Effects of temperature on the dynamic evolution of two-photon photorefractive screening spatial solitons*

JI Xuan-mang（吉选芒）[1**], **JIANG Qi-chang**（姜其畅）[1], and **LIU Jin-song**（刘劲松）[2]

1. Department of Physics and Electronic Engineering, Yuncheng University, Yuncheng 044000, China

2. College of Optoelectronic Science and Engineering, Huazhong University of Science and Technology, Wuhan 430074, China

(Received 23 January 2011)

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

Document code: A **Article ID:** 1673-1905(2011)04-0317-4

DOI 10.1007/s11801-011-9065-7

Spatial solitons in photorefractive media have aroused much interest in the past few years. At present, three types of steady-state solitons have been investigated, namely, screening solitons[1], photovoltaic solitons[2] and screening-photovoltaic solitons[3]. All of them are from the single-photon photorefractive effect. In 2003, Castro-Camus and Magana[4] provided a new model of the two-photon photorefractive effect. Later, Hou chunfeng[5-8] firstly demonstrated the spatial solitons in two-photon photorefractive media and predicted that bright, dark, gray, incoherent coupled bright-bright, dark-dark and bright-dark spatial solitons could be formed in two-photon photorefractive media.

The photorefractive effects are dependent on the dark irradiance of the crystal, and the dark irradiance is dependent on the temperature[9,10]. As a result, the shape and evolution of photorefractive spatial solitons are affected by the crystal temperature. Zhang Yu[11] investigated the temperature influence on the characteristics of lower-amplitude screening spatial solitons in two-photon photorefractive crystal, but that on the dynamic evolution of screening solitons has not been investigated. In this paper, we investigate the effect of temperature on the dynamic evolution of screening solitons in two-photon photorefractive crystals.

We consider an optical beam that propagates in a photorefractive medium with the two-photon photorefractive effect along the z axis and is permitted to diffract only along the x direction. The photorefractive crystal is put with its optical axis oriented along the x direction and is illuminated by the gating beam. Moreover, it's assumed that the polarization of the incident optical beam is parallel to the optical axis, and an external electric field is applied in the same direction. As usual, we express the optical field of the incident beam in terms of slowly varying envelope ϕ, i.e.,

$$\boldsymbol{E} = x\phi(x,z)\exp(\mathrm{i}kz) \quad , \tag{1}$$

where $k = k_0 n_e = (2\pi/\lambda_0) n_e$, n_e is the unperturbed extraordinary index of refraction, and λ_0 is the free-space wavelength. Under these conditions, the optical beam satisfies the following envelope evolution equation:

$$\mathrm{i}\phi_Z + \frac{1}{2k}\phi_{xx} - \frac{k_0 n_e^3 r_{33} E_{sc}}{2}\phi = 0 \quad , \tag{2}$$

where $\phi_Z = \partial\phi/\partial z$, $\phi_{xx} = \partial^2\phi/\partial x^2$, r_{33} is the electro-optic coefficient, and E_{sc} is the space charge field in the medium. Under strong bias conditions E_0 will be large enough, and therefore the drift component of the current in the medium will be dominant. In this case, the diffusion effect can be considered to be small and can be ignored. Thus the expres-

* This work has been supported by the Science and Technology Development Foundation of Higher Education of Shanxi Province, China (No. 200611042).

** E-mail: jixuanmang@126.com

sion for the space charge field can be simplified as[5]

$$E_{sc} = E_0 \frac{(I_{2\infty} + I_{2d})(I_2 + I_{2d} + \gamma_1 N_A / s_2)}{(I_{2\infty} + I_{2d} + \gamma_1 N_A / s_2)(I_2 + I_{2d})} , \quad (3)$$

where the biased electric field is E_0, I_2 is the intensity of the soliton beam, $I_{2\infty} = I_2(\infty, z)$, N_A is the acceptor of trap density, γ_1 is the recombination factor between the intermediate allowed level and valence band, $I_{2d} = \beta_2 / s_2$ is the dark irradiance intensity, β_2 is the thermoionization probability constant for the transitions between the intermediate allowed level and conduction band, and s_2 is the hotoexcitation crosses. The temperature dependence of I_{2d} is described as follows[9]

$$I_{2d} = I_{2d0} (\frac{T}{300})^{3/2} \exp\left[\frac{E_t}{k_B}\left(\frac{1}{300} - \frac{1}{T}\right)\right] , \quad (4)$$

where I_{2d0} is the value of I_{2d} at T=300 K, E_t=10^{-9} J is the level location in the gap, and k_B is Boltzmann's constant. Substituting Eq.(3) into Eq.(2), and adopting the following dimensionless coordinates and variables: $s = x/x_0$, $\xi = z/(kx_0)^2$, $U = (2\eta_0 I_{2d}/n_e)^{-1/2}\phi$, where x_0 is an arbitrary spatial width, the following dynamic evolution equation can be obtained

$$\mathrm{i}U_\xi + \frac{1}{2}U_{ss} - \frac{\beta(\rho+1)}{\rho+1+\sigma}(1 + \frac{\sigma}{1+|U|^2})U = 0 , \quad (5)$$

$$\sigma = \gamma_1 N_A / s_2 I_{2d} = \sigma_0 (\frac{T}{300})^{-3/2} \exp\left[-\frac{E_t}{k_B}\left(\frac{1}{300} - \frac{1}{T}\right)\right], \quad (6)$$

where $\sigma_0 = \gamma_1 N_A / s_2 I_{2d0}$ is the value of σ at T = 300 K, and $\beta = (k_0 x_0)^2 (n_e^4 r_{33}/2) E_0$.

To get dark soliton solution, we put $U = \rho^{1/2} y(s) \exp(\mathrm{i}u\xi)$, where $y(s)$ is a normalized odd function of s and satisfies the following boundary conditions: $y(0) = 0; y(s \to \pm\infty) = 1$, $y'(s \to \pm\infty) = y''(s \to \infty) = 0$, and all the derivatives of $y(s)$ vanish at infinity. Substituting this form of U into Eq.(5) leads to the following equation:

$$s = \pm\int_y^0 \{[-\frac{2\beta\sigma}{1+\sigma+\rho}][(y^2-1) - \frac{1+\rho}{\rho}\ln(\frac{1+\rho y^2}{1+\rho})]\}^{-1/2} \mathrm{d}y. \quad (7)$$

Dark solitary beam profile can be easily obtained by Eq.(7) through simple numerical integration. If $\rho_0 = I_{2\infty} / I_{2d0}$ is the value of ρ at T = 300 K, we can easily obtain:

$$\rho = \rho_0 (\frac{T}{300})^{-3/2} \exp[-\frac{E_t}{k_B}(\frac{1}{300} - \frac{1}{T})] . \quad (8)$$

The bright solitary solution can be derived from Eq.(5) by expressing the beam envelope U in the usual function: $U = r^{1/2} y(s) \exp(\mathrm{i}\nu\xi)$. Here ν represents a nonlinear shift of the propagation constant, and $y(s)$ is a normalized real function with $0 \le y(s) \le 1$. By integrating Eq.(5) under the boundary conditions: $y(0) = 1, y'(0) = 0, y(s \to \pm\infty) = 0$, we find that

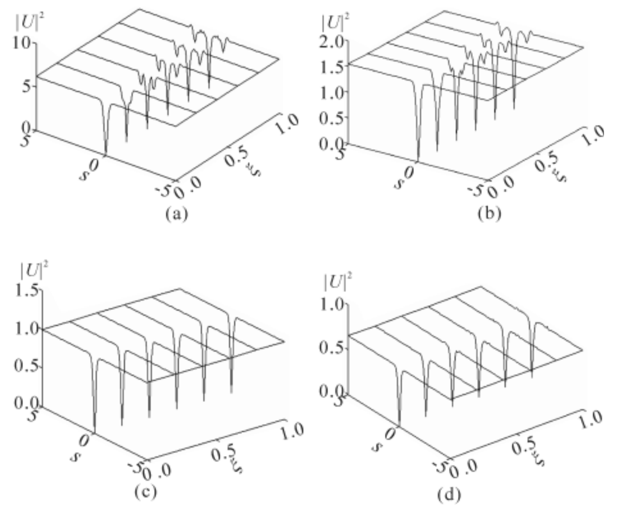
$$[2\beta\sigma/(1+\sigma)]^{1/2} s = \pm\int_y^1 \frac{r^{1/2}\,\mathrm{d}\tilde{y}}{[\ln(1+r\tilde{y}^2) - \tilde{y}^2 \ln(1+r)]^{1/2}} , \quad (9)$$

where $\nu = -[\beta/(1+\sigma)][1 + \sigma \ln(1+r)/r]$. The bright solitary beam profile can be obtained from Eq.(9) by simple numerical integration. Letting $r_0 = I_2(0)/I_{2d0}$ to be the value of r at T = 300 K and using Eq.(4), $r = I_2(0)/I_{2d}$ can be expressed as

$$r = r(T) = \frac{I_{20}}{I_{2d}(T)} = r_0 (\frac{T}{300})^{-3/2} \exp[-\frac{E_t}{k_B}(\frac{1}{300} - \frac{1}{T})] . \quad (10)$$

The dark or the bright soliton solution in Eq.(7) or (9) is the incident optical beam. Using Eqs.(6), (8) and (10), we can investigate the dynamic evolutions of both bright and dark screening spatial solitons in biased two-photon photorefractive crystals.

We firstly consider the temperature effects on the evolution of an incident dark screening soliton in the biased photorefractive crystal with parameters[5] of n_e=2.2, r_{33}=30×10^{-12} mV^{-1}, s_1=s_2=1.06 × 10^{-6} m^2, β_1=β_2=0.05 s^{-1}, γ_1=3.3 × 10^{-17} m^{3}s^{-1}, N_A=10^{22} m^{-3}, λ_0=514.5 nm, x_0= 40 μm, and ρ_0=1 at T = 300 K. Fig.1(a)-(e) are the evolutions of dark soliton in two-photon photorefractive crystal with E_0=−1 × 10^6 V/m (β=−88.8) at T = 280 K, 295 K, 300 K, 305 K and 360 K respectively. As expected, the incident solitary beam is stable at T=300 K. We then examine the case that the crystal temperature deviates slightly from 300 K. Fig.1(b) and (d) give the evolutions of incident dark soliton in the crystal at T = 295 K and T = 305 K, respectively. We can see that the incident beam reshapes itself and tends to evolve into another stable dark screening soliton. However, the incident beam cannot evolve into a stable one and even tends to break down if the temperature change is large enough, as shown in Fig.1 (a) and (e).



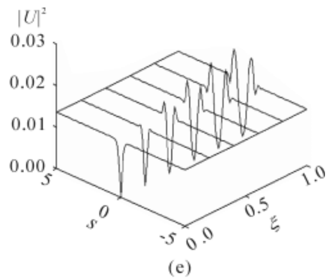


Fig.1 Evolutions of the screening dark spatial solitons in two-photon photorefractive crystal under different temperatures: (a) *T*=280 K; (b)*T*=295 K; (c) *T*=300 K; (d) *T*=305 K; (e) *T*=360 K

Fig.2 gives the intensity profiles of dark screening solitons with ξ=1 under different temperatures. We can see that the full width of half maximum (FWHM) of dark screening soliton is increasing while the intensity is decreasing with the temperature increase of the two-photon photorefractive crystal.

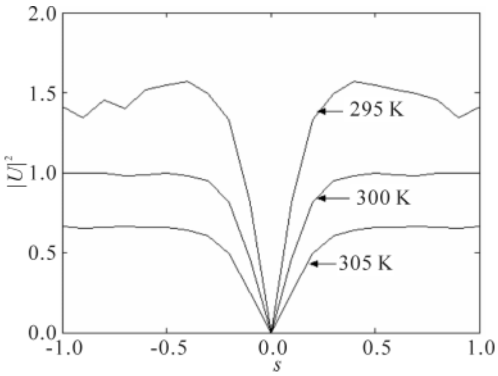


Fig.2 Intensity profiles of the screening dark spatial solitons with ξ =1 under different temperatures

Then we investigate the temperature effects on the evolution of the bright screening soliton in two-photon photorefractive crystal with parameters of E_0=1 × 10^6 V/m (β=88.8) and r=r_0 =10 at T=300 K, and the other parameters are the same as those for dark soliton. The evolutions of the incident bright screening soliton in two-photon photorefractive crystal under different temperatures T=280 K, 295 K, 300 K, 305 K and 360 K are shown in Fig.3, respectively. We can see that the incident solitary beam is stable at T=300 K. However, when the crystal temperature deviates slightly from 300 K, the incident beam cannot remain varying with propagation distance, but reshapes itself and tends to evolve into another stable bright screening soliton, as shown in Fig.3(b) and (d). Then, we consider the case that the crystal temperature deviates significantly from 300 K. We can see that the incident beam cannot evolve into a stable bright soliton but tends to experience large cycles of compression and expansion for its maximum amplitude at T=280 K. If the temperature of crystal is increasing continuously, the incident beam will break down with propagation distance as shown in Fig.3(e).

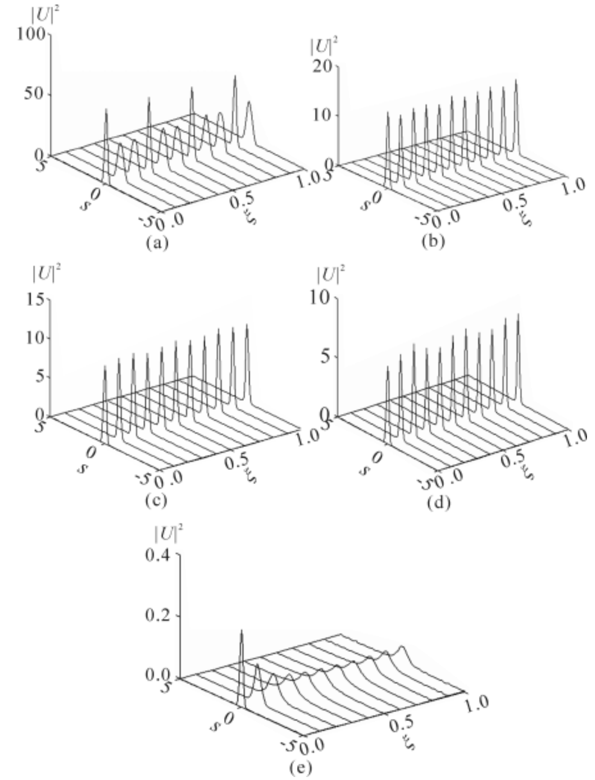


Fig.3 Evolutions of the screening bright spatial solitons in two-photon photorefractive crystal under different temperatures: (a) *T*=280 K; (b) *T*=295 K; (c) *T*=300 K; (d) *T*=305 K; (e) *T*=360 K

Fig.4 gives the intensity profiles of bright screening solitons with ξ=1 under different temperatures. We can see that both the FWHM and the intensity of bright screening soliton are decreasing with the temperature increase of two-photon photorefractive crystal. The spatial shapes of both stable

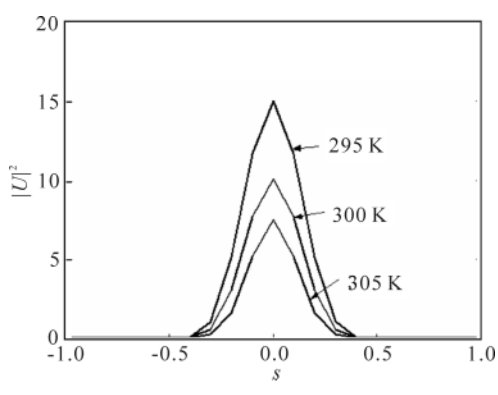


Fig.4 Intensity profiles of the screening bright spatial solitons with ξ=1 under different temperatures

bright and dark screening solitons can be reshaped by appropriately adjusting the crystal temperature.

In conclusion, we present a theoretical investigation of the temperature effects on the evolutions of both dark and bright screening solitons in two-photon photorefractive crystal. When the temperature of crystal changes, the spatial shapes of solitons can be reshaped. The FWHM of dark screening soliton will increase while that of bright screening soliton will decrease with the temperature increase in a range. The intensities of both solitons decrease with the temperature rising. Soliton will evolve into another stable screening soliton if the temperature change is quite small, while it will become unstable or break down if the temperature change is large enough. The spatial shape of a stable two-photon screening spatial soliton can be changed by appropriately adjusting the crystal temperature.

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