc} as,

$$E_{\text{pysc}} = -E_{\text{py}}\frac{t_p}{2}\frac{\sigma_{\text{ph}}}{\varepsilon_0\varepsilon_r} \approx -E_{\text{py}}\frac{\lambda I}{I_d} \tag{7}$$

where σ_{ph} is the photoconductivity, t_p is the pulse duration, λ is a parameter related to the crystal. This approximation can be justified as the photoconductivity σ_{ph} is proportional to the intensity I, and considering the values of the parameters E_{py}, t_p, ε_0, ε_r [11–14, 19] we can say that $\frac{\lambda I}{I_d} < 1$. This is especially true as the amplitude of the pyroelectric space charge field can reach an appreciable fraction of the pyroelectric field even under CW laser beam [13]. The value of E_0 can be found from the following potential condition in steady state,

$$-\int_{-l/2}^{l/2} E_{\text{sc}}dx = \varepsilon \tag{8}$$

where l is the transverse thickness of the crystal, and ε is the external voltage (see Fig. 1).

Substituting (5) and (7) in (8), we get,

$$E_{\text{sc}} = -(\varepsilon\eta + E_p\sigma\eta - E_{\text{py}}\gamma\lambda\eta)\frac{I_\infty + I_d}{I + I_d} + E_p\frac{I_\infty - I}{I + I_d} - E_{\text{py}}\frac{\lambda I}{I_d} \tag{9}$$

where $\eta = \frac{1}{\int_{-l/2}^{l/2}\frac{I_\infty + I_d}{I + I_d}dx}$, $\sigma = \int_{-l/2}^{l/2}\frac{I_\infty - I}{I + I_d}dx$ and $\gamma = \int_{-l/2}^{l/2}\frac{I}{I_d}dx$.

The total optical power density or intensity of the beam is,

$$I = \frac{n_e}{2\eta_0}\left(|A|^2\right) \tag{10}$$

with $\eta_0 = (\mu_0/\varepsilon_0)^{1/2}$.

We can get the value of E_{sc} from (4). Substituting E_{sc} and Δn in (1) and in terms of dimensionless variables, one gets the following equation,

$$iU_\xi + \frac{1}{2}U_{ss} + \beta\left(|U|^2\right)U - \frac{\alpha(\rho - (|U|^2))}{(1 + |U|^2)}U - \delta\frac{(1 + \rho)}{(1 + |U|^2)}U = 0 \tag{11}$$

where we have written, $A = (2\eta_0 I_d/n_e)^{1/2}U_j$, $\xi = z/kx_0^2$, $s = x/x_0$ and $U_\xi = \frac{\partial U}{\partial \xi}$, $U_{ss} = \frac{\partial^2 U}{\partial s^2}$, $\rho = I_\infty/I_d$, $\beta = \lambda\tau E_{\text{py}}$, $\tau = (k_0 x_0)^2 n_e^4 r_{\text{eff}}/2$, $\alpha = \tau E_p$, $\delta = -(\varepsilon\eta + E_p\sigma\eta - E_{\text{py}}\gamma\lambda\eta)\tau$.

We have used dimensionless coordinates here whence we transform from x and z to s and ξ respectively [1–9]. As is usual with these dimensionless coordinates, the intensity scales as, $I = I_d|U|^2$.

3. Results and discussion

3.1. Bright solitons

In the case of a bright soliton, we express the solutions as,

$$U = r^{\frac{1}{2}}f(s)\exp(i\mu\xi) \tag{12}$$

where μ is the nonlinear shift of the propagation constant, and $f(s)$ is a normalized bounded function which satisfies the conditions, $0 \le f(s) \le 1$ and $f(\pm\infty) = 0$, $\dot{f}(0) = 0$, $\dot{f}(\pm\infty) = 0$, $\ddot{f}(\pm\infty) = 0$, $f(0) = 1$. Substituting (12) in Eq. (11), we get,

$$\ddot{f} = 2\mu f - 2\beta\left(rf^2\right)f - 2\alpha\frac{(rf^2)f}{1 + rf^2} + 2\delta\frac{f}{1 + rf^2} \tag{13}$$

where $\ddot{f} = \frac{d^2 f}{ds^2}$.

Integrating once, and using the boundary conditions, we find,

$$\dot{f}^2 = 2\mu f^2 - \beta r f^4 + \frac{(2(\delta+\alpha)\log(1+rf^2) - 2\alpha r f^2)}{r} + c \quad (14)$$

with

$$c = 0 \quad (15)$$

$$\mu = \frac{\beta r}{2} - \left(\frac{\delta}{r} + \frac{\alpha}{r}\right)\log(1+r) + \alpha \quad (16)$$

Integrating (14) once again, we get the envelope,

$$s = \pm \int_y^1 \frac{r^{1/2} d\tilde{f}}{[2\mu r \tilde{f}^2 - \beta r^2 \tilde{f}^4 + 2(\delta+\alpha)\log(1+r\tilde{f}^2) - 2\alpha r \tilde{f}^2]^{1/2}} \quad (17a)$$

Since $\dot{f}$ has to be real and $0 \le f(s) \le 1$, we can see from Eq. (14) that the sufficient condition so as to keep RHS positive is,

$$-\frac{\beta r}{2} + \mu - \alpha \ge -\frac{\delta+\alpha}{r}\log(1+r) \quad (17b)$$

Bright spatial solitons require that the crystal's total refractive index perturbation be positive. But in the case of a lithum niobate crystal, there is a self-defocussing due to the photovoltaic effect on account of its negative photovoltaic coefficient. So the refractive index perturbation due to the photovoltaic effect is negative. For open circuit crystals if the pyroelectric self focussing outweighs the self-defocussing due to the photovoltaic effect, a bright spatial soliton can still be formed [18].

Application of an external bias changes this condition slightly. An external electric field applied in the positive x-direction (along the c-axis) leads to a self focussing mechanism and an external electric field applied in the opposite direction leads to self defocussing [1]. So, depending upon the direction of the bias, the photovoltaic self defocussing is enhanced or reduced. This, in turn affects the degree of self focussing by the pyroelectric effect and hence, the FWHM of the soliton.

As an illustration, we consider the $LiNbO_3$ crystal. In Ref. [18], the authors use green light of wavelength 532 nm. In the present investigation, we emphasize that the wavelength of incident radiation should be in such a wavelength range in which the absorption of the $LiNbO_3$ crystal is significant. This is because significant amount of energy of the incident beam should be absorbed for causing a heating of the crystal. The light absorption in $LiNbO_3$ increases when the wavelength decreases from red to blue-violet (~405 nm) in the visible range of the electromagnetic spectrum [15]. Hence, we shall consider this blue-violet wavelength in our simulation. On the other hand, the photovoltaic field is inversely proportional to the photoconductivity [20]. As the photoconductivity in blue-violet spectral region is much larger than in green, the photovoltaic field is much smaller in comparison with that in green. The photovoltaic field decreases from a magnitude of approximately 10 kV/cm [21,22] for green light (532 nm) in the visible range of the electromagnetic spectrum, to about 550 V/cm UV light (351 nm) [23]. Also, in undoped $LiNbO_3$, the photovoltaic field depends sub-linearly on the incident light intensity [24]. At 532 nm wavelength, the photovoltaic field increases from 2 kV/cm to 70 kV/cm according to the relation I^q, with q = 0.5–0.6, in the intensity range 30–9000 W/cm^2 [24]. Since the photovoltaic effect is intimately connected with the self trapping process, the value of the photovoltaic field and hence, E_p profoundly affects the spatial profiles of the solitons. At the desired wavelength and intensity in our investigation, we can conclude that a lesser value of E_p should be considered in our simulation than that considered in previous researches like in References [4–9]. We take a reasonable

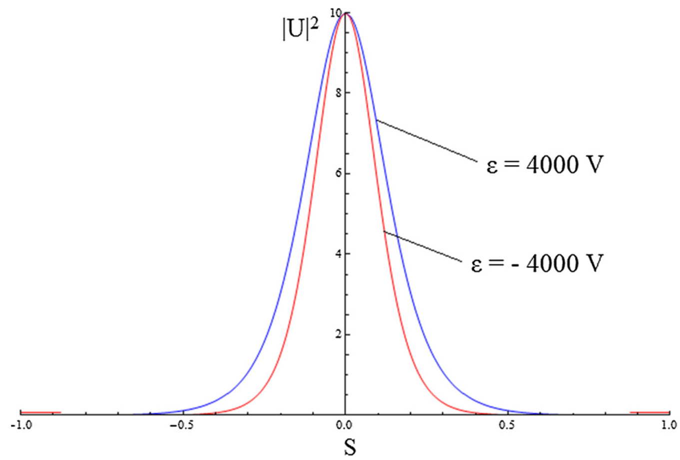

Fig. 2. The normalized intensities of the solitons when $\alpha = -6.846$, $\beta = 67.275$, $r = 10$.

assumption of $E_p = -2 \times 10^5$ V/m. As regards the electro-optic coefficients, in congruent $LiNbO_3$, $r_{33} = 31.8$ pm/V, $r_{13} = 10.1$ pm/V, measured at 529 nm and $r_{33} = 34$ pm/V, $r_{13} = 11$ pm/V, measured at 458 nm [25]. The electro-optic coefficients at 405 nm are expected to be even higher than those at 458 nm [15]. Also, the pyroelectric field E_{py} is taken to be ~40 kV/cm, which corresponds to a temperature change of 10–12 K of the crystal [26]. To summarize, $\lambda_0 = 405$ nm, $x_0 = 20$ μm, $E_p = -2 \times 10^5$ V/m ~ -2 kV/cm, $E_{py} = 4.0 \times 10^6$ V/m, $r_{eff} = r_{33} \sim 35 \times 10^{-12}$ m V^{-1}, $n_e = 2.2$, $\lambda = 0.5$, $r = 10$.

Hence, the value of $\alpha = -6.846$ and $\beta = 67.275$. The soliton profiles under the applied emf or voltage $\varepsilon = \pm 4000$ V for thickness of the crystal $l = 10$ mm are shown in Fig. 2. The FWHM of the solitons comes out to be 5.9 μm and 7.7 μm for $\varepsilon = -4000$ V and $\varepsilon = 4000$ V respectively.

Now, we consider the hypothetical situation of the photovoltaic field constant to be positive, i.e., $E_p = +2$ kV/cm and rest of the parameters are same as those considered for the $LiNbO_3$ crystal. As the refractive index perturbation due to photovoltaic effect is positive, keeping all other parameters the same, the photovoltaic effect will work in tandem with the pyroelectric effect in such a crystal, and enhance the self trapping mechanism. This case is shown in Fig. 3. FWHM of the solitons are 4.9 μm and 6.6 μm for $\varepsilon = -4000$ V and $\varepsilon = 4000$ V respectively. We emphasize that this is a hypothetical case considered just to illustrate the interplay between the photovoltaic effect and the external bias and pyroelectric field.

3.2. Dark solitons

In the case of a dark soliton, we express the solution as,

$$U = \rho^{\frac{1}{2}} g(s) \exp(i\nu\xi) \quad (18)$$

where ν is the nonlinear shift of the propagation constant, and $g(s)$ is a normalized bounded function which satisfies the conditions, $0 \le g(s) \le 1$ and $g(\pm\infty) = 0$, $\dot{g}(0) = 0$, $\dot{g}(\pm\infty) = 0$, $\ddot{g}(\pm\infty) = 0$, $g(0) = 1$. Substituting (18) in (11), we get,

$$\ddot{g} = 2\nu g - 2\beta(\rho g^2)g + 2\alpha\frac{(\rho - \rho g^2)g}{1+\rho g^2} + 2\delta\frac{(\rho+1)g}{1+\rho g^2} \quad (19)$$

where $\ddot{g} = \frac{d^2 g}{ds^2}$.

We can find out the constant ν by using the boundary conditions $\ddot{g}(\pm\infty) = 0$ and $g(\pm\infty) = \pm 1$ in (19),

$$\nu = \beta\rho - \delta \quad (20)$$

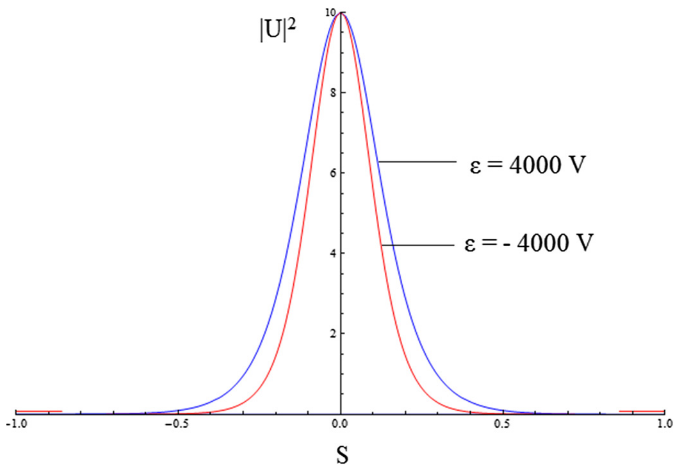

Fig. 3. The normalized intensities of the solitons when $\alpha = 6.846$, $\beta = 67.275$, $r = 10$.

Integrating (19) once, and using the boundary conditions, we find,

$$\dot{g}^2 = 2\nu g^2 - \beta\rho g^4 + \frac{2\delta(1+\rho)\log(1+\rho g^2)}{\rho} - 2\alpha g^2 + \frac{2\alpha(1+\rho)\log(1+\rho g^2)}{\rho} + 2c \tag{21}$$

$$c = -\nu + \frac{\beta\rho}{2} + \alpha - \frac{(\alpha+\delta)(1+\rho)\log(1+\rho)}{\rho} \tag{22}$$

Integrating once again, we get the soliton envelope,

$$s = \pm \int_0^y (\rho^{1/2} d\tilde{g})\big[2\nu\rho\tilde{g}^2 - \beta\rho^2\tilde{g}^4 + 2(\delta+\alpha)(1+\rho) \times \log\big(1+\rho\tilde{g}^2\big) - 2\alpha\rho\tilde{g}^2 + 2\rho c\big]^{-1/2} \tag{23a}$$

Since $\dot{g}$ has to be real, we can see from (21) that the sufficient condition for keeping the RHS positive is,

$$\nu - \alpha - c \geq \frac{\beta\rho}{2} - \frac{(\delta+\alpha)(1+\rho)}{\rho}\log(1+\rho) \tag{23b}$$

For the formation of dark solitons, the refractive index change should be negative for self-defocussing to occur. The self-focussing effect of the external bias field and the pyroelectric effect should be cumulatively less than the self-defocussing induced by the photovoltaic effect for the dark soliton formation. So, we consider slightly changed values of the external bias, i.e. $\varepsilon = 4000$ V and $\varepsilon = 40{,}000$ V. This is so because at negative values of the bias, i.e. when the electric field is in the direction of the c-axis, the required self defocussing cannot occur due to the large self focussing effect of the pyroelectric space charge field. A negative photovoltaic coefficient in $LiNbO_3$ supports the formation of a dark soliton. In summary, we consider, the following parameters, $\lambda_0 = 405$ nm, $x_0 = 20$ μm, $E_p = -2.0 \times 10^5$ V/m, $E_{py} = 4.0 \times 10^5$ V/m, $r_{eff} = 35 \times 10^{-12}$ $\mathrm{m V^{-1}}$, $n_e = 2.2$, $\lambda = 0.5$, $\rho = 10$. Also, we have, $\alpha = -6.846$, $\beta = 6.7275$.

The soliton profiles are shown in Fig. 4. The FWHM of the solitons comes out to be 8.9 μm and 16.3 μm for $\varepsilon = 40000$ V and $\varepsilon = 4000$ V respectively.

If the sign of the pyroelectric coefficient is reversed, and all other parameters remain same as taken previously, then $E_{py} = -4.7 \times 10^5$ V/m, and the pyroelectric effect works in tandem with the photovoltaic effect and the self trapping mechanism is enhanced. The FWHM for this case now comes out to be 6.2 μm and 11.7 μm for $\varepsilon = 40000$ V and $\varepsilon = 4000$ V respectively. The intensity profiles are shown in Fig. 5.

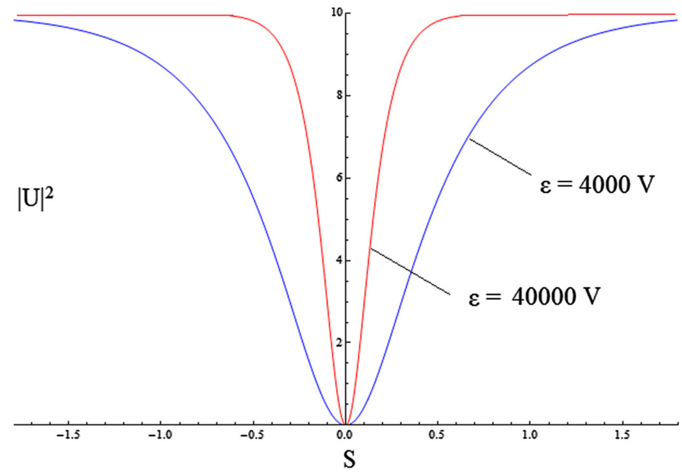

Fig. 4. The normalized intensities of the solitons when $\alpha = -6.846$, $\beta = 6.7275$, $\rho = 10$.

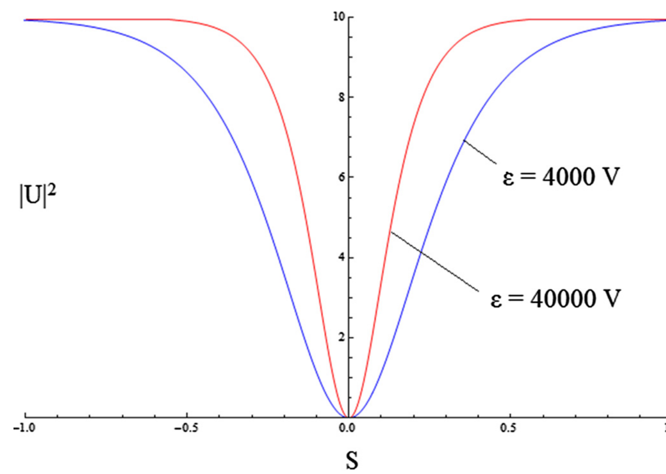

Fig. 5. The normalized intensities of the solitons when $\alpha = -6.846$, $\beta = -6.7275$, $\rho = 10$.

4. Conclusions

We study the effect of pyroelectricity induced by the beam illumination for both the bright and dark solitons in the case of screening photovoltaic solitons. The self trapping depends upon the direction of the external electric field, and the magnitude and direction of the pyroelectric space charge field induced as well as the photovoltaic space charge field. The soliton width increases if the external bias opposes the self focussing (in case of bright solitons) or self defocusing (in case of dark solitons) due to the cumulative photovoltaic and pyroelectric effect. Again, the soliton width decreases if the external bias supports the self focussing or self defocusing due to the cumulative photovoltaic and the pyroelectric effect.

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