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Effect of temperature on the evolution of bright and dark screening-photovoltaic spatial solitons*

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We investigate theoretically the temperature effects on the evolution of both bright and dark screening-photovoltaic optical spatial solitons in biased photovoltaic-photorefractive crystals in the case of neglecting the diffusion process. For a stable bright or dark screening-photovoltaic soliton originally formed in a crystal at a given temperature, when the crystal temperature changes, it will evolve into another stable screening-photovoltaic soliton if the change is quite small, whereas it will become unstable or break down if the temperature change is large enough. The spatial shape of a stable screening-photovoltaic soliton can be reshaped by appropriately adjusting the crystal temperature.

Keywords: nonlinear optics, spatial optical solitons, photorefractive effects
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1. Introduction

Spatial solitons in photorefractive media have aroused much interest in the past few years.[1−15] At present, three types of steady-state scalar solitons (screening solitons,[1−6] photovoltaic solitons[7−9] and screening-photovoltaic solitons[10−15]) have been predicted, and the first two have been found experimentally. Screening solitons are possible in the steady state when an external bias voltage is appropriately applied to a non-photovoltaic-photorefractive crystal.[1−6] These screening solitons result from nonuniform screening of the bias field. Photovoltaic solitons are possible in the steady state in a photovoltaic-photorefractive crystal without a bias field. These photovoltaic solitons result from the photovoltaic effect.[7−9] Recently, it has been predicted theoretically that the screening-photovoltaic (SP) solitons are possible in the steady state when an electric field is applied to a photovoltaic-photorefractive crystal.[10−15] These SP solitons result from both the photovoltaic effect and spatially nonuniform screening of the applied field. We can think of SP solitons as the unity form of screening and closed-circuit photovoltaic solitons. If the bias field is much stronger than the photovoltaic field, the SP solitons are just like the screening solitons. If the applied field is absent, the SP solitons degenerate into the photovoltaic solitons in the close-circuit condition. The evolution of bright SP solitons have been discussed and their stability then investigated.[11] The incoherently coupled SP soliton pairs have also been investigated.[13]

As is known, the photorefractive effects are dependent on the dark irradiance of the crystal, and the dark irradiance is dependent on the temperature.[19−21] As a result, the photorefractive effects, such as two-beam coupling and four-wave mixing, are strongly dependent on the crystal temperature.[16−21] Obviously, the evolution, stability and the spatial shape of a photorefractive spatial soliton will be dependent on the crystal temperature. However, so far the effects of temperature on the photorefractive solitons have not been studied. In this paper, we investigate the temperature effects on the evolution of both bright and dark SP solitons in biased photovoltaic-photorefractive crystals. Our results show that the width and maximum amplitude of both bright and dark SP solitons are sensitive to the crystal temperature. For a stable SP soliton originally formed in a crystal at a given temperature, when the crystal temperature deviates from the given temperature, it will become unstable or break down if the temperature difference is large enough, whereas it can evolve into another stable SP soliton if the temperature difference is quite small.

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2. Theoretical model

We derive and solve equations for beam propagation in biased photovoltaic-photorefractive media and obtain the properties of SP solitons in one transverse dimension. Let us consider an optical beam that propagates in a biased photovoltaic-photorefractive crystal along the z-axis and is permitted to diffract only along the x-direction, which is also the direction of the photovoltaic field of the crystal. We assume that the optical beam is linearly polarized along x and that the external bias electric field is applied in the same direction. In this physical system, by employing standard procedures and neglecting the loss in the material, we readily obtain the following envelope evolution equation[10-12]

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

Here the electric-field component $\boldsymbol{E}$ of the optical beam with a slowly varying envelope ϕ is given by $E = \hat{x}\phi(x,z)\exp(\mathrm{i}kz)$, $\phi_z = \partial\phi/\partial z$, $\phi_{xx} = \partial^2\phi/\partial x^2$, $k = k_0 n_\mathrm{e}$, $k_0 = 2\pi/\lambda_0$, λ_0 is the free-space wavelength of the light wave employed, n_e is the unperturbed extraordinary index of refraction, r_eff is the effective electro-optic coefficient, and E_sc is the space-charge field induced in this photovoltaic-photorefractive crystal.

In typical photovoltaic-photorefractive media and for relatively broad beam configurations, the value of the steady-state space-charge field can be obtained from the Kukhtarev's transport model by neglecting the diffusion process. It is approximately given by[10-12]

$$E_\mathrm{sc} = E_0\frac{I_\infty + I_\mathrm{d}}{I + I_\mathrm{d}} + E_\mathrm{p}\frac{I_\infty - I}{I + I_\mathrm{d}}, \qquad (2)$$

where $E_\mathrm{p}[= k_\mathrm{p}\gamma_\mathrm{R}N_\mathrm{A}/(e\mu)]$ is the photovoltaic field constant, γ_R is the carrier recombination rate, μ is the electron mobility, k_p is the photovoltaic constant, E_0 is the applied field, $I_\infty = I(x \to \pm\infty, z)$ and $I = I(x,z)$ is the power density of the optical beam in the crystal, and I_d is the so-called dark irradiance which depends strongly on the temperature. Here we use the one-level and one-carrier model presented by Cheng and Partovi,[16] which has been successfully used to explain the temperature dependence of the photorefractive effect in $LiNbO_3$,[17,18] and to describe the temperature dependence of I_d as the following

$$I_\mathrm{d} = I_{\mathrm{d}0}\left(\frac{T}{300}\right)^{3/2}\exp\left[\frac{E_\mathrm{t}}{K_\mathrm{B}}\left(\frac{1}{300} - \frac{1}{T}\right)\right], \qquad (3)$$

where $I_{\mathrm{d}0}$ is the value of I_d at T=300K, and E_t is the level location in the gap. For photovoltaic-photorefractive crystals, such as $LiNbO_3$, $E_\mathrm{t} \sim 10^{-19}$J.[17,18] For simplicity, we take $E_\mathrm{t} = 10^{-19}$J.

The envelope evolution equation can now be established by inserting Eq.(2) into Eq.(1). 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: $\xi = z/(kx_0^2)$, $s = x/x_0$ and $\phi = (2\eta_0 I_\mathrm{d}/n_\mathrm{e})^{1/2}U$. Here $\eta_0 = (\mu_0/\varepsilon_0)^{1/2}$, x_0 is an arbitrary spatial width, and the power density has been scaled with respect to the dark irradiance I_d. Using Eqs.(1) and (2), we can then show that the normalized envelope U satisfies the following dynamical evolution equation

$$\mathrm{i}U_\xi + \frac{1}{2}U_{ss} - \beta(\rho+1)\frac{U}{1+|U|^2} - \alpha\frac{(\rho - |U|^2)U}{1+|U|^2} = 0, \qquad (4)$$

where $\alpha = (k_0x_0)^2(n_\mathrm{e}^4 r_\mathrm{eff}/2)E_\mathrm{p}$, $\beta = (k_0x_0)^2(n_\mathrm{e}^4 r_\mathrm{eff}/2)$ E_0 and $\rho = I_\infty/I_\mathrm{d}$. Generally, α and β do not depend strongly on temperature. In this paper, we pay attention primarily to the temperature dependence of I_d.

In the case of bright soliton states the optical beam intensity is expected to vanish at infinity ($s \to \pm\infty$), and thus $\rho = I_\infty/I_\mathrm{d} = 0$. By expressing the beam envelope U in the usual fashion, $U = r^{1/2}y(s)\exp(\mathrm{i}\nu\xi)$. Here 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 r is defined as $r = I(0)/I_\mathrm{d}$. By integrating Eq.(4) under the boundary conditions, $y(0) = 1$, $\dot{y}(0) = 0$ and $y(s \to \pm\infty) = 0$, we find that[10-12]

$$[2(\beta+\alpha)]^{1/2}s = \pm\int_{y(s)}^{1}\frac{r^{1/2}\mathrm{d}\hat{y}}{[\ln(1+r\hat{y}^2) - \hat{y}^2\ln(1+r)]^{1/2}}, \qquad (5)$$

and $\nu = -\dfrac{\beta+\alpha}{r}\ln(1+r) + \alpha$. The bright solitary beam profile can be easily obtained from Eq.(5) by simple numerical integration. Letting $r_0[= I(0)/I_{\mathrm{d}0}]$ denote the value of r at T=300K, using Eq.(3), the quantity $r = I(0)/I_\mathrm{d}$ can be expressed as

$$r = r_0\left(\frac{T}{300}\right)^{-3/2}\exp\left[-\frac{E_\mathrm{t}}{K_\mathrm{B}}\left(\frac{1}{300} - \frac{1}{T}\right)\right]. \qquad (6)$$

The dark SP solitary solution can be derived from Eq.(4) by expressing the beam envelope U in the usual

fashion: $U = \rho^{1/2} y(s) \exp(\mathrm{i}\nu\xi)$. For the dark spatial solitons, we require that $y(0) = 0$, $\dot{y}(\infty) = 0$ and $y(s \to \pm\infty) = 1$. Substitution of this latter form of U into Eq.(4) yields that the normalized dark-field profile $y(s)$ can be determined from the following equation

$$[-2(\beta+\alpha)]^{1/2} s = \pm \int_{y(s)}^{1} \frac{\mathrm{d}\hat{y}}{\left[(\hat{y}^2 - 1) - \dfrac{\rho+1}{\rho} \ln\left(\dfrac{1+\rho\hat{y}^2}{1+\rho}\right)\right]^{1/2}}, \quad (7)$$

and $\nu = -\beta$. The dark solitary beam profile can be easily obtained from Eq.(7) by simple numerical integration. Letting $\rho_0 [= I_\infty / I_{\mathrm{d}0}]$ denote the value of ρ at T=300K, using Eq.(3), the quantity $\rho = I_\infty / I_{\mathrm{d}}$ can be expressed as

$$\rho = \rho_0 \left(\frac{T}{300}\right)^{-3/2} \exp\left[-\frac{E_{\mathrm{t}}}{K_{\mathrm{B}}}\left(\frac{1}{300} - \frac{1}{T}\right)\right]. \quad (8)$$

The sign of β is dependent on the polarity of E_0, whereas the sign of α is dependent on the characteristics of the photovoltaic crystal and the polarization of the light.[22] Therefore, either positive or negative signs of β and α are possible. However, from Eqs.(5) and (7), the conditions to obtain bright and dark SP solitons are $(\alpha+\beta) > 0$ and $(\alpha+\beta) < 0$, respectively.

3. Results and discussion

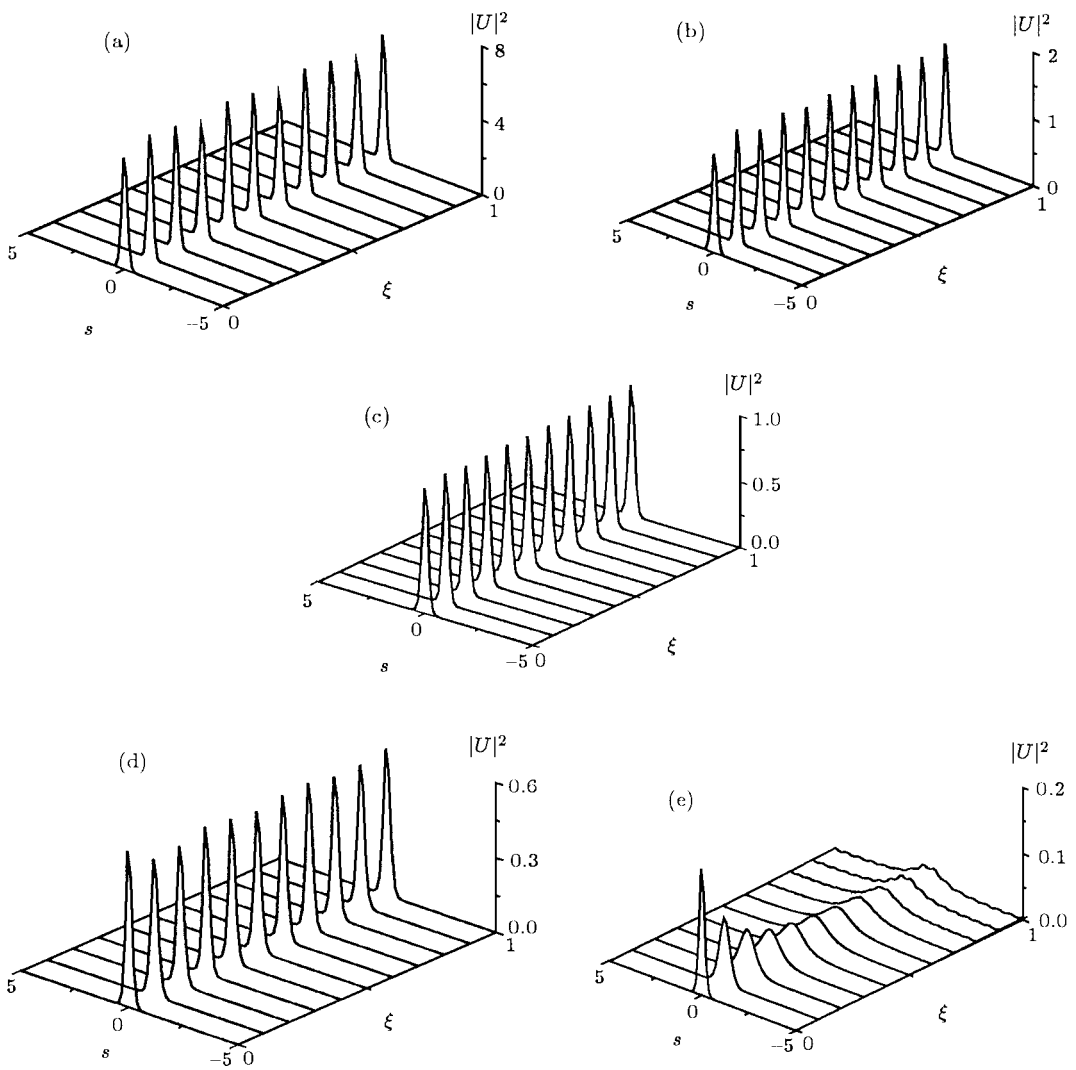


Fig.1. Dynamical evolution of an input bright SP soliton in the crystal with α=−223, β=300, r_0=1 and $E_{\mathrm{t}} = 10^{-19}$J at (a) T=280K, (b) $T = 295K$, (c) T=300K, (d) T=305K and (e) T=320K. The input bright SP solitary state was obtained originally from Eq.(5) with α=−223, β=300, r_0=1 and $E_{\mathrm{t}} = 10^{-19}$J at T=300K.

We begin our investigation with the temperature effects on the evolution of the bright SP solitons in biased photovoltaic-photorefractive crystals. In doing so, a bright SP soliton is obtained from Eq.(5) with the system parameters chosen to be $\alpha = -223$, β=300, r_0=1 and $E_t = 10^{-19}$J at T=300K. Taking the bright solitary state as the input beam, its evolution in the crystal with the same system parameter is analysed by numerically solving Eq.(4) at T=280K, 295K, 300K, 305K and 320K, respectively, as shown in Fig.1. First, let us examine the case of T=300K, as shown in Fig.1(c). As expected, our results confirm that the bright soliton beam remains invariant with propagation distance in the crystal at 300K. We then examine the case that the crystal temperature deviates slightly from 300K. Figs.1(b) and (d) give the evolution of the incident bright SP soliton in the crystal at T=295K and T=305K, respectively. We can see that the incident beam reshapes itself and tends to evolve into another stable bright SP soliton. Finally, we consider the case that the crystal temperature deviates significantly from 300K. Figs.1(a) and (e) give the evolution of the incident bright SP soliton in the crystal at T=280K and T=320K, respectively. We can see that the incident beam cannot evolve into a stable bright SP soliton but instead tends to experience larger cycles of compression and expansion, and its maximum amplitude oscillates with propagation distance at T=280K, or to be divergent at T=320K.

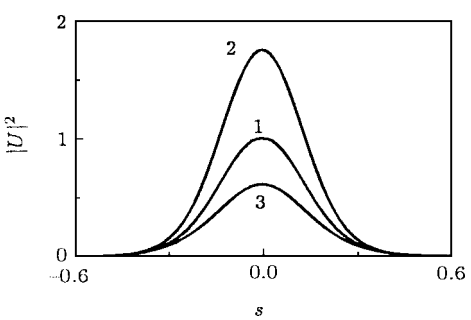


Fig.2. Intensity profiles of bright SP solitons formed in the crystal with α=–223, β=300, r_0=1 and $E_t = 10^{-19}$J at ξ=1: 1, T=30K; 2, T=295K; 3, T=305K.

Figure 2 gives the intensity profiles of the stable bright SP soliton at ξ=1; curves 1, 2 and 3 represent T=300K, 295K and 305K, respectively. We can see that the width and maximum amplitude of the stable bright SP solitons at ξ=1 change with temperature. This means that the spatial shape of a stable bright SP soliton can be reshaped by appropriately adjusting the crystal temperature.

We now investigate the temperature effects on the evolution of dark SP solitons in biased photovoltaic-photorefractive crystals. In doing so, we choose a dark SP soliton as the incident beam. The dark SP soliton is obtained from Eq.(7) with α=–223, β=118, ρ_0=1 and $E_t = 10^{-19}$J at T=300K. The evolution of the incident dark SP soliton in the crystal with the same parameters at T=300K is shown in Fig.3(c), and its intensity profile at ξ=1 is shown in Fig.4 by curve 1. As expected, our results confirm that the dark soliton beam remains invariant with propagation distance. However, when the crystal temperature deviates slightly from 300K, the incident beam cannot remain invariant with propagation distance, but instead reshapes itself and tends to evolve into another stable dark SP soliton, as shown in Figs.4(b) and 4(d) for T=295K and T=305K, respectively. The intensity profiles of the dark SP soliton evolved at ξ=1 for the two temperatures are shown in Fig.4 by curve 2 for T=295K and by curve 3 for T=305K. The width and maximum amplitude of the dark SP soliton change with crystal temperature, similar to the bright SP soliton.

Finally, we consider the case that the crystal temperature deviates significantly from 300K. Figs.3(a) and 3(e) give the evolution of the incident dark SP soliton in the crystal at T=280K and T=320K, respectively. We can see that the optical beam in the crystal becomes unstable at T=320K, but it can still evolve into another stable dark SP soliton at T=280K. In contrast to the case of bright SP solitons, dark SP solitons are more insensitive to crystal temperature. When the crystal temperature decreases further, the optical beam in the crystal also becomes unstable.

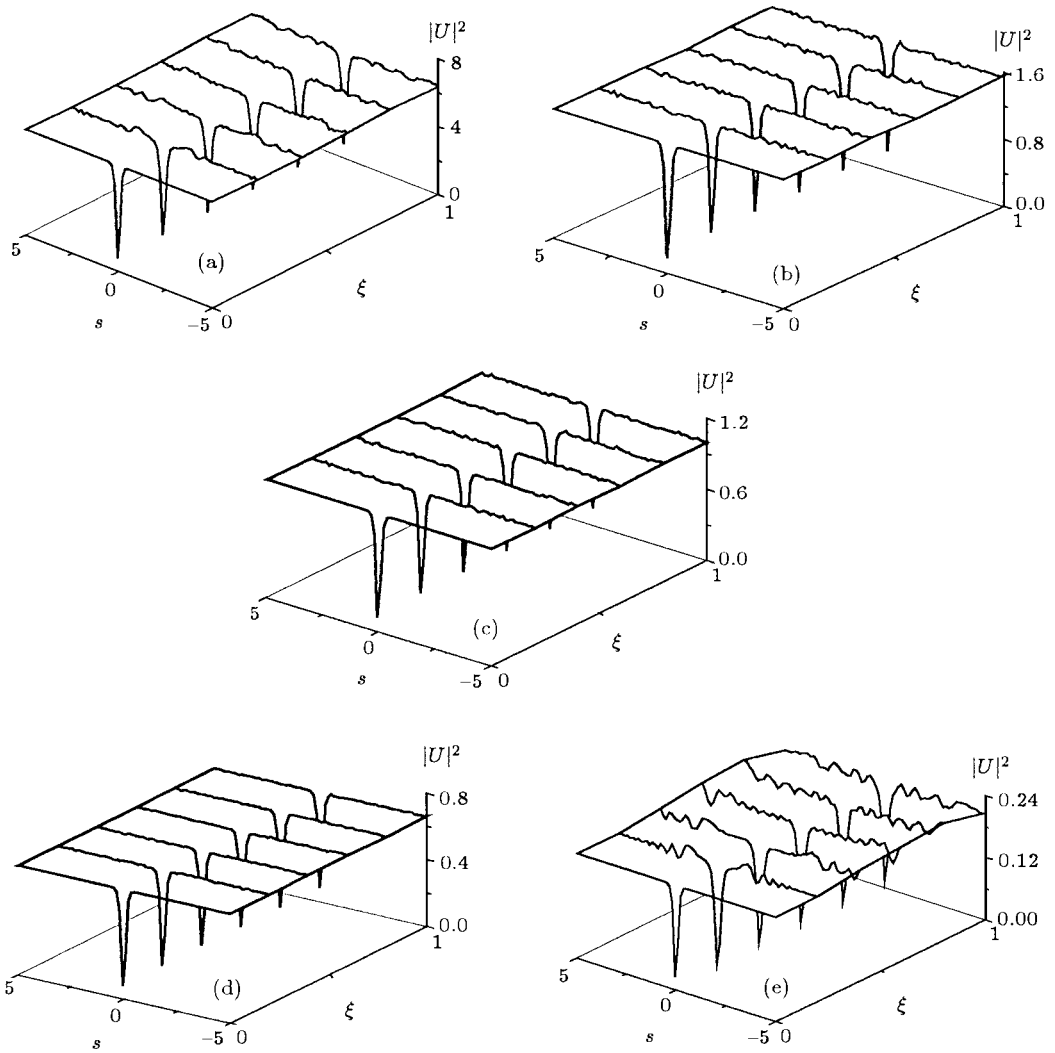


Fig.3. Dynamical evolution of an input dark SP soliton in a crystal with α=−223, β=118, ρ_0=1 and $E_t = 10^{-19}$J at (a) T=280K, (b) T=295K, (c) T=300K, (d) T=305K and (e) T=320K. The dark SP soliton was originally formed from Eq.(7) with the same system parameters at T=300K.

The results obtained above indicate that the temperature effects on the evolution of both bright and dark SP solitons are obvious. For a stable bright (dark) SP soliton formed in a crystal at temperature T_0, when the crystal temperature changes from T_0 to T, the solitary state can evolve into another stable bright (dark) SP soliton when the temperature difference between T and T_0 is quite small. Whereas the solitary state cannot remain stable but instead tends to experience larger cycles of compression and expansion, and its maximum amplitude oscillates with propagation distance or tends to break up into beam filaments when the difference between T and T_0 is large enough. The spatial shapes of both stable bright and dark SP solitons can be reshaped by appropriately adjusting the crystal temperature.

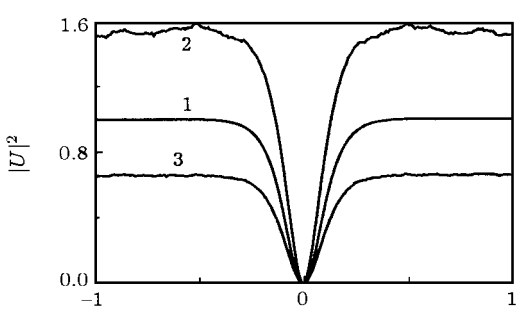


Fig.4. Intensity profiles of dark SP solitons formed in the crystal with α=−223, β=118, ρ_0=1 and $E_t = 10^{-19}$J at ξ=1: 1, T=300K; 2, T=295K; 3, T=305K.

4. Conclusion

In conclusion, we present a theoretical investigation of the temperature effects on the evolution of both

dark and bright SP solitons in biased photovoltaic-photorefractive crystals under steady-state conditions. The spatial shapes of stable SP solitons in a crystal at different temperatures are calculated. The dynamical evolutions of SP solitons in a crystal at different temperatures are discussed.

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 and 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, Crosignani B, Yariv A, 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 and Lu K Q 1999 *J. Opt. Soc. Am.* B **16** 550

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

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

[13] Hou C F, Yuan B H, Sun X D and Xu K B 2000 *Acta Phys. Sin.* **49** 1969 (in Chinese)

[14] Liu J S 2001 *Acta Phys. Sin.* **50** 880 (in Chinese)

[15] Liu J S 2001 *Chin. Phys.* **10** 1037

[16] Cheng L J and Partovi A 1986 *Appl. Phys. Lett.* **49** 1456

[17] Liu J S, Liang C K, An Y Y, Li M G, Jing C and Xu Y H 1995 *Ferroelectrics* **168** 127

[18] Liu J S, Liang C K, An Y Y, Li M G, Xu Y H and Wu Z K 1996 *Chin. Phys. Lett.* **13** 135

[19] Liu J S, Liang C K, An Y Y, Li M G, Xu Y H and Wu Z K 1995 *Appl. Phys. Lett.* **67** 2020

[20] Nouchi P, Partanen P J and Hellwarth R W 1992 *J. Opt. Soc. Am.* B **9** 1428

[21] Hu J G, Xu X G, Mu X D, Chen H C and Shao Z S 1999 *Opt. Commun.* **164** 219

[22] Sturman B I and Fridkin V M 1992 *The Photovoltaic and Photorefractive Effect in Non-centrosymmetric Materials* (Philadelphia: Gordon and Breach)