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Effects of temperature on the stability of separate screening bright–dark spatial soliton pair*

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We investigate theoretically the temperature effects on the evolution and stability of a separate screening bright–dark soliton pair formed in a serial non-photovoltaic photorefractive crystal circuit. Our numerical results show that, for a stable bright–dark soliton pair originally formed in a crystal circuit at given temperatures, when one crystal temperature changes, the soliton supported by the other crystal will evolve into another stable soliton if the temperature change is quite small, whereas it will become unstable and experience larger cycles of compression or break up into beam filaments if the temperature difference is big enough. The dark soliton is more sensitive to the temperature change than the bright one.

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

Spatial solitons in photorefractive (PR) media have been a topic of research in nonlinear optics in the past few years.[1−25] PR solitons rely on a change in the refractive index driven by space-charge fields (via the Pockels effect) to exactly balance the effects of diffraction. At present, three types of steady-state solitons (screening solitons,[1−5] photovoltaic (PV) solitons[6−13] and screening-photovoltaic (SP) solitons)[14,15] have been predicted and already found experimentally.[16−18] At the same time, soliton pairs and soliton interaction have also been extensively investigated.[19−25] In 1996, Christodoulides *et al* [19] investigated the incoherent coupling of two screening solitons. Very recently, Hou *et al* [23−25] predicted that the incoherent PV and SP soliton pairs can also be supported in a biased or unbiased PV–PR crystal. However, almost all the investigations on PR soliton, soliton pair and soliton interaction were concerned with only one piece of PR crystal.[1−25] Recently, Liu and Hao[26] predicted a new type of soliton pair, named separate spatial soliton pair, which is formed in a crystal circuit in which two PR crystals are connected in a chain by electrode leads with a voltage source. Separate soliton pair can be of bright–dark, bright–bright and dark–dark three types, the two solitons in such a soliton pair are coupling with each other by parameters, and the most interesting phenomenon is that the change of the intensity of the dark soliton can affect the other soliton whereas the bright one cannot.

As is known, the photorefractive effects are dependent on the dark irradiance of the crystal, and the latter is dependent on the temperature.[27] The effects of the crystal's temperature on the evolution, stability and the spatial shape of a photorefractive solitons formed in the corresponding crystal have been investigated in Refs.[28] and [29]. Whether the temperature of one crystal can affect the characteristics of the other soliton formed in another crystal in a separate soliton pair or not, has not been researched so far as we know. In this paper, we investigate the temperature effects on the stability of a bright–dark separate soliton pair in a biased crystal circuit. Our numerical results indicate that, for a bright–dark soliton pair, earlier formed in a crystal circuit at a given temperatures, the bright (dark) soliton formed in a crystal tends to be unstable when the other crystal's temperature change is big enough. However, if the temperature change is small enough, the soliton tends to evolve into another stable soliton, that is, there exists a stable temperature regime in which the soliton is stable against small

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perturbations. The bright soliton has a larger stable temperature range than the dark one, and the latter is more sensitive to the temperature change.

2. Theoretical model

Consider the steady-state PR solitons formed in a series PR crystal circuit in which two non-photovoltaic PR crystals denoted by P and $\hat{\mathrm{P}}$, are connected electronically in a chain by electrode leads with an external voltage source V_{A}, as shown in Fig.1.

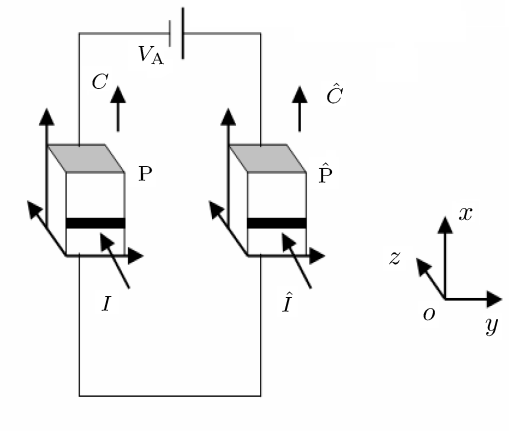


Fig.1. Illustration of the serial PR crystal circuit. C and $\hat{C}$ denote the c axes. I and $\hat{I}$ denote the incident one-dimensional soliton-like laser beams.

For each crystal, electrodes are made on the surfaces with their normal parallel to c-axis of the crystal, and each crystal can support a spatial bright (dark) soliton, known as a separate screening spatial soliton pair. Consider two optical beams that propagate in the two crystals along the z and $\hat{z}$ axes, and are permitted to diffract only along the x and $\hat{x}$ directions, respectively. The optical c axes of the two crystals P and $\hat{\mathrm{P}}$ are oriented along the x and $\hat{x}$ coordinates, respectively. Moreover, assume that the polarizations of the two incident optical beams are both linearly polarized along x and $\hat{x}$ directions, respectively. Let $I = I(x, z)$ and $\hat{I} = \hat{I}(\hat{x}, \hat{z})$ denote the intensities of the two incident beams, which can also be expressed as $I = I_{\mathrm{d}}|U|^2$ and $\hat{I} = \hat{I}_{\mathrm{d}}|\hat{U}|^2$, where I_{d} and $\hat{I}_{\mathrm{d}}$ are the so-called dark irradiance, which depend on the crystal's temperature. U and $\hat{U}$ are the normalized envelopes of the optical beams. Employing standard procedures and neglecting the loss in the material, we readily obtain the following dynamical evolution equations of $U$and $\hat{U}$:[26]

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

$$\mathrm{i}\hat{U}_{\hat{\xi}} + \frac{1}{2}\hat{U}_{\hat{s}\hat{s}} - \hat{\beta}(\hat{\rho}+1)\frac{\hat{U}}{1+|\hat{U}|^2} = 0\,, \qquad (1b)$$

where $U_{\xi} = \partial U/\partial\xi$, $U_{ss} = \partial^2 U/\partial s^2$, $\beta = \sigma E_0$, $\sigma = (k_0 x_0)^2(n_{\mathrm{e}}^4 r_{33}/2)$, and $\rho = I_{\infty}/I_{\mathrm{d}}$. $\xi = z/(kx_0^2)$, $s = x/x_0$, x_0 being an arbitrary spatial width, $k = n_{\mathrm{e}}k_0 = (2\pi/\lambda_0)n_{\mathrm{e}}$, with λ_0 the free-space wavelength of the lightwave employed, n_{e} the unperturbed extraordinary index of refraction; r_{33} is the electro-optic coefficient of the PR crystal, $I_{\infty} = I(x \to \pm\infty, z)$, e is the electron charge, k_{B} is Boltzmann's constant, T is the absolute temperature of the crystal P. In this paper, the parameters with the symbol $\hat{\cdot}$ denoting the other optical beam, have the same physical meaning.

We pay our attention to the bright–dark screening soliton pair, and discuss only this type of soliton pair. Assume that the bright soliton formed in crystal P and the dark one formed in crystal $\hat{\mathrm{P}}$. The expressions for E_0 and $\hat{E}_0$ necessary for a bright–dark soliton pair are as follows:[26]

$$E_0 = gE_{\mathrm{A}}, \qquad (2a)$$

$$\hat{E}_0 = \hat{g}\hat{E}_{\mathrm{A}}, \qquad (2b)$$

where $g = \hat{\delta}(\hat{I}_{\infty} + \hat{I}_{\mathrm{d}})/[\delta(I_{\infty} + I_{\mathrm{d}}) + \hat{\delta}(\hat{I}_{\infty} + \hat{I}_{\mathrm{d}})]$, $\hat{g} = \delta(I_{\infty}+I_{\mathrm{d}})/[\delta(I_{\infty}+I_{\mathrm{d}})+\hat{\delta}(\hat{I}_{\infty}+\hat{I}_{\mathrm{d}})]$, $E_{\mathrm{A}} = V_{\mathrm{A}}/W$, $\hat{E}_{\mathrm{A}} = V_{\mathrm{A}}/\hat{W}$, $\delta = S\mu s_{\mathrm{i}}(N_{\mathrm{D}} - N_{\mathrm{A}})/(\gamma_R N_{\mathrm{A}} W)$ and $\hat{\delta} = \hat{S}\hat{\mu}\hat{s}_{\mathrm{i}}(\hat{N}_{\mathrm{D}} - \hat{N}_{\mathrm{A}})/(\hat{\gamma}_R\hat{N}_{\mathrm{A}}\hat{W})$. S denotes the electrode surfaces, μ is the electron mobility, s_{i} is the photoexcitation cross section, N_{D} denotes the donor density, N_{A} is the acceptor density, γ_R is the carrier recombination rate. The parameters g and $\hat{g}$ are known as coupling coefficients between the two solitons, with $g + \hat{g} = 1$.

The bright and dark soliton solutions of Eq.(1) have been found as follows:[26,28]

$$(2\beta)^{1/2}s = \pm\int_{y(s)}^{1}\frac{r^{1/2}\mathrm{d}\,\widetilde{y}}{[\ln(1+r\widetilde{y}^{\,2}) - \widetilde{y}\ln(1+r)]^{1/2}}, \qquad (3a)$$

$$(-2\hat{\beta})^{1/2}s = \pm\int_{\hat{y}(s)}^{0}\frac{\mathrm{d}\,\widetilde{y}}{[(\widetilde{y}^{\,2}-1) - \frac{1+\hat{\rho}}{\hat{\rho}}\ln(\frac{1+\hat{\rho}\widetilde{y}^{\,2}}{1+\hat{\rho}})]^{1/2}}, \qquad (3b)$$

where $\beta = \sigma g E_{\mathrm{A}}$, $\hat{\beta} = \hat{\sigma}\hat{g}\hat{E}_{\mathrm{A}}$, r and $\hat{\rho}$ are defined as $r = I(0)/I_{\mathrm{d}}$ and $\hat{\rho} = \hat{I}_{\infty}/\hat{I}_{\mathrm{d}}$. It is important to note that the dark irradiance changes with temperature, therefore the values of $r = I(0)/I_{\mathrm{d}}$ and $\hat{\rho} = \hat{I}_{\infty}/\hat{I}_{\mathrm{d}}$ also change with the crystal's temperature. Letting $r_0 = I(0)/I_{\mathrm{d}0}$ and $\hat{\rho}_0 = \hat{I}_{\infty}/\hat{I}_{\mathrm{d}0}$ denote the values of r and $\hat{\rho}$ at $T = 300$ K and $\hat{T} = 300$ K, where $I_{\mathrm{d}0}$ and $\hat{I}_{\mathrm{d}0}$ are the values of I_{d} and $\hat{I}_{\mathrm{d}}$ at 300 K respectively. Here we use the one-level and one-carrier model presented

by Cheng and Partovi[27] to describe the temperature dependences of r and $\hat{\rho}$ as follows:

$$r = r_0\Big(\frac{T}{300}\Big)^{-3/2}\exp\Big[-\frac{E_t}{k_B}\Big(\frac{1}{300}-\frac{1}{T}\Big)\Big], \tag{4a}$$

$$\hat{\rho} = \hat{\rho}_0\Big(\frac{\hat{T}}{300}\Big)^{-3/2}\exp\Big[-\frac{\hat{E}_t}{k_B}\Big(\frac{1}{300}-\frac{1}{\hat{T}}\Big)\Big], \tag{4b}$$

where E_t is the level location in the gap. For photovoltaic photorefractive crystals, such as $LiNbO_3$, we have $E_t \approx 10^{-19}$ J.[27] In this paper, for simplicity, we take $E_t = 10^{-19}$ J.

Equation (3) indicates that a bright and a dark screening solitons can co-exist in the crystal circuit provided that $\beta > 0$ and $\hat{\beta} < 0$. The profiles of the bright and dark solitons depend on β and $\hat{\beta}$, respectively. Inserting the expressions of g and $\hat{g}$ in Eq.(2) into β and $\hat{\beta}$, we have $\beta = \sigma\hat{\delta}(\hat{I}_\infty + \hat{I}_d)/[\delta I_d + \hat{\delta}(\hat{I}_\infty + \hat{I}_d)]E_A$, $\hat{\beta} = \hat{\sigma}\delta I_d/[\delta I_d + \hat{\delta}(\hat{I}_\infty + \hat{I}_d)]\hat{E}_A$, from which we can see that the two soliton's parameters β and $\hat{\beta}$ are related to the dark irradiance I_d and $\hat{I}_d$, and the two solitons couple with each other through the parameters. The changes of temperatures of the crystals result in the changes of β and $\hat{\beta}$, thus we can investigate the temperature effects on the evolution and stability of such screening soliton pair.

3. Temperature effects on the stability of the separate screening bright–dark spatial soliton pair

In order to investigate the temperature effects on the evolution and stability of the separate bright–dark soliton pair, as shown in Fig.1, we assume that two SBN crystals are taken to compose the circuit, one crystal is taken as P to support the bright soliton and the other is taken as crystal $\hat{P}$ to support the dark soliton. The two crystals have the following parameters: $r_{33} = \hat{r}_{33} = 237\times10^{-12}$ mV^{-1}, $n_e = \hat{n}_e = 2.33$, $W = \hat{W} = 1$ cm, $I_{d0} = \hat{I}_{d0}$. Assume that $\delta = \hat{\delta}$, $S = \hat{S}$, the arbitrary scales are $x_0 = \hat{x}_0 = 40$ μm and the wavelengths are $\lambda_0 = \hat{\lambda}_0 = 0.5$ μm. The voltage of the source is $V_A = 500$ V. For this set of values, we have $\sigma = \hat{\sigma} = 88.24\times10^{-5}$ mV^{-1}, $E_A = 5\times10^4$ V / m and $\hat{E}_A = -5\times10^4$ V/m. The values of I_d and $\hat{I}_d$ are, in general, different.

Firstly, we investigate the effect of temperature of crystal $\hat{P}$ on the bright soliton. We can adjust the temperature of crystal P to $T = 300$ K and then keep it unchanged, therefore we have $I_d = I_{d0} = \hat{I}_{d0}$. The dependences of β and $\hat{\beta}$ on temperature $\hat{T}$ can be obtained by substituting Eq.(4) into the expressions of g and $\hat{g}$, using the above obtained parameters: $g = (1+\hat{\rho})/(1+\hat{\rho}+\varphi)$, $\hat{g} = \varphi/(1+\hat{\rho}+\varphi)$, and

$$\varphi = (\frac{\hat{T}}{300})^{-3/2}\exp\Big[-\frac{\hat{E}_t}{k_B}\Big(\frac{1}{300}-\frac{1}{\hat{T}}\Big)\Big],$$

thus we obtain the temperature dependences of β and $\hat{\beta}$ as follows:

$$\beta = (1+\hat{\rho})/(1+\hat{\rho}+\varphi)\sigma E_A, \tag{5a}$$

$$\hat{\beta} = \varphi/(1+\hat{\rho}+\varphi)\hat{\sigma}\hat{E}_A. \tag{5b}$$

From Eqs.(5a) and (5b) we can see that the values of β and $\hat{\beta}$ are all dependent on temperature $\hat{T}$. Two solitons are coupled with each other through the coupling parameter. When the temperature of crystal $\hat{P}$ changes, the values of β and $\hat{\beta}$ also change, which will affect the normalized intensities of the two solitons.

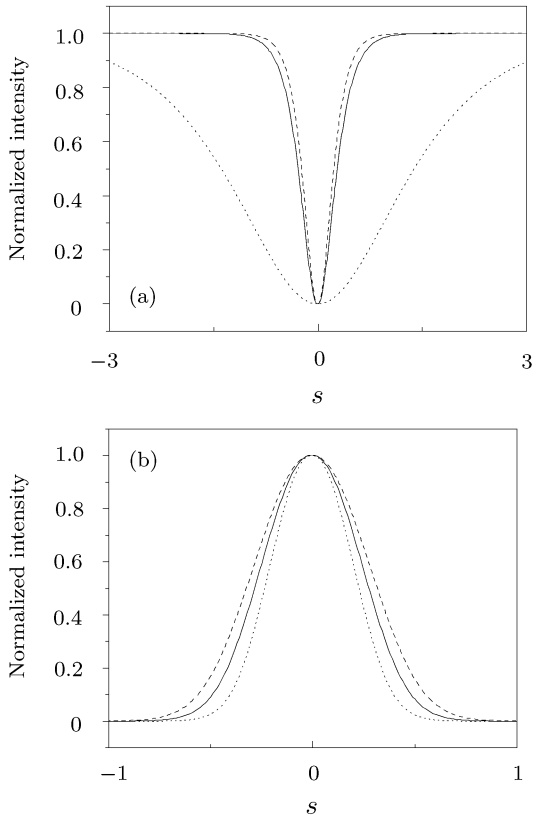


Fig.2. The effect of the temperature of crystal $\hat{P}$ on the normalized intensity profile in the separate screening soliton pair. (a) Dark soliton, (b) Bright soliton. Solid curve denotes the case of $\hat{T} = 300$ K, and the dashed and dotted curves denote the case of $\hat{T} = 260$ K and $\hat{T} = 360$ K, respectively.

We choose the input light beam to be of $I_0 =$

$10I_{\rm d}$, $I_\infty = 0$, $\hat{I}_\infty = \hat{I}_{\rm d}$ and $\hat{T} = 300$ K, which result in $r = 10$, $\hat{\rho} = 1$, $g = 2/3$, $\hat{g} = 1/3$, $\beta = 29.41$ and $\hat{\beta} = -14.71$. Using the above parameters, we obtain the normalized intensities of the two solitons from Eq.(3), as shown in Fig.2 (solid curve). Then we change the temperature $\hat{T}$ to investigate the temperature effect on the normalized intensities, as shown in Fig.2 (dashed and dotted curves). From the results we can see that the change of temperature $\hat{T}$ can affect the normalized intensities of the two solitons. The higher the temperature of crystal $\hat{\rm P}$, the smaller the intensity in full width at half maximum (FWHM) of the bright soliton.

We now investigate the effect of the temperature of crystal $\hat{\rm P}$ on the evolution and stability of the bright soliton. In doing so, a bright soliton is obtained from Eq.(3a) with the system parameters chosen as $r = 10$, $\beta = 29.41$, $T = 300$ K and $\hat{T} = 300$ K. Taking the solitary state as the input beam, we solve Eq.(1a) numerically at different temperature $\hat{T}$ to obtain the dynamical evolution of the bright soliton, as shown in Fig.3.

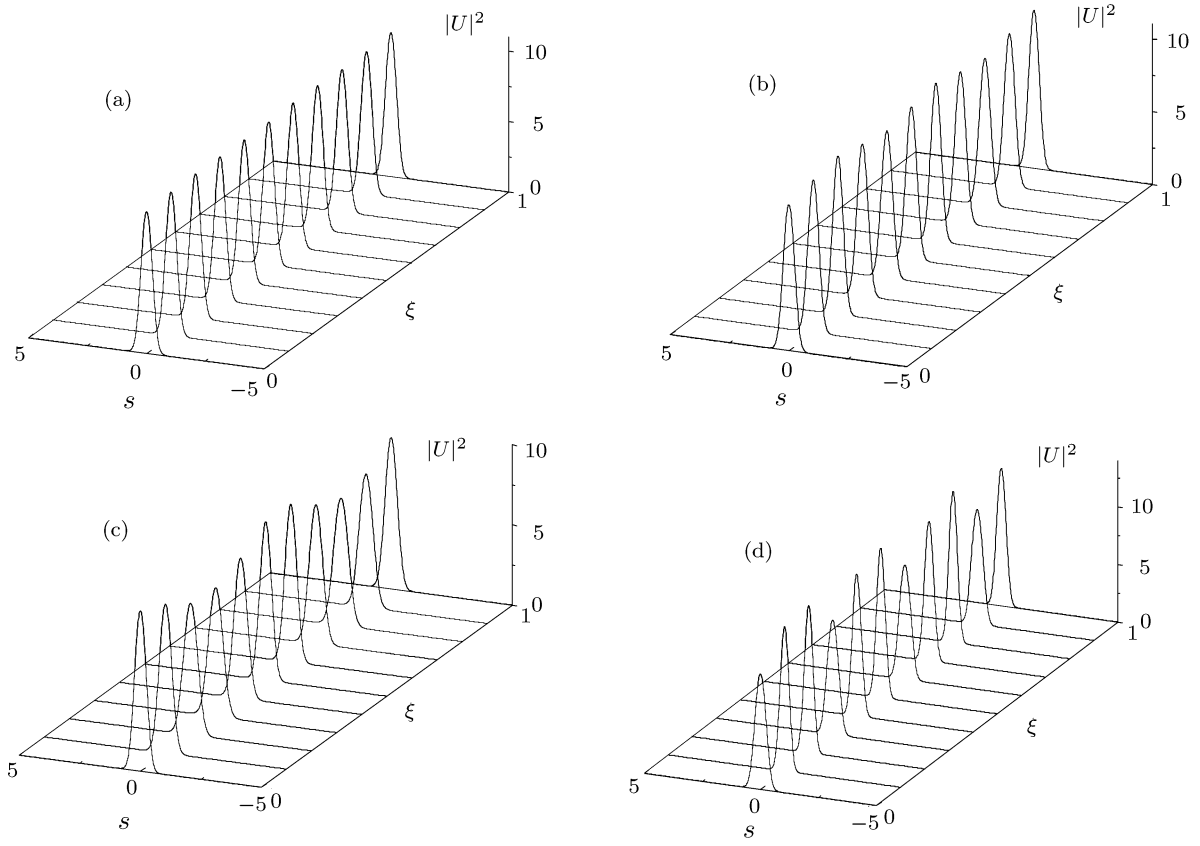


Fig.3. The effect of the temperature of crystal $\hat{\rm P}$ on the dynamical evolution of the bright soliton in the separate screening soliton pair. (a) $\hat{T} = 300$ K, (b) $\hat{T} = 305$ K, (c) $\hat{T} = 260$ K and (d) $\hat{T} = 360$ K. The input incident bright solitary state is obtained from Eq.(3a) with $r = 10\beta = 29.41$ and $T = 300$ K.

The results indicate that changing the temperature $\hat{T}$ can obviously affect the dynamical evolution and the stability of the bright soliton in a separate screening soliton pair. First, we examine the case of $\hat{T} = 300$ K, as shown in Fig.3(a). As expected, our numerical results confirm that the bright soliton beam remains invariant with increasing propagation distance in the crystal. The reason is that the bright soliton is just the bright solitary solution supported by crystal P at $\hat{T} = 300$ K, thus the bright soliton

can evolve in an adiabatic fashion. Then we examine the case that the temperature $\hat{T}$ deviates slightly from $\hat{T} = 300$ K. From the result of Fig.3(b), we can see that the incident beam reshapes itself and tends to evolve into another stable bright soliton. Finally, we consider the case that the temperature $\hat{T}$ deviates significantly from $\hat{T} = 300$ K. Figures 3(c) and 3(d) give the evolution of the bright soliton in the crystal at $\hat{T} = 260$ K and $\hat{T} = 360$ K. From the results we can see that the incident beam cannot evolve into a stable bright soliton but instead tends to experience larger cycles of compression, and its maximum amplitude oscillates with propagation distance at these temperatures.

Next we investigate the effect of the temperature of crystal P on the evolution and stability of the dark soliton formed in crystal $\hat{\mathrm{P}}$. In doing so, we adjust the temperature of the crystal $\hat{\mathrm{P}}$ to $\hat{T} = 300$ K, and keep it unchanged, thus we have

$$\hat{I}_{\mathrm{d}} = \hat{I}_{\mathrm{d}0} = I_{\mathrm{d}0}.$$

Similarly, we can obtain the dependences of β and $\hat{\beta}$ on temperature T as follows:

$$\beta = (1 + \hat{\rho}_0)/(1 + \hat{\rho}_0 + \phi)\sigma E_{\mathrm{A}}, \tag{6a}$$

$$\hat{\beta} = \phi/(1 + \hat{\rho}_0 + \phi)\hat{\sigma}\hat{E}_{\mathrm{A}}, \tag{6b}$$

where

$$\phi = \Big(\frac{T}{300}\Big)^{3/2} \exp\Big[\frac{E_{\mathrm{t}}}{k_{\mathrm{B}}}\Big(\frac{1}{300} - \frac{1}{T}\Big)\Big].$$

From Eq.(6) and we can see that both β and $\hat{\beta}$ are dependent on the temperature T. Changing T can affect the normalized intensity of the two solitons. Figure 4 gives the dependence of normalized intensity of the two solitons on T, from which we can see that the change of the temperature of bright soliton can affect the normalized intensity of the dark soliton: the larger the temperature of crystal P, the smaller the intensity (FWHM) of the dark soliton.

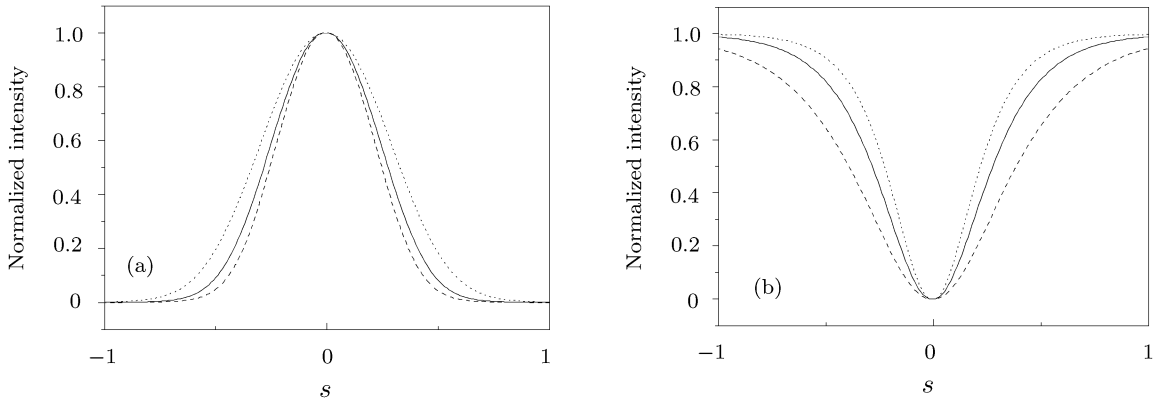


Fig.4. The effect of the temperature of crystal P on the normalized intensity profile in the separate screening soliton pair. (a) bright soliton, (b) dark soliton. Solid curve denotes the case of $T = 300$ K, and the dashed and dotted curves denote the cases of $T = 290$ and 310 K, respectively.

The effect of the temperature of crystal P on the evolution and stability of the dark soliton in such separate soliton pair is shown in Fig. 5. The fundamental dark solitary state is obtained from Eq.(3b) with the system parameters $\hat{\beta} = -14.71$, $\hat{\rho} = 1$, $\hat{T} = 300$ K and $T = 300$ K. The results indicate that changing the temperature of crystal P can sharply affect the dynamical evolution and the stability of the dark soliton. When $T = 300$ K, the dark soliton is just the fundamental solitary solution supported by the crystal, therefore, the soliton can evolve in an adiabatic fashion during its propagation in the crystal. Figure 5(b) shows that the dark soliton can reshape itself and tend to evolve into another stable dark soliton when the temperature of the bright soliton deviates slightly from $T = 300$ K. However, if the tempera-

ture of crystal P further deviates from $T = 300$ K, such as, $T = 260$ and 315 K, as shown in Figs.5(c) and 5(d), the dark soliton cannot evolve into a stable dark soliton but instead tends to break up into beam filaments, and its maximum amplitude oscillates with the propagation distance at these temperatures. By a close examination of the above results, in contrast to that of bright soliton shown in Figs.3 (c) and 3(d), we can see that the dark soliton has a narrower stable temperature region, and it is more sensitive to the temperature change than the bright one in a separate bright–dark soliton pair.

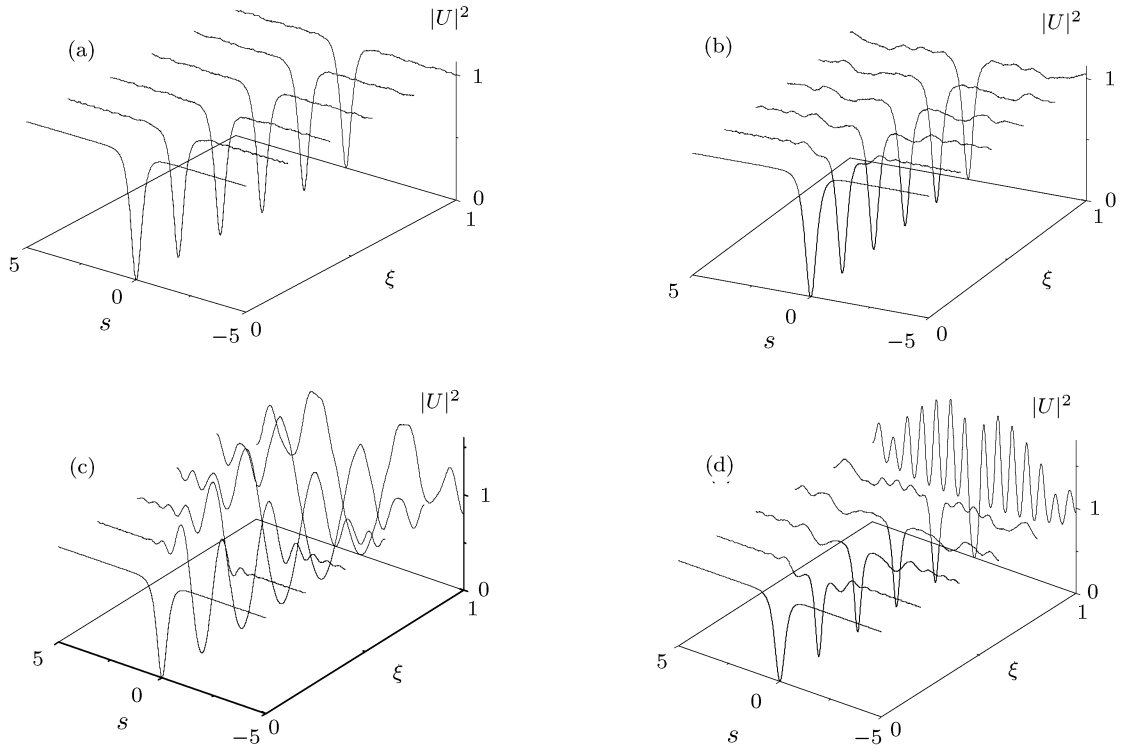


Fig.5. The effect of the temperature of crystal P on the dynamical evolution of the dark soliton in the separate screening soliton pair. (a) $T = 300$ K, (b) $T = 305$ K, (c) $T = 260$ K and (d) $T = 315$ K. The input incident bright solitary state is obtained from Eq.(3b) with $\hat{\rho} = 1$, $\hat{\beta} = -14.71$ and $\hat{T} = 300$ K.

4. Conclusions

The temperature effects on the evolution and stability of a separate screening bright–dark soliton pair formed in a serial non-photovoltaic photorefractive crystal circuit have been investigated under steady-state conditions for the case of neglecting the materials loss and diffusion process. Our numerical results show that the bright and dark solitons can affect each other in a stable bright–dark soliton pair formed in a crystal circuit at given temperatures, but this interaction is bilateral. This behaviour is obviously different from the results obtained in Ref.[26], in which the dark soliton can affect the bright one, whereas the bright soliton cannot affect the dark one. When the temperature of one crystal changes, the soliton supported by the other crystal tends to be unstable and experiences larger cycles of compression or breaks up into beam filaments if the temperature difference is big enough, whereas it tends to evolve into another stable soliton when the temperature difference is small enough. The dark soliton has a narrower stable temperature range than the bright one in such a separate soliton pair, therefore the dark soliton is more sensitive to the temperature change.

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