第 26 卷　第 4 期
2002 年 8 月

激　光　技　术
LASER TECHNOLOGY

Vol. 26, No. 4
August, 2002

文章编号: 1001-3806(2002)04-0279-05

The effects of temperature on the stability of bright screening-photovoltaic spatial solitons*

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Abstract: We present a theoretical analysis of temperature effects on the stability of screening-photovoltaic spatial bright solitons in biased photovoltaic-photorefractive materials. A stable screening-photovoltaic bright soliton formed at a temperature is stable against small perturbations when the temperature changes in a regime by name the stable temperature regime whereas tends to be unstable when the temperature exceeds the regime. An unstable optical solitary beam can evolve into a stable screening-photovoltaic bright soliton by adjusting the crystal temperature.

Key words: nonlinear optics; spatial optical solitons; photorefractive effects

温度对屏蔽光伏明孤子稳定性的影响

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摘要: 研究了温度对加外电压的光伏光折变晶体中屏蔽光伏明孤子稳定性的影响。在某一晶体温度下形成的稳定屏蔽光伏明孤子, 当温度在一个较小范围内变化时, 孤子能够克服较小的微扰而保持其稳定性。当温度发生足够大的变化而超出这一稳定温度范围时, 孤子将变得不稳定。通过改变晶体的温度能使一个不稳定的孤子变得稳定。

关键词: 非线性光学; 空间光孤子; 光折变效应
中图分类号: O437　　文献标识码: A

Introduction

Optical spatial solitons in photorefractive media have found a growing interest in the last decade[1~14]. At present, three types of steady-state photorefractive solitons have been predicted and, part of them have been found experimentally. Screening solitons are possible in 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 steady state in an open-closed-circuit photovoltaic-photorefractive crystal without a bias field. These photovoltaic solitons result from the photovoltaic effect[7~9]. The screening and photovoltaic solitons have been found experimentally. Recently, it has been predicted theoretically that the screening-photovoltaic (SP) solitons are possible in steady-state when an electric field is applied to a photovoltaic-photorefractive crystal[10~12]. These SP solitons result from both the photovoltaic effect and spatially nonuniform screening of the applied field. In fact, 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 photovoltaic field, the SP solitons are just like the screening solitons. If the applied field is absence, the SP solitons degenerate into the photovoltaic solitons in the close-circuit condition.

Mihalache et al.[13] and Singh et al.[14] provided a theoretical analysis of the stability of walking vector and screening solitons, respectively. Recently, the stability of SP solitons was investigated by

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* 国家自然科学基金资助项目。

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收稿日期: 2001-07-10; 收到修改稿日期: 2001-09-29

numerically solving the dynamical evolution equation[12]. The SP solitons tend to be stable against small perturbations. However, beams whose wave parameters significantly depart from those of a self-trapped solution do not retain their form but instead tend to experience cycles of compression and expansion or can breakup into beam filaments and their maximum amplitudes oscillate with propagation distances. The larger the perturbations are, the stronger the oscillation is. The SP solitons have a similar way to screening solitons in stability. Although the stability of photovoltaic solitons has not been discussed yet, the closed-circuit photovoltaic solitons should have a similar way to SP solitons in stability because the closed-circuit photovoltaic solitons are the special case of the SP solitons.

As we know, the photorefractive effects are dependent on the dark irradiance of the crystal and, the irradiance is dependent on temperature[15~18]. As a result, the photorefractive effects, such as two-beam coupling and four-wave mixing, are strongly dependent on the crystal temperature[15~20]. 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 researched. Is a photorefractive soliton, which is stable or tends to be stable against small perturbations at a crystal temperature, stable at another temperature? In the paper, we investigate the effects of temperature on the stability of SP solitons in the biased photovoltaic-photorefractive crystal. Our results show that a stable SP bright. Soliton, early formed at a temperature T_0, such as room temperature, tends to be unstable when the temperature changes from T_0 to T if the temperature difference is big enough. However, if the temperature dependence is small enough, the stable SP brigth soliton can reshape itself and tends to evolve into another stable SP bright soliton, that is, there is a stable temperature regime in which the screening-photovoltaic bright solitons are stable against small perturbations. An unstable optical solitary beam can evolve into a stable screening-photovoltaic bright soliton by adjusting the crystal temperature.

1 Theoretical formulation

To analyze the evolution of a SP soliton in biased photovoltaic-photorefractive crystal, let us consider an optical beam that propagates in the crystal along the z-axis and is permitted to diffract only along the x-direction, and the optical c-axis of the crystal is oriented along the x-coordinate. Moreover, let us assume that the optical beam is linearly polarized along x and that the external bias electric field is applied in the same direction. Let $I = I(x, z)$ denote the power density profile of the optical beam, which can be also expressed as $I = I_d|U|^2$, where I_d is the so-called dark irradiance and U is the normalized envelope of the optical beam. For this physical model, in the case of neglecting the diffusion process, the basic theory and formulation have been built up and the normalized envelope U obeys the following dynamical evolution equation[11~12]:

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

where $\alpha = (k_0x_0)^2(n_e^4r_{33}/2)E_p$, $\beta = (k_0x_0)^2 \times (n_e^4r_{33}/2)E_0$, $\rho = I_\infty/I_d$, $I_\infty = I(x \to \pm\infty, z)$, $k_0 = 2\pi/\lambda_0$, λ_0 is the free-space wavelength of the light wave employed, n_e is the unperturbed extraordinary index of refraction, r_{33} is the electro-optic coefficient, E_p is the photovoltaic field constant, E_0 is the value of external field strength, $\xi = z/(n_ek_0x_0^2)$, $s = x/x_0$, x_0 is an arbitrary spatial width, $U_\xi = \partial U/\partial\xi$, $U_{ss} = \partial^2 U/\partial s^2$.

The dimensionless quantities α and β are associated with the photovoltaic effect and drift process, respectively. Generally, α and β do not depend strongly on temperature. In the paper, we pay our attention on the temperature dependence of I_d. Here we use the one-level and one-carrier model presented by Cheng and Partovi[15], which was successfully used to explain the temperature dependence of photorefractive effects in $LiNbO_3$[16~17], to describe the temperature dependence of I_d as the following

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

where K_{B} is Boltzmann's constant, T is the absolute temperature, $I_{\mathrm{d}0}$ is the value of I_{d} at $T = 300\mathrm{K}$, E_{t} is the level location in the gap. For photovoltaic photorefractive crystal, such as LiNbO$_3$, $E_{\mathrm{t}} \sim 10^{-19}$ J[16~17], for simplicity, we take $E_{\mathrm{t}} = 10^{-19}$J. Bright SP solitary solution can be derived from Eq. (1) by entirely neglecting the diffusion effects and, by expressing the beam envelope U in the usual fashion: $U = r^{1/2}y(s)\exp(\mathrm{i}\nu\xi)$, where ν represents a nonlinear shift of the propagation constant, $y(s)$ is a normalized real function bounded between $0 \leqslant y(s) \leqslant 1$. The positive quantity r is defined as $r = I(0)/I_{\mathrm{d}}$. For the bright spatial solitons, we require that $y(0) = 1$, $\dot{y}(0) = 0$ and $y(s \to \pm\infty) = 0$. Substitutions of this latter form of U into Eq. (1) with $\rho = 0$ and $\gamma = 0$, we find that:

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

and $\nu = -\frac{\beta+\alpha}{r}\ln(1+r)+\alpha$. Bright solitary beam profile $y(s)$ can be easily obtained from Eq. (3) by use of simple numerical integration procedures. Let $r_0[=I(0)/I_{\mathrm{d}0}]$ denote the value of r at $T = 300\mathrm{K}$, by use of Eq. (2), the quantity $r = I(0)/I_{\mathrm{d}}$ can be expressed as

$$r = r_0\left(\frac{T}{300}\right)^{-3/2}\exp\left[-\frac{E_{\mathrm{t}}}{K_{\mathrm{B}}}\left(\frac{1}{300}-\frac{1}{T}\right)\right] \qquad (4)$$

The sign of β is dependent on the polarity of E_0, whereas the sign of α is dependent on the characteristic of the photovoltaic crystal and the polarization of the light[21]. Therefore, either positive or negative of the sign of β and α is possible. However, form Eq. (3), the conditions to obtain a bright SP soliton are $(\alpha+\beta) > 0$.

In order to give the quantificational information about the temperature effects on the stability of SP solitons, we introduce two functions. One function $\Delta|U(T)|^2$ is defined as

$$\Delta|U(T)|^2 = \left|\frac{|U(s=0,\xi=1,T\neq 300\mathrm{K})|^2-|U(s=0,\xi=1,T=300\mathrm{K})|^2}{|U(s=0,\xi=1,T=300\mathrm{K})|^2}\right| \qquad (5)$$

The function denotes the relative difference of the optical beam maximum amplitude at $\xi = 1$ between $T = 300\mathrm{K}$ and others. Another function $\Delta|W(T)|$ is defined as.

$$\Delta|W(T)| = \left|\frac{W(\xi=1,T\neq 300K)-W(\xi=1,T=300K)}{W(\xi=1,T=300K)}\right| \qquad (6)$$

Where W denotes the FWHM of the optical beam at $\xi = 1$. The function $\Delta|W(T)|$ denotes the relative difference of the FWHM of the optical beam at $\xi = 1$ between $T = 300\mathrm{K}$ and others.

2　Temperature dependence of stability of screening-photovoltaic bright solitons

We firstly consider the temperature effects on the evolution of an incident bright SP soliton in the biased photovoltaic-photorefractive crystal with the parameters of $\alpha = -100$, $\beta = 135$ and $E_{\mathrm{t}} = 10^{-19}$J. This incident SP bright soliton solution can be obtained from Eq. (3) with the parameters of $\alpha = -100$, $\beta = 135$, $E_{\mathrm{t}} = 10^{-19}$J and $r_0 = 10$ at $T = 300\mathrm{K}$. The dynamical evolution of the incident SP soliton beam is exhibited by numerically solving Eq. (1) under different temperature with $\alpha = -100$, $\beta = 135$, $E_{\mathrm{t}} = 10^{-19}$J and $r_0 = 10$. As expected, our results confirm that the incident solitary beam remains invariant with propagation distance at $T = 300\mathrm{K}$ as shown in Fig. 1a, i. e., the incident solitary beam is stable at $T = 300\mathrm{K}$. However, when $T \neq 300\mathrm{K}$ the incident beam cannot evolve a stable SP bright soliton, but tends to experience larger cycles of compression and expansion, and its maximum amplitude oscillates with propagation distances at $T = 280\mathrm{K}$ or to breakup into beam filaments at $T = 360\mathrm{K}$, as shown in Fig. 1b and Fig. 1c. The results indicate that a stable SP bright soliton formed at a temperature tends to be unstable at another temperature. In other words, to change crystal temperature will destroy the stability of a photorefractive soliton. The reason that the incident beam cannot evolve a stable SP bright soliton at

$T = 280$K and $T = 360$K is that the value of $r = I(0)/I_d(T)$ at $T \neq 300$K is different from that at $T = 300$K and, as a result, the wave parameters of the incident beam deviate significantly from those of a SP bright solitary wave supported by the crystal at $T = 280$K and $T = 360$K.

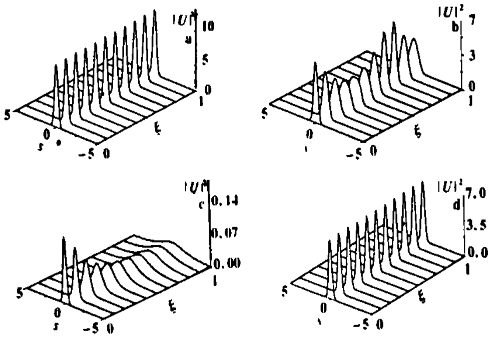

Fig. 1 Temperature effects on the dynamical evolution of an input SP bright soliton in the biased photovoltaic-photorefractive crystal with the parameters of $\alpha = -100$, $\beta = 135$ and $r_0 = 10$

a- $T = 300$K b- $T = 280$K c- $T = 360$K d- $T = 305$K

The input SP bright soliton is early obtained from Eq. (3) with $r_0 = 10$, $E_t = 10^{-19}$J, $\alpha = -100$ and $\beta = 135$ at $T = 300$K

When the crystal temperature deviates slightly from 300K, such as $T = 305$K, the incident beam reshapes itself and tries to evolve into a solitary wave after a short distance, as shown in Fig. 1d. The results indicate that a stable SP bright soliton can evolve into another stable SP bright soliton when the crystal temperature changes from one value to another if the temperature difference is small enough. In other words, there is a stable temperature regime in which the SP solitons are stable against small perturbations. In order to determine the width of the stable temperature regime, we calculate the temperature dependence of function $\Delta|U(T)|^2$ and $\Delta|W(T)|$ by numerically solving Eq. (1) with $\alpha = -100$, $\beta = 135$, $E_t = 10^{-19}$J and $r_0 = 10$ at different temperature, as shown in Fig. 2, and the incident SP bright soliton is early obtained from Eq. (3) with $\alpha = -100$, $\beta = 135$, $E_t = 10^{-19}$J and $r_0 = 10$ at $T = 300$K. As we can see that the maximum amplitude is more sensitive to temperature than FWHM. It is difficult to define the stable temperature regime strictly. Here we define the regime $|\Delta T|$ as

$$|\Delta T| = \min\{|\Delta T|: \Delta|U(T)|^2 \leqslant 5\%,\ |\Delta T|: \Delta|W(T)|\} \leqslant 5\% \tag{7}$$

From Fig. 2, we have $|\Delta T| \approx 16$K.

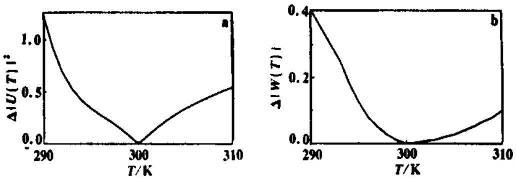

Fig. 2 Temperature dependence of function $\Delta|U(T)|^2$ and $\Delta|W(T)|$ when the incident beam is a bright SP soliton with $\alpha = -100$, $\beta = 135$, $E_t = 10^{-19}$J and $r_0 = 10$

We then investigate the following problem. Can we adjust the crystal temperature to make an unstable optical beam become a stable SP bright soliton? For example, an incident beam, with its wave parameters deviating significantly from those of a SP bright soliton early formed in a crystal with $\alpha = -100$, $\beta = 135$, $E_t = 10^{-19}$J and $r_0 = 10$ at $T = 300$K, must not evolve into a stable SP bright soliton in the same crystal at $T = 300$K. Can it evolve into a SP bright soliton at another temperature? At first, we consider the case that the deviation comes from the beam width. In doing so, we take a Gaussian beam $U = (10)^{1/2}\exp[-s^2/0.83^2]$ as the incidence beam. Fig. 3a and Fig. 3b give the evolution of the Gaussian beam in a biased photovoltaic-photorefractive crystal by numerically solving Eq. (1) with $\alpha = -100$, $\beta = 135$, $E_t = 10^{-19}$J and $r_0 = 10$ at $T = 300$K and 365K, respectively. Obviously, the Gaussian beam cannot evolve into a stable SP bright soliton in the crystal at $T = 300$K. However, if the crystal temperature is adjusted to 365K, the Gaussian beam can evolve into a stable SP bright soliton in the crystal. Secondly, we consider the case that the deviation comes from the beam amplitude. In doing so, we take a Gaussian beam $U = (40)^{1/2}\exp[-s^2/0.43^2]$ as the incidence beam. Fig. 4a and Fig. 4b give the evolution of the Gaussian beam in the crystal at $T = 300$K and $T = 317$K, respectively. As we can see, although the Gaussian beam cannot evolve into a stable SP bright soliton at $T = 300$K, it can at $T = 317$K. These results indicate that although a Gaussian beam cannot evolve into a stable SP bright soliton in a crystal at one crystal temperature, it can evolve into a stable SP bright soliton at another one temperature. This means that one can adjust the crystal temperature to make an unstable optical beam become into a stable SP bright soliton.

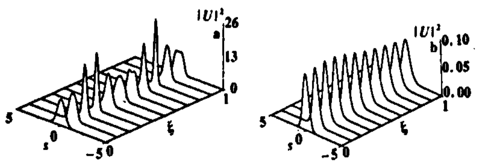

Fig. 3 a—an input Gaussian beam $U = (10)^{1/2}\exp[-s^2/0.83^2]$ can not evolve into a stable SP bright soliton in a biased photovoltaic photorefractive crystal with the parameters of $\alpha = -100$, $\beta = 135$K and r_0 at $T = 300$K b—it can evolve into a stable SP bright soliton in the crystal at $T = 365$K

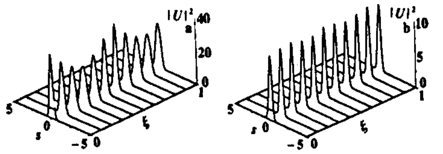

Fig. 4 a—an input Gaussian beam $U = (40)^{1/2}\exp[-s^2/0.43^2]$ can not evolve into a stable SP bright soliton in a biased photovoltaic photorefractive crystal with the parameters of $\alpha = -100$, $\beta = 135$ and $r_0 = 10$ at $T = 300$K b—it can evolve into a stable SP bright soliton in the crystal at $T = 317$K

3 Conclusion

In conclusion, we have investigated theoretically the temperature effects on the stability of bright screening-photovoltaic solitons in biased photovoltaic-photorefractive crystals under steady-state conditions for the case of neglecting the material loss and diffusion process. Our numerical study indicates that a stable SP soliton formed at a temperature tends to be unstable at another temperature when the temperature difference is big enough. There is a stable temperature regime in which the screening-photovoltaic solitons are stable against small perturbations. An unstable optical solitary beam can evolve into a stable screening-photovoltaic soliton by adjusting the crystal temperature.

The physical factor related to the temperature effects is the dark irradiance. As we know, for a given physical system, including a given photovoltaic-photorefractive crystal, the biased voltage and the intensity of the input optical beam, only one stable SP soliton can form in it for a given temperature. The spatial profile of the stable SP soliton, including the maximum amplitude, width and functional form, depends on the ratio of the input intensity to the dark irradiance that varies with the crystal temperature. Therefore, when the crystal temperature changes, the ratio will change. As a result, the input beam will evolve into another stable SP soliton when the temperature difference is small enough, whereas it will tend to be unstable when the temperature difference is big enough.

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