Propagation of Incoherently Coupled Soliton Pairs in Photorefractive Crystals and their Self-Deflection

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Abstract— Propagation of incoherently soliton pairs in photorefractive crystals under steady-state conditions is studied. These soliton states can be generated when the two mutually incoherent optical beams with the same polarization and wavelength incident on the biased photorefractive crystal. Such soliton pairs can exist in bright-bright, dark-dark, gray-gray as well as in bright-dark types. In this paper the stability against small perturbation in amplitude is investigated while they do not break up, and instead oscillates around the soliton solution. Results show that the bright-bright pairs can travel a longer distance without broadening in comparison with the other types. Finally the effect of self-deflection is simulated numerically.

KEYWORDS: Nonlinear optics, Photorefractive soliton, Soliton pairs, Incoherently coupled soliton, Self-deflection.

I. INTRODUCTION

Photorefractive (PR) spatial solitons and their coherent and incoherent interaction have attracted considerable attention for many years [1]-[9]. It is now well established that PR nonlinearities can support self-trapping of optical beams in both transverse dimensions and that these solitons can be observed even at low power levels in order of microwatts and lower [1]-[4]. Self-trapped optical beams are generated when the process of diffraction is exactly balanced by light-induced PR waveguide. Both one dimensional (1D) and two-dimensional (2D) spatial solitary waves have a unique shape which is determined by the strength of the external electric field, the light intensity, and the beam diameter. Spatial solitons is considered to be important because of their possible applications for optical switching, routing, optical storage and optical interconnectors, etc [10], [11]. Nowadays, many types of steady-state PR spatial soliton such as screening solitons [6]-[8], [20], photovoltaic (PV) solitons [2], [9] and screening–photovoltaic (SPV) solitons [10], [11] and also two-photon soliton have been predicted and observed experimentally. At the same time, coherent and incoherent soliton pairs and soliton interaction have also been investigated [11]-[13]. For two mutually incoherent beams the total intensity can be considered as the term of the two intensities. In a particular case, where the PR crystal is externally biased, bright and dark as well as gray solitary wave have been predicted under steady state conditions [14]-[16]. Investigation of screening solitons, which occurs in steady state when an external bias voltage, is appropriately applied to a PR crystal [7], [13], [17]. Such soliton states are possible provided that the optical beam is linearly polarized. In addition, vector solitons involving the two polarization components of an optical beam have also been predicted in biased PR materials. Depending on the symmetry class of the appropriate crystal and its orientation, these solitary beams were found to obey a self-coupled or a cross-coupled system of nonlinear evolution equations. Self-coupled vector solitons can be realized only in certain non-centro-symmetric crystals where the perturbed diagonal permittivity terms must be equal. Cross-coupled solitons require phase matching between the two polarizations. All of the investigations mentioned above are applied to one-component PR, meanwhile these observations can be done for the two-component solitons which indicate two incoherently coupled solitons propagated without distorting in PR crystal. In the other words, knowing the phase at a given point on the self-trapped beam, one can predict the phase at any point across the beam [18], [19].

Here, we find the beam profiles of incoherently coupled soliton pairs in biased photorefractive crystals under steady-state conditions and investigate its stability under propagation. Such solitons can propagate in bright-bright, dark-dark, gray-gray as well as in bright-dark types. Since the two sources are mutually incoherent, no phase matching arrangement is required. In follow, the functional form of solitons and propagation characteristics of these self-trapped pairs are introduced. Finally, the effect of self-deflection is investigated. Our simulation refers to convert wave equation to integral equation and seek soliton solution numerically.

II. MODEL AND DISCUSSION

Consider a Struntium Barium Niubite (SBN) crystal with optical c-axis oriented in the x-direction. Two mutually incoherent laser beams are used to illuminate the lossless PR crystal. It is not necessary that the two beams share the same frequency. Similar results for the incoherent interactions are also expected when the two carrier beams with different frequency are larger than the inverse response time of the photorefractive medium. The two beams may originate from the same laser source with appropriate coherence length. The polarization of both optical beams is assumed to be parallel to the x axis.

The two optical beams can also propagate collinearly along the z-axis and are allowed to diffract only along the x-direction. In one dimensional case diffraction in y-direction has been neglected. Furthermore, the external biased electric field is applied in the x-direction (i.e., the c axis). In this case, the perturbed refractive index along the x-axis for both beams is introduced by $n_e'^2 = n_e^2 - n_e^4 r_{33} E_s$, where n_e is the unperturbed extraordinary index of refraction and $\boldsymbol{E}_s = E_s \hat{x}$ is the space charge field in the PR crystal.

The optical fields in terms of slowly varying envelopes which are introduced as $\varepsilon_1 = \hat{x}\phi(x,z)e^{ikz}$ and $\varepsilon_2 = \hat{x}\psi(x,z)e^{ikz}$ satisfy in the following evolution equations [13]:

$$i\,\phi_z + \frac{1}{2k}\phi_{xx} - \frac{k_0(n_e^3 r_{33} E_s)}{2}\phi = 0 \tag{1}$$

$$i\,\psi_z + \frac{1}{2k}\psi_{xx} - \frac{k_0(n_e^3 r_{33} E_s)}{2}\psi = 0 \tag{2}$$

where $\phi_z = \partial\phi/\partial z$, etc. The propagation constant is $k = k_0 n_e = (2\pi/\lambda_0) n_e$, and λ_0 is the free-space wavelength. Moreover, under strong biased and for relatively broad beam configurations, the steady-state space charge electric field generated by the total power density of the two optical beams $I = (n_e/2\eta_0)\left(|\phi|^2 + |\psi|^2\right)$ is approximately given by:

$$E_s(x,z) = E_0 \frac{I_d + I_\infty}{I_d + I(x,z)} \tag{3}$$

where I_d is the so-called dark irradiance and $I_\infty = I(x \to \pm\infty)$. E_0 is the space charge electric field at $x \to \pm\infty$. If the spatial extent of the optical waves involved is much less than the x-width of the PR crystal (W), then under a constant voltage bias V, E_0 will be approximately given by ±V/W. It is convenient to make the following dimensionless variables and coordinates as $\xi = z/\left(kx_0^2\right)$, $s = x/x_0$, $\phi = (2\eta_0 I_d/n_e)^{1/2} U$ and $\psi = (2\eta_0 I_d/n_e)^{1/2} U$. Here, x_0 is an arbitrary spatial width and the power densities of the optical beams which have been scaled with respect to the dark irradiance I_d .

Therefore, the normalized planar envelopes U and V are satisfied in:

$$iU_{\xi}+\frac{U_{ss}}{2}-\beta(1+\rho)\frac{U}{1+|U|^{2}+|V|^{2}}=0 \quad (4)$$

$$iV_{\xi}+\frac{V_{ss}}{2}-\beta(1+\rho)\frac{V}{1+|U|^{2}+|V|^{2}}=0 \quad (5)$$

where $\rho=I_{\infty}/I_{2d}$ and $\beta=(kx_0^2)^2 n_e^4 r_{33}E_0/2$. In the case of bright-bright soliton pairs, the intensity is expected to vanish at infinity $(s\to\pm\infty)$, and thus $I_{\infty}=\rho=0$. Soliton solutions can be obtained by expressing the envelopes $U=r^{1/2}y(s)\cos\theta\exp(i\mu\xi)$ and $V=r^{1/2}y(s)\sin\theta\exp(i\mu\xi)$.

Where μ represents a nonlinear shift to the propagation constant and the parameter θ is an arbitrary projection angle. The $y(s)$ is a normalized real function applies in $0\le y(s)\le 1$ condition, indicates the soliton pairs component and satisfies in the following equation:

$$\frac{d^2y}{d^2s}-2\mu y-\frac{2\beta}{1+ry^2}y=0 \quad (6)$$

This allows bright solitons when β or E_0 are positive quantities. By applying the boundary condition one can obtain the $\mu=-(\beta/r)\ln(1+r)$, and correspond integral equation for $y(s)$:

$$\left(\frac{dy}{ds}\right)^2=(2\beta/r)\left[\ln(1+ry^2)-y^2\ln(1+r)\right] \quad (7)$$

Normally, E_0 and the normalized peak intensity *r* determine the bright soliton profile. Consider a SBN crystal with the parameters $n_e=2.33$ and $r_{33}=237$ pm/V at a wavelength of $\lambda_0=0.5\ \mu$m, which induces the material sensitivity. By choosing the arbitrary spatial scale $x_0=25\mu$m and $E_0=1$kV/cm, we find that $\beta=34.5$. The total peak intensity of the pair *r*, is assumed to be 10 and $\theta=30°$. Fig. 1(a) depicts the normalized intensity profiles of bright-bright soliton pair related to these conditions. The horizontal axis shows '*s*' and the vertical axis represents 'Normalized Intensity'.

Dark-dark soliton pairs can also be achieved by choosing a constant intensity background I_{∞} and finite quantity ρ, with the envelopes U and V as $U=\rho^{1/2}y(s)\cos\theta\exp(i\mu\xi)$ and $V=\rho^{1/2}y(s)\sin\theta\exp(i\mu\xi)$, where $|y|\le 1$. Therefore, from Eqs. (4) and (5) dark type pair satisfies in:

$$\frac{d^2y}{d^2s}-2\mu y-2\beta(1+\rho)\frac{y}{1+\rho y^2}=0 \quad (8)$$

or in integral form with $\mu=-\beta$ as:

$$\left(\frac{dy}{ds}\right)^2=(-2\beta)\left[(y^2-1)-\frac{(1+\rho)}{\rho}\ln\left(\frac{1+\rho y^2}{1+\rho}\right)\right] \quad (9)$$

Which can be numerically solved provided that the biased voltage is negative i.e., β or $E_0<0$. The pair components can then be simply obtained by a θ projection. By solving Eq.(9) numerically with $\rho=10$ and $E_0=-1$kV/cm for chosen SBN crystal, we obtain the dark-dark soliton pair profiles that is shown in Fig. 1(b).

Another interesting class of these solitary states namely gray-gray pair is that the wave power density attains a constant value I_{∞} at infinity, resulting in a finite ρ. Thus, this family of waves is also expected to evolve according to Eqs. (4) and (5). To obtain these solutions, let us express U and V in the following fashion:

$$U=\rho^{1/2}y(s)\cos\theta\exp\left[i\left(\mu\xi+\int^{s}\frac{Jds'}{y^2(s')}\right)\right] \quad (10)$$

$$V=\rho^{1/2}y(s)\sin\theta\exp\left[i\left(\mu\xi+\int^{s}\frac{Jds'}{y^2(s')}\right)\right] \quad (11)$$

where J is a real constant which must be determined. For this manner, the normalized amplitude $y(s)$ is an even function of s and satisfies the boundary condition $y(s\to\pm\infty)=1$. All the derivatives of y are also zero at infinity. Moreover, we will assume that $y^2(s=0)=m$ (i.e., the intensity is finite at the origin) and $\dot{y}(0)=0$. Substitution of Eqs. (10) and (11) into Eqs. (4) and (5) the following differential equation is obtained:

$$\frac{d^2y}{d^2s} - 2\mu y - \frac{J^2}{y^3} - 2\beta(1+\rho)\frac{y}{1+\rho y^2} = 0 \tag{12}$$

Using the boundary conditions of y at infinity, we find that:

$$J^2 = -2(\beta+\mu) \tag{13}$$

Further, integrating of Eq. (12) yields:

$$\mu = \frac{(-\beta)}{(m-1)^2}\left[\frac{m(1+\rho)}{\rho}\ln\left(\frac{1+\rho m}{1+\rho}\right) + (1-m)\right] \tag{14}$$

and corresponding integral equation as:

$$\frac{d^2y}{ds^2} = 2\mu\left(y^2-1\right) + \frac{2\beta}{\rho}(1+\rho)\ln\left(\frac{1+\rho y^2}{1+\rho}\right) + 2(\mu+\beta)\left(\frac{1-y^2}{y^2}\right) \tag{15}$$

The set (β, ρ, m) has to be judiciously selected so that $(\dot{y})^2$ is positive for all values of y^2 and that $J>0$. Subsequently, the normalized amplitude $y(s)$ can be readily obtained by numerical integration of Eq. (15). It can be shown that these solitary waves are possible only when $m<1$ and $\beta>0$.

Therefore, this class of the dark family, unlike their bright or dark counterparts, their phase is no longer constant across 's' but instead varies in a rather involved fashion. Fig. 1(c) shows the normalized intensity profile of a gray-gray pairs for $\rho=5$, $x_0 = 40\mu$m, $m=0.4$ and $\beta=-34.5$. Note that the beam width also increases with the degree of grayness m.

Finally, bright-dark soliton pair is also studied. To find the soliton solutions, we seek an envelope functions as $U = r^{1/2} f(s)\exp(i\mu\xi)$ and $V = \rho^{1/2} g(s)\exp(i\nu\xi)$, where $f(s)$ and $g(s)$ correspond to the bright and dark beam profiles, respectively. By using Eqs. (4) and (5), the governed equation for $f(s)$ and $g(s)$ are obtained:

$$\frac{d^2f}{d^2s} = 2\left[\mu + \frac{\beta(1+\rho)}{1+rf^2+\rho g^2}\right]f \tag{16}$$

$$\frac{d^2g}{d^2s} = 2\left[\nu + \frac{\beta(1+\rho)}{1+rf^2+\rho g^2}\right]g \tag{17}$$

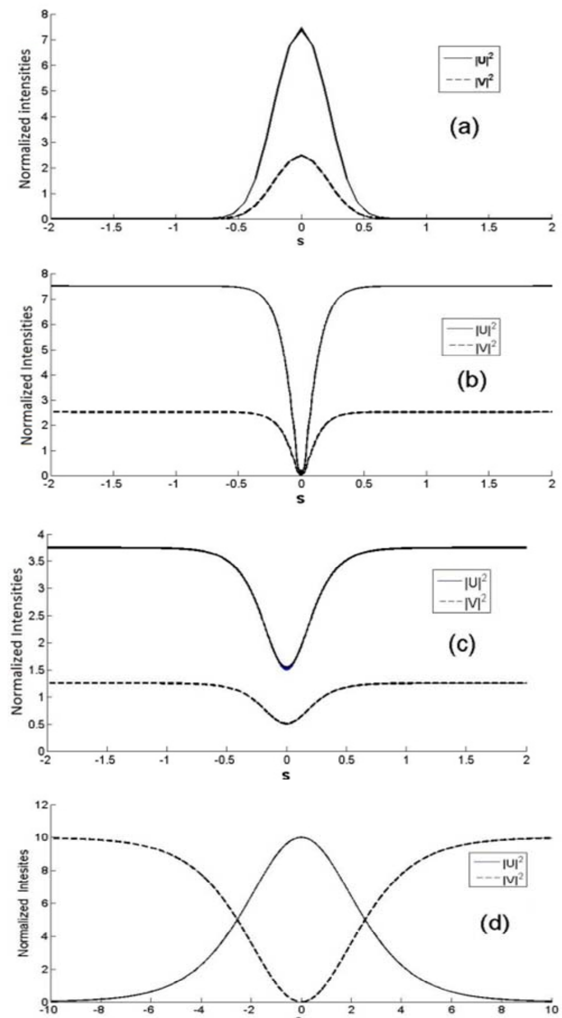

Fig. 1 Soliton components, $|U|^2$ (solid curve) and $|V|^2$ (dash–curve) for:(a) bright-bright pair when $r=10$ and $\theta=30°$, (b) dark-dark pair when ρ=10 and $\theta=30°$, (c) gray-gray pair when $\rho=5$ and $\theta=30°$, $m=0.4$,(d) bright-dark pair when $\rho=10$, $r=10$ and $\delta=-0.01$.

Using appropriate boundary conditions and applying the constraint $f^2 + g^2 = 1$, μ and ν can be found as $\mu = -(\beta/\delta)\ln(1+\delta)$ and $\nu = -\beta$, where $\delta = (r-\rho)/(1+\rho)$.

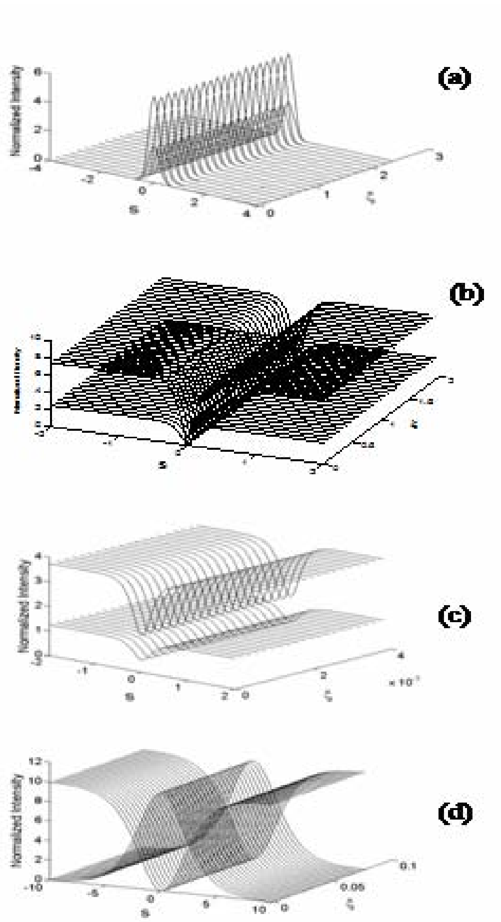

Fig. 2 Stable propagation of (a) the bright-bright soliton pair $r=10$, $\theta = 30°$ when its larger intensity component is perturbed by 20% at the input and soliton oscillate and don't become width. (b) The dark-dark pair when $\rho = 10$ and $\theta = 30°$. (c) The gray-gray pair when $\rho = 5$ and $\theta = 30°$, $m = 0.4$. (d) The bright-dark pair when $\rho = 10$, $r = 10$ and $\delta = -0.01$.

We solve Eqs. (16) and (17) numerically and the results for the bright-dark soliton pair with $\rho = 10$, $\delta = -0.01$ and $E_0 = -1\,\text{kV/cm}$ in introduced SBN crystal is shown in Fig. 1(d). Our solutions are in good agreement with approximate solution given by [13]:

$$U = r^{1/2} \sec h\left[(\beta\delta)^{1/2} s\right] \exp\left[-i\beta(1-\delta/2)\xi\right] \quad (18)$$

$$V = \rho^{1/2} \tan h\left[(\beta\delta)^{1/2} s\right] \exp(-i\beta\xi) \quad (19)$$

The above equations clearly show that these solutions are possible only when the product ($\beta\delta$) is a positive quantity.

In this case, the peak intensity of the bright beam is slightly lower than that of the dark background intensity.

Propagation and dynamical evolution of the beam is a main topic of nonlinear interaction between the beam and medium. In soliton state solution, simulation of the behavior of the beam under propagation show the stability properties. In particular, their stability is investigated here using numerical techniques and as usual we attend to simulate propagation of soliton pairs under perturbation.

Fig. 2(a) show bright-bright pair obtained at $r = 10$ and $\theta = 30°$ and depicts the evolution of the pair components when the high intensity beam has been perturbed by 20% in its amplitude. In general, we have found that bright-bright, dark-dark and gray-gray pairs are stable against small perturbations in amplitude. Numerical simulation shows that the pairs exhibit robustness and does not break up, and instead have small oscillates around the soliton solution which is increased by increasing the perturbation.

In the case of the bright-dark pair, it is claimed that they are stable only when β is negative. Stable propagation of this pair is shown in Fig. 2(d). In all cases each component propagates through the other one without any changes or interferences.

III. Effect of Self-Deflection

In this part, we investigate self-deflection of the optical beam in addition to self-focusing. It achieves when the diffusion process are considered in the wave equation. In the case of soliton pairs, Eqs. (4) and (5) are transformed to the following equations [10, 16]:

$$iU_{\xi}+\frac{U_{ss}}{2}-\beta(1+\rho)\frac{U}{1+|U|^2+|V|^2}+ \gamma\frac{U\left(|U|^2+|V|^2\right)_S}{1+|U|^2+|V|^2}=0 \tag{20}$$

$$iV_{\xi}+\frac{V_{ss}}{2}-\beta(1+\rho)\frac{V}{1+|U|^2+|V|^2}+ \gamma\frac{V\left(|U|^2+|V|^2\right)_S}{1+|U|^2+|V|^2}=0 \tag{21}$$

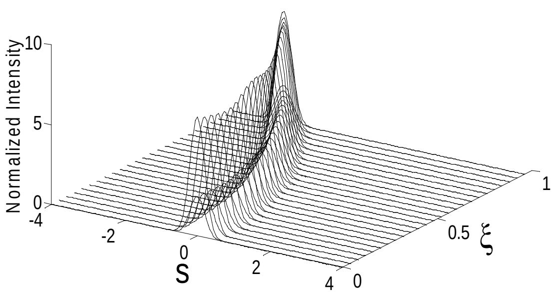

Fig. 3 3-D representation of bright-bright soliton pair propagation when $r=10$ and $\gamma=0.56$ in.

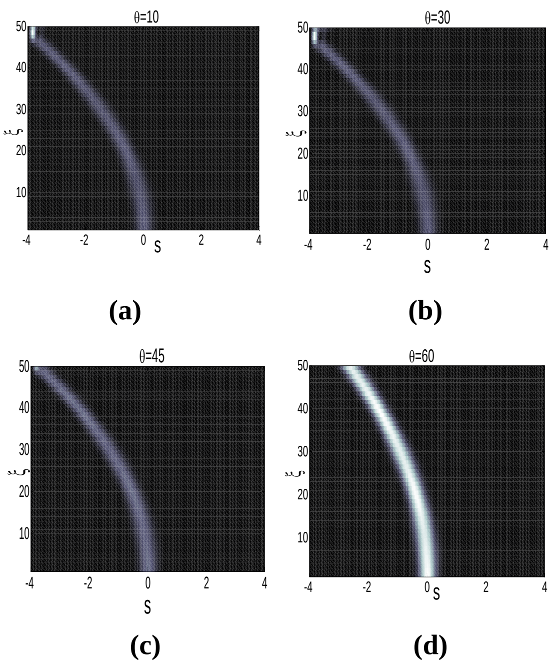

Fig. 4 Bright-bright soliton pair propagation when r=10 and $\gamma=0.56$ for (a) θ=10°, (b) θ=30°, (c) θ=45° and (d) θ=60°.

In follow, we numerically simulate the propagation of the bright-bright soliton pairs by considering different θ, for $r=10$ and $\gamma=0.56$.

Figure 3 shows deviation of bright-bright soliton pair from their original straight trajectory after taking into account the diffusion process.

It is interesting that the diffusion effect depending on the total intensity of the pair and the two components of the pair have the same deflection. The effect of parameter θ on self-bending for different values of θ is shown in Fig. 4. As it can be seen in this figure by increasing θ, the self-bending decreases. We also investigate the self-deflection of the other types of pairs numerically and find the same results.

IV. CONCLUSION

In conclusion, we study the incoherently coupled soliton pairs (bright-bright, dark-dark, gray-gray as well as bright-dark types) in one photon photorefractive crystals under steady-state conditions. These soliton states can be established when carrier beams share the same polarization, wavelength, and are mutually incoherent. Stability properties against small perturbation in amplitude are also discussed. Numerical results show robustness, and instead the peak power oscillates around the soliton solution slowly. Then bright-bright pairs can traverse a longer distance without broadening in comparison to the other types. These pairs propagate through each other without any change in shape or exchange the power. These investigations are useful in many applications. For example soliton interaction, that is one of the most fascinating aspects in soliton physics, and the soliton pair, that is an intriguing issue about the interaction between two solitons. Also directional couplers are another type of optical switches that can be formed by two parallel photorefractive spatial solitons. Finally, we investigated the self-deflecting process for bright-bright case and we found out that they deviate from their original straight without breaking up. Thus, by changing θ and the input intensity, the output point for soliton changes and the intensity can be changed a little in different θ. This can be useful for designing and producing optical devices such as sensitive optical switches.

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REFERENCES

[1] L. Yan, H. Wang, Q. Jin, and W. Gu, "Self-deflection of partially spatially incoherent beams and solitons in photovoltaic photorefractive crystals," Opt. Commun. vol. 281, pp. 5610-5613, Aug. 2008.

[2] N. Asif, S. Shwetanshumala, and S. Konar, "Photovoltaic spatial solitons pairs in two-photon photorefractive materials," Phys. Lett. A, vol. 372, pp. 735-740, Jan. 2008.

[3] A. Keshavarz and Z. Khalife, "One-dimensional optical bright screening photovoltaic photorefractive solitons, soliton pairs and incoherent interaction between them in $BaTiO_3$ crystal," Optic Int. J. for Light and Electron. Opt. vol. 120, pp. 535-542, Oct. 2009.

[4] G.F. Calvo, F.A. Lopez, M. Carrascosa, M.R. Belic, and D. Vujic, "Two-dimensional soliton-induced refractive index change in photorefractive crystals," Opt. Commun. vol. 227, pp. 193-202, Sep. 2003.

[5] J. Liu, "Separate spatial soliton pairs and soliton interaction in an unbiased series photorefractive crystal circuit," Phys. Lett. A, vol. 300, pp. 200-213, July 2002.

[6] J. Liu and Z. Hao, "Evolution of separate screening soliton pairs in a biased series photorefractive crystal circuit," Phys. Rev. E, vol. 65, pp. 066601 (1-12), Jun. 2002.

[7] M. Segev, G.C. Valley, B. Crosignani, P. Diporto, and A. Yariv, "Steady-State Spatial Screening Soliton in Photorefractive Materials with External Applied Field," Phys. Rev. Lett. vol. 73, pp. 3211–3214, no. 24, 1994.

[8] K. Kos, H. Meng, G. Salamo, M.F. Shih, M. Segev, and G.C. Valley, "One-dimensional steady-state photorefractive screening soliton," Phys. Rev. E, vol. 53, pp. R4330-R4333, May 1996.

[9] M. Segev, G.C. Valley, M.C. Bashaw, M. Taya, and M.M. Fejer, "Photovoltaic spatial solitons," J. Opt. Soc. Am. B, vol. 14, pp. 1772-1781, Jul. 1997.

[10] J. Liu and L. Keqing, "Screening-photovoltaic solitons in a biased photovoltaic-photorefractive crystals and their self-deflection," J. Opt. Soc. Am. B, vol. 16, pp. 550-555, no. 4, 1999.

[11] G. Zhang and J. Liu, "Screening-photovoltaic spatial solitons in a biased two-photon photovoltaic photorefractive crystals," J. Opt. Soc. Am. B, vol. 26, pp. 113-120, Jun. 2009.

[12] X. Ji, Q. Jiang, J. Yao, and J. Liu, "Separate spatial soliton pairs in an unbiased series two-photon photorefractive crystal circuit," Opt. Laser. Technol. vol. 42, pp. 322-327, July 2009.

[13] D.N. Christodoulides, S.R. Singh, M.I. Carvalho, M. Segev, "Incoherently coupled soliton pairs in biased photorefractive crystals," Appl. Phys. Lett. vol. 68, pp. 1763-1765, Jan. 1996.

[14] M.I. Carvalho and D.N. Christodoulides, "Bright, dark, and gray spatial soliton states in photorefractive media," J. Opt. Soc. Am. B, vol. 12, no. 9, pp. 1628-1633, Sep. 1995.

[15] A.G. Grandpierre, D.N. Christodoulides, T.H. Coskun, M. Segev, and Y.S. Kivshar, "Gray spatial solitons in biased photorefractive media,"J. Opt. Soc. Am. B, vol. 18, no. 1, pp. 55-63, 2001.

[16] M.I. Carvalho, S.R. Singh, and D.N. Christodoulides, "Self-deflection of steady-state bright spatial solitons in biased photorefractive crystals," Opt. Commun, vol. 120, pp. 311-315, Nov. 1995.

[17] L. Jinsong, "Universal theory of steady-state one-dimentional photorefractive solitons," Chin. Phys. Soc. vol. 10, no. 11, pp. 1037-1042, Nov. 2001.

[18] M. Mitchell, Z. Chen, M. Shih, and M. Segev, "Self-Trapping of Partially Spatially Incoherent Light," Phys. Rev. Lett. vol. 77, no. 3, pp. 490-493, July 1996.

[19] M. Mitchell, M. Segev, T.H. Coskun, and D.N. Christodoulides, "Theory of Self-Trapped Spatially Incoherent Light Beams," Phys. Rev. Lett. vol. 79, no. 25, pp. 4990-4993, Dec. 1997.

[20] Z. Chen, M. Mitchell, M. Shih, M. Segev, M. H. Garrett, G. C. Valley, "Steady-state dark photorefractive screening solitons,"Opt. Lett. vol. 21, no. 19, pp. 629-631, no. 9, 1996.

[21] G. Evans, J. Blackledge, and P. Yardley, *Numerical methods for partial differential equation*, Springer Verlag, Berlin, 2000.

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