Vol 17 No 7, July 2008
1674-1056/2008/17(07)/2539-05

Chinese Physics B

© 2008 Chin. Phys. Soc.
and IOP Publishing Ltd

# Temporal development of open-circuit bright photovoltaic solitons*

Zhang Lei(张 磊)[a)b)†], Lu Ke-Qing(卢克清)[a)], Zhang Mei-Zhi(张美志)[a)b)], Liu Xue-Ming(刘雪明)[a)], and Zhang Yan-Peng (张彦鹏)[c)]

[a)] *State Key Laboratory of Transient Optics and Photonics, Xi'an Institute of Optics and Precision Mechanics, Chinese Academic of Sciences, Xi'an* 710119, *China*
[b)] *Graduate School of Chinese Academy of Science, Beijing* 100039, *China*
[c)] *Department of Electronic Science and Technology, Xi'an Jiaotong University, Xi'an* 710049, *China*

(Received 8 October 2007; revised manuscript received 25 December 2007)

This paper investigates the temporal behaviour of open-circuit bright photovoltaic spatial solitons by using numerical techniques. It shows that when the intensity ratio of the soliton, the ratio between the soliton peak intensity and the dark irradiance, is small, the quasi-steady-state soliton width decreases monotonically with the increase of $\tau$, where $\tau$ is the parameter correlated with the time, that when the intensity ratio of the soliton is big, the quasi-steady-state soliton width decreases with the increase of $\tau$ and then increases with $\tau$, and that the formation time of the steady-state solitons is not correlated with the intensity ratio of the soliton. It finds that the local nonlinear effect increases with the photovoltaic field, which behaves as that the width of soliton beams is small and the self-focusing quasi-period is short. On the other hand, we also discuss that both the time and the temperature have an effect on the beam bending.

**Keywords:** nonlinear optics, photovoltaic effect, temporal behaviour, temperature
**PACC:** 4265J, 7820, 7240

## 1. Introduction

Self-trapping of beam and formation of optical spatial solitons have been studied for several decades.[1−19] Due to their potential applications in all-optical switching, three-dimensional optical interconnects, and beam steering, this field has attracted considerable attentions. To our knowledge, three generic types of photorefractive (PR) solitons, which are quasi-steady-state,[2,3] screening[4,5] and photovoltaic (PV)[6−8] solitons, have been extensively studied theoretically and experimentally. Of particular interests are PV solitons, which are separated from other solitons because they strongly depend on the PV effect but not the external field. Considering that the intensity of incident beam plays a very important role in the formation time of solitons, we find that investigating the temporal behaviours of PV spatial solitons is of great interest.

By exploring the connection between quasi-steady-state solitons and screening ones, the formation of solitons has been studied theoretically and experimentally based on the bidimensional band transport model by Fressengeas *et al* in Ref.[9]. The equality of external applied voltage and PV effect has been elaborated. Moreover, under some given conditions, the analytical solution of time-dependent charge field has been obtained, and the temporal nonlinear beam propagation equation has been derived. In Ref.[10], Maufoy *et al* have numerically simulated the spatiotemporal evolution properties of screening solitons by using split-step Fourier method. Furthermore, optical-branching and interaction of solitons have been discussed. In Ref.[11], Chauvet has established the formation theory of one dimensional PV solitons, and studied the temporal behaviours of open-circuit dark PV solitons theoretically and experimentally. Yet, to date, the temporal behaviours of bright PV solitons and the effect of temperature on the beam bending have not been done, however, and these properties have a significant meaning on the application of bright PV solitons.

In this paper, on the basis of the temporal nonlinear beam propagation equation, we simulate the evolution of full width of half maximum (FWHM) of one-dimensional open-circuit PV PR spatial solitons.

*Project supported by the National Natural Science Foundation of China (Grant No 10674176).
†E-mail: lei_zhang312@126.com

We find that when the intensity ratio of the soliton is small, the quasi-steady-state soliton width decreases with an increase in $\tau$, where $\tau$ is the parameter correlated with the time, that when the intensity ratio of the soliton is big, the quasi-steady-state soliton width decreases with the increase of $\tau$ and then increases with $\tau$, and that the formation time of the steady-state solitons is not related with the intensity ratio of the soliton. By employing the steady-state PV soliton as the incident beam, the propagation of beam in $BaTiO_3$ has been simulated by using numerical techniques. We elaborate that the local nonlinear effect increases with the PV field, which behaves as that the width of soliton beams is small and the self-focusing quasi-period is short. In addition, we also discuss that both the time and temperature have an effect on the beam bending.

## 2. Spatial charge field and propagation equation

At appropriate intensity the electron density $n$ is negligible in comparison with the density of ionized donors or acceptors in PR crystals. The time-dependent space-charge field is given by Ref.[11]

$$E = \left(\frac{E_{\rm ph}I_{\rm em}}{I_{\rm em}+I_{\rm d}} + \frac{k_{\rm B}T}{e}\frac{1}{I_{\rm em}+I_{\rm d}}\frac{\partial I_{\rm em}}{\partial x}\right) \times \left[\exp\left(-\frac{I_{\rm em}+I_{\rm d}}{T_{\rm d}I_{\rm d}}t\right)-1\right], \quad (1)$$

where $T_{\rm d} = (\varepsilon_0\varepsilon_{\rm r}/e\mu) \times [\zeta N_{\rm a}/\beta\,(N_{\rm d}-N_{\rm a})]$ is the dielectric relaxation time in the absence of an illuminating field, $E_{\rm ph} = \beta_{\rm ph}\zeta N_{\rm a}/e\mu S$ is the PV field, $I_{\rm em}$ is the light intensity, $I_{\rm d} = \beta/S$ is the dark irradiance, $I = I_{\rm em} + I_{\rm d}$ is the total intensity, $N_{\rm d}$ is the total donor density, $N_{\rm a}$ is the density of ionized acceptors, $\beta$ and $S$ are the thermal and photoexcitation coefficient respectively, $\zeta$ is the recombination coefficient, $\mu$ is the electron mobility, $\varepsilon_{\rm r}$ is the relative dielectric constant, $\beta_{\rm ph}$ is the PV constant, $\varepsilon_0$ is the vacuum permeability, $T$ is the absolute temperature, and $k_{\rm B}$ is Boltzmann's constant.

Let us assume an optical beam uniform along the $y$ axis that propagates along the $z$ axis and is permitted to diffract only along the $x$ direction. The propagation of such optical field in a medium with a low index modulation is theoretically described by the scalar wave propagation equation[1,11]

$$\left(\frac{\partial}{\partial z} - \frac{\rm i}{2k}\frac{\partial^2}{\partial x^2}\right)A\,(x,z,t) = {\rm i}\frac{k}{n_{\rm e}}\Delta n A\,(x,z,t)\,, \quad (2)$$

where $k = 2\pi n_{\rm e}/\lambda$ is the wave number in the medium whose unperturbed extraordinary refractive index is $n_{\rm e}$, $\lambda$ is the vacuum wavelength, $A$ is a slowly varying envelop and $\Delta n = -0.5n_{\rm e}^3 r_{33}E$ is the refractive-index variation due to space-charge field $E$, where $r_{33}$ is the electro-optic coefficient.

By ignoring the constant variable of refractive index induced by $I_{\rm d}$, from Eqs.(1) and (2) we can obtain the temporal nonlinear beam propagation equation as following

$$ {\rm i}\frac{\partial U}{\partial z} + \frac{1}{2k}\frac{\partial^2 U}{\partial x^2} - \left(L\,|U|^2 + B\frac{\partial\,|U|^2}{\partial x}\right) \times \left(\exp\left[-\left(1+|U|^2\right)\tau\right]-1\right)\frac{U}{1+|U|^2} = 0, \quad (3)$$

where $U(x,z,\tau) = A(x,z,t)/\sqrt{I_{\rm d}}$, $\tau = t/T_{\rm d}$, $L = kn_{\rm e}^2 r_{33}E_{\rm ph}/2$ and $B = kn_{\rm e}^2 r_{33}k_{\rm B}T/(2e)$ are related to quasi-local nonlinearity and diffusion, respectively. The self-deflection of beam originates from the term of $B\partial|U|^2/\partial x$.[12]

We can ignore the deflection component, i.e. $B = 0$ provided that the PV field $E_{\rm ph}$ is strong enough. Under this condition, the normalized light field can be written as

$$U\,(x,z,\tau) = \sqrt{r}y\,(x,\tau)\exp\,({\rm i}\nu z)\,, \quad (4)$$

where $r$ is the ratio of soliton peak intensity $I_{\max}$ to dark irradiance $I_{\rm d}$, $\nu$ is the propagation constant, and $y(x,\tau)$ is a normalized real function bounded between $0 \le y(x,\tau) \le 1$.

Substituting Eq.(4) into Eq.(3), we obtain

$$y'' = 2k\nu y + 2kL\frac{ry^3}{1+ry^2} \times \left(\exp\left[-\left(1+ry^2\right)\tau\right]-1\right), \quad (5)$$

where $y''$ is the second order derivative of $y$ versus $x$. Integrating Eq.(5) by using the boundary conditions of bright solitons $y(0,\tau) = 1$ and $y'(0,\tau) = 0$, we then obtain

$$\begin{aligned}&(y')^2\\ &= 2k\,(v-L)\left(y^2-1\right) + \frac{2kL}{r}\ln\left(\frac{1+ry^2}{1+r}\right)\\ &\quad -\frac{2kL}{r\tau}\left[\exp\left(-\left(1+ry^2\right)\tau\right) - \exp\left(-\left(1+r\right)\tau\right)\right]\\ &\quad -\frac{2kL}{r}\left\{E_{\rm i}\left[-\left(1+ry^2\right)\tau\right] - E_{\rm i}\left[-\left(1+r\right)\tau\right]\right\},\end{aligned} \quad (6)$$

where

$$E_{\rm i} = \int_{-\theta}^{+\infty}\frac{\exp\,(-\theta)}{-\theta}{\rm d}\theta.$$

By employing the boundary conditions $y(\infty,\tau)=0$ and $y'(\infty,\tau)=0$, the propagation constant can be calculated as

$$\nu = L - \frac{L}{r}\ln(1+r) - \frac{L}{r\tau}\left[\exp(-\tau) - \exp(-(1+r)\tau)\right] - \frac{L}{r}\left\{E_{\rm i}(-\tau) - E_{\rm i}[-(1+r)\tau]\right\}. \quad (7)$$

Let the PR crystal be $BaTiO_3$ crystal.[13] The propagating beam is polarized along $x$ axis ($x$-direction being taken parallel to the $c$-axis) in the media. In this case, $r_{33}=80\times10^{-12}\,\mathrm{m/V}$, $n_{\rm e}=2.365$. For different given $r$, the widths of solitons evolve at different ways. Figure 1 shows the evolving curves of the FWHM of intensity of solitons. We can see that, when $r$ equals to 1, the quasi-steady-state soliton width decreases with the increase of $\tau$. However, when $r$ equals to 100 or 10, the quasi-steady-state soliton width decreases with the increase of $\tau$ and then increases with $\tau$. For $r$ equaling to 10 or 100, the minimum width of soliton emerges at $\tau$ approaching to $2/r$, and the minimum value is independent on intensity. Interestingly, it is also obvious that the formation time of steady-state solitons is close to a fixed value $T_{\rm d}$ for a variety of $r$.

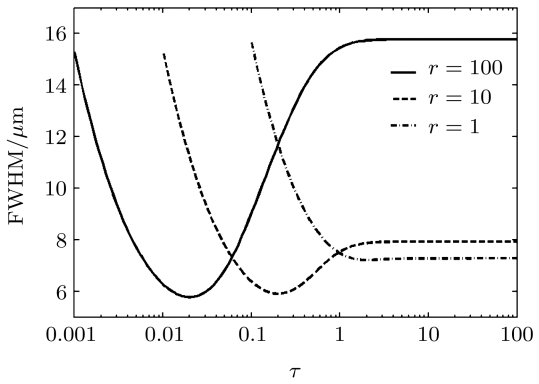



**Fig.1.** Intensity FWHM of PV bright spatial soliton versus $\tau$. The calculation parameters are $E_{\rm ph}=40\,\mathrm{kV/cm}$, $T=300\,\mathrm{K}$ for $r=100$ (solid curves), 10 (dash curves) and 1 (dash-dot curves)

## 3. Propagation of solitons in $BaTiO_3$

We study the propagation of a soliton with the input beam profile $U(x,0,t)=\sqrt{r}y(x,\infty)$, which is polarized along $x$ axis at wavelength $0.5\,\mu$m. When $r=100$, $E_{\rm ph}=40\,\mathrm{kV/cm}$ and $T=300\,\mathrm{K}$, $L$ and $B$ equal to $11.25\times10^3/\mathrm{m}$ and $7.72\times10^{-5}$ respectively, and the width of the incident soliton is $15.87\,\mu$m with a propagation distance 10.6 mm. At $\tau=0$, the space-charge field has not been established yet, and $\Delta n=0$. The incident beam propagates in the homogeneous media. In Fig.2(a), obviously, the width of incident beam broadens along $z$ axis because there is no self-focusing effect. As the time is evolving, the width of quasi-steady-state soliton reaches the minimum at $\tau=0.02=2/r$. When $\tau$ approximately equals to 1, the width of output soliton starts to evolve steadily as the way of $\tau\to\infty$ with the width $15.82\,\mu$m. Figures 2(b)–2(f) clearly show that self-deflection effect takes

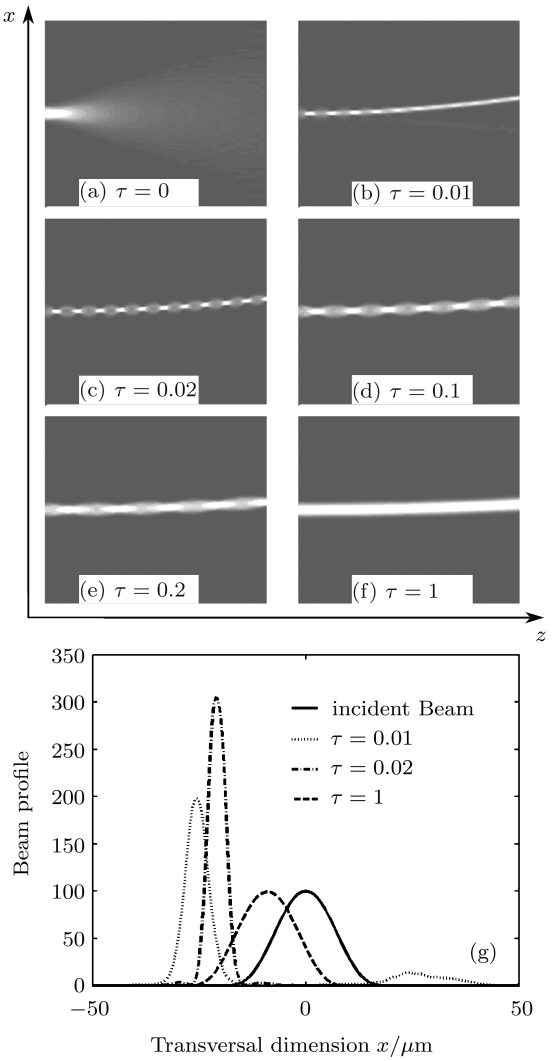



**Fig.2.** Evolution of PV bright soliton. The calculation parameters are $r=100$, $E_{\rm ph}=40\,\mathrm{kV/cm}$, $T=300\,\mathrm{K}$ with the input profile $U(x,0,t)=y(x,\infty)$. (a) $\tau=0$, (b) $\tau=0.01$, (c) $\tau=0.02$, (d) $\tau=0.1$, (e) $\tau=0.2$, (f) $\tau=1$, (g) report the comparison among the output beam profile and the beam profiles at $\tau=0.01$, $\tau=0.02$ and $\tau=1$ respectively. Here $x\in[-150\,\mu\mathrm{m}, 150\,\mu\mathrm{m}]$ and $z\in[0, 10.6\,\mathrm{mm}]$.

takes place during the propagation of soliton. And the maximum of the deflection distance, which equals to 25.49 $\mu$m, appears roughly at $\tau = 0.01$. In particular, it is obvious that the intensity of soliton varies periodically along $z$ axis. The focused periods for the different moment lengthen as the $\tau$ increases. When $\tau = 0.02$, $\tau = 0.1$ and $\tau = 0.2$, the focused periods are 1.0 mm, 1.7 mm and 2.4 mm, respectively. When $\tau = 0.2$, the phenomenon of the periodic variety of intensity begins to get indistinct and it disappears at $\tau = 1$, which can be realized as the focused period being infinite.

After changing $E_{\rm ph}$ to 20 kV/cm and maintaining $r$ and $T$, $L$ and the width of incident soliton change to $5.62 \times 10^3$/m and 11.26 $\mu$m, respectively. $L$ is a quantity related to quasi-local nonlinearity and is proportional to $E_{\rm ph}$. As $E_{\rm ph}$ is small, the local nonlinear effect becomes weak. Compared with Fig.2 at the each same moment, the width of soliton broadens in Fig.3, and in Figs.3(b)–3(d), furthermore, we can clearly see that the focused periods of beam during the propagations increase.

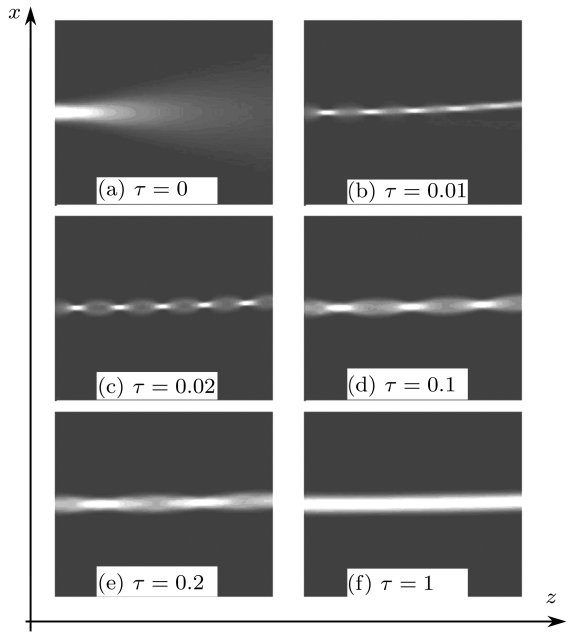



**Fig.3.** Evolution of PV bright soliton. The calculation parameters are $r = 100$, $E_{\rm ph} = 20$ kV/cm, $T = 300$ K with the input profile $U(x, 0, t) = y(x, \infty)$. (a) $\tau = 0$, (b) $\tau = 0.01$, (c) $\tau = 0.02$, (d) $\tau = 0.1$, (e) $\tau = 0.2$, (f) $\tau = 1$. Here $x \in [-150\,\mu$m, $150\,\mu$m] and $z \in$[0, 10.6 mm].

Figure 4 exhibits the evolvement of soliton at $E_{\rm ph} = 40$ kV/cm and $r = 10$, where $L = 11.25 \times 10^3$/m, $B = 7.72 \times 10^{-5}$ and the width of input soliton is 7.92 $\mu$m. Because the ratio of soliton peak intensity to dark irradiance becomes small, in Figs.4(a) and 4(b), we can easily observe that the input beam diffracts rapidly at $\tau = 0$ and $\tau = 0.02$. After the solitons being formed, there are no quasi-periodic structures. Nevertheless, the self-deflection effect is still clear at $\tau = 0.2$ and $\tau = 1$. When the beam exports steadily after $\tau = 1$, the width of steady-state soliton reaches 7.32 $\mu$m. In comparison with $r = 100$, the width becomes narrower and that is consistent with Fig.1 when $r = 10$.

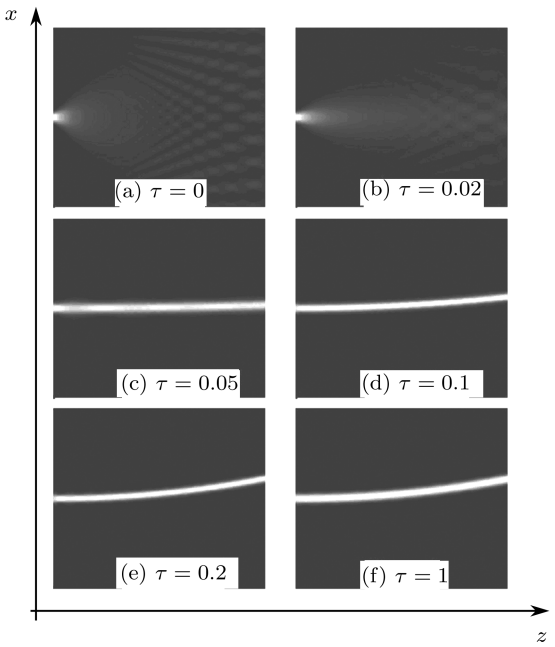



**Fig.4.** Evolution of PV bright soliton. The calculation parameters are $r = 10$, $E_{\rm ph} = 40$ kV/cm, $T = 300$ K with the input profile $U(x, 0, t) = y(x, \infty)$. (a) $\tau = 0$, (b) $\tau = 0.02$, (c) $\tau = 0.05$, (d) $\tau = 0.1$, (e) $\tau = 0.2$, (f) $\tau = 1$. Here $x \in [-100\,\mu$m, $100\,\mu$m] and $z \in$[0, 10.6 mm].

Self-deflection effect appears in Figs.2–4. Under different physical conditions, the deflection distances change accordingly. Figure 5 shows that the centre of output beam deflects along the negative direction of $x$ axis versus $\tau$ at a variety of temperatures. The deflection goes forward steadily after $\tau = 1$. $B$ is a parameter which is related to the self-deflection of beams. The bigger it is, the more obvious phenomenon of the self-deflection effect is. Knowing that $B$ is proportional to $T$, here we display the movement of the deflection distance of the centre of output solitons at different temperatures, $T = 300$ K, $T = 400$ K and $T = 500$ K. In Fig.5, it is clear that the distance increases with the rising temperature at the each same moment. In other words, the higher temperature

makes the self-deflection effect more significant. Furthermore, for each temperature, deflection distance of output steady-state soliton tends to increase with an increment of $\tau$ and then decreases with $\tau$, and the largest distance appears at a fixed time approaching to $\tau = 0.01 = 1/r$.

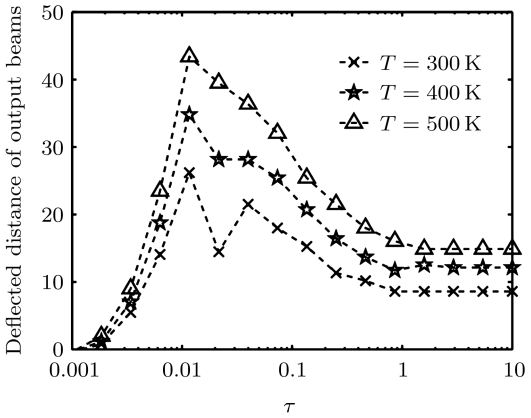



**Fig.5.** Deflection distance of the centre of the output beams along the negative direction of $x$ axis versus $\tau$ at different temperatures. Here $r = 100$ and $E_{\rm ph} = 40\,{\rm kV/cm}$.

# 4. Conclusion

To conclude, we have investigated the temporal behaviour of open-circuit bright PV spatial solitons by using numerical techniques. We have shown that when the intensity ratio of the soliton is small, the quasi-steady-state soliton width decreases with an increase of $\tau$, that when the intensity ratio of the soliton is big, the quasi-steady-state soliton width decreases with an increase of $\tau$ and then increases with $\tau$, and that the formation time of the steady-state solitons is closed to a fixed value $T_{\rm d}$ for a variety of intensity ratio of the soliton. Moreover, we have found that the local nonlinear effect increases with the PV field, which behaves as that the width of soliton beams is small and the self-focusing quasi-period is short. In addition, we have discussed that both time and temperature have an effect on the beam bending. For a given temperature, there exists a largest deflection distance appearing roughly at $\tau = 1/r$. For the same propagation time, the higher temperature is, the larger deflection distance is.

# References

[1] Christodoulides D N and Carvalho M I 1995 *J. Opt. Soc. Am.* B **12** 1628
[2] Morin M, Duree G, Salamo G and Segev M 1995 *Opt. Lett.* **20** 2066
[3] He G G, Wang X S and She W L 2002 *Acta Phys. Sin.* **51** 2270 (in Chinese)
[4] Segev M, Shih M F and Valley G C 1996 *J. Opt. Soc. Am.* B **13** 706
[5] Lu K Q, Zhao W, Yang Y L, Zhang M Z, Li J P, Liu H J and Zhang Y P 2006 *Chin. Phys.* **15** 403
[6] Lu K Q, Tang T T and Zhang Y P 2000 *Phys. Rev.* A **61** 053822
[7] Segev M, Valley G C, Bashaw M C, Taya M and Fejer M M 1997 *J. Opt. Soc. Am.* B **14** 1772
[8] Hou C F, Pei Y B, Zhou Z X and Sun X D 2005 *Chin. Phys.* **14** 349
[9] Fressengeas N, Maufoy J and Kugel G 1996 *Phys. Rev.* E **54** 6866
[10] Maufoy J, Fressengeas N, Wolfersberger D and Kugel G 1999 *Phys. Rev.* E **59** 6116
[11] Chauvet M 2003 *J. Opt. Soc. Am.* B **20** 2515
[12] Carvalho M I, Singh S R and Christodoulides D N 1995 *Opt. Commun.* **120** 311
[13] Liu J S and Hao Z H 2003 *Chin. Phys.* **12** 1124
[14] Sturman B I and Fridkin V M 1992 *The Photovoltaic and Photorefractive Effect in Non-centrosymmetric Materials* (Philadelphia: Gordon and Breach)
[15] Zhang G Y and Liu J S 2006 *Chin. Phys.* **15** 2631
[16] She W L, Zheng X G, Ni X H and Guo H 2001 *Chin. Phys. Lett.* **18** 1346
[17] Guo R, Ling Z F, Chen X H, Zhang G Q, Zhang X Z, Wen H D, Jiang Y and Liu S M 2000 *Chin. Phys. Lett.* **17** 804
[18] Zhang B Z, Wang H C and She W L 2007 *Chin. Phys.* **16** 1052
[19] Chen S M, Shi S X and Dong H Z 2007 *Acta Phys. Sin.* **56** 1379 (in Chinese)