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Incoherent interaction between bright–bright photovoltaic soliton in an unbiased series two-photon photorefractive crystal circuit

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ABSTRACT

We have investigated incoherent interaction between photovoltaic bright–bright soliton pairs in photorefractive crystals under steady-state condition in an unbiased series two-photon photorefractive crystal circuit in one dimension. The numerical scheme according to the Crank-Nicholson and Runge-kutta methods are applied to simulate the propagation of incoherent interaction for different normalized separation distances and different E_0. Results show that in the case of one-dimensional interaction between these photovoltaic solitons, attraction occurs and width of beams decreases with increasing biased field E_0 and two soliton interact in longer distance for smaller E_0. The result can be used for design optical switches that controlled by biased field.

1. Introduction

Spatial solitons have drawn considerable attention for their potential applications in the signal process and optical communications [1]. It is because of the formation of these spatial solitons in low light intensity and the wavelength dependence of material response. So one can generate solitons with power in the order of microwatts which induced a waveguide to propagate high power beams at other wavelengths. The other property of photorefractive solitons is their stability in two transverse dimensions in the bulk material [2–4]. Soliton interaction is one of the most fascinating aspects in soliton physics [5–8]. The interaction between coherent [9] and incoherent [10–15] soliton pairs are investigated theoretically [16,17] experimentally [18,19] in one and two-dimensional. One of the most interesting properties of optical solitons is the nonlinear interaction between two solitons that intersect or propagate close to each other. It is well known that in the Kerr media solitons in most respects behave as particle-like objects, leading to elastic collisions and a preservation of the solitons' identities. However, solitons in photorefractive crystals behave completely differently because of the saturation nonlinearity that is responsible the self-focusing effect [1,16]. Previously more researches were done in single photon model but recently the investigations are focused on two-photon model for two photorefractive crystal in a circuit. Castro-Camus and et al. [20] provided the model of two-photon photorefractive effect. The Castro-Camus model includes a valence band (VB), a conduction band (CB), and an intermediate allowed level (IL). The intermediate allowed level is used to maintain a quantity of excited electrons from the valence band by photons with energy $\hbar\omega_1$ (gating beam). These electrons are excited again to the conduction band by another photon with energy $\hbar\omega_2$. The pattern of the signal beam ($\hbar\omega_2$) can induce a spatial dependent charge distribution that gives rise to nonlinear changes of refractive index in the medium where this method could overcome the problems that existed in photon model [25].

In this paper we simulate a theoretical study of incoherent interaction of photovoltaic soliton pairs in an unbiased two-photon photorefractive crystal circuit.

2. Theatrical model

We consider two optical beams that propagate collinearly in the two-photon $LiNO_3$ photovoltaic photorefractive crystal, along the z-axis and are permitted to diffract only along the x direction. We take optical c-axis oriented of photorefractive medium along the x coordinate and is illuminated by the gating beam. The two incident beams have the same polarization, wavelength, and are mutually incoherent. Moreover, let us assume that the polarizations of the two incident optical beams are both parallel to the c-axis as the model used by Liu et al. in Ref. [22] except that we have considered the incoherent solitons propagate in crystal P as shown in Fig. 1.

As usual, we express the optical field of the incident beams in terms of slowly varying envelopes $\phi(x,z)$ and $\psi(x,z)$, i.e $\vec{E}_A=\hat{x}\psi(x,z)e^{ikz}$, $\vec{E}_B=\hat{x}\phi(x,z)e^{ikz}$ where $k=k_0n_e=(2\pi/\lambda_0)n_e$ that λ_0 and n_e are the

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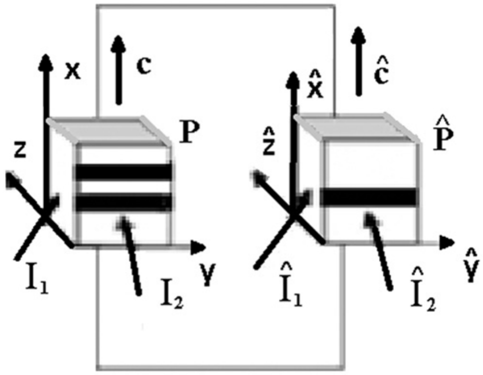

Fig. 1. Illustration of the series two-photon PR crystal circuit for study of incoherent interaction bright–bright pairs. The circuit consists of two PR crystals. One crystal's c-axis is oriented in a right-handed screw sense but the other crystal c-axis is opposite handed screw sense (↑↓).

free-space wavelength and the unperturbed extraordinary index of refraction respectively. Under these conditions, the two optical beams satisfy the following envelope evolution equations [10]:

$$i\phi_z+\frac{1}{2k}\phi_{xx}-\frac{k_0n_e^3r_{33}E_{sc}}{2}\phi=0 \quad (1)$$

$$i\psi_z+\frac{1}{2k}\psi_{xx}-\frac{k_0n_e^3r_{33}E_{sc}}{2}\psi=0 \quad (2)$$

where $\phi_z=\partial\phi/\partial z$, $\phi_{xx}=\partial^2\phi/\partial x^2$, $\psi_z=\partial\psi/\partial z$, $\psi_{xx}=\partial^2\psi/\partial x^2$ and r_{33} is the electro-optic coefficient. $\vec{E}_{sc}=\vec{x}_0E_{sc}$ is the induced space charge field in the medium.

In the steady-state and under close-circuit condition, the space charge field in Eq. (1) can be obtained from the Castro-Camus model. We know that in a close-circuit condition with two crystal, at least one of them should be photovoltaic [21,22]. The photovoltaic field is dominant in the close-circuit condition so, the space charge field in Eq. (1) can be expressed as [22,23]:

$$E_{sc}=E_0\frac{(I_\infty+I_{2d})(I+I_{2d}+\gamma_1N_A/s_2)}{(I+I_{2d})(I_\infty+I_{2d}+\gamma_1N_A/s_2)}+E_P\frac{s_2(I_\infty-I)(I+I_{2d}+\gamma_1N_A/s_2)}{(s_1I_1+\beta_1)(I+I_{2d})}-\frac{D\gamma_1N_A}{\mu s_2(I+I_{2d}+\gamma_1N_A/s_2)(I+I_{2d})}\frac{\partial I}{\partial x} \quad (3)$$

where $E_P=k_p\gamma N_A/e\mu$ is the photovoltaic field, k_p is the photovoltaic constant, N_A is the acceptor or trap density, μ and e are the electron mobility and the charge respectively, γ and γ_1 are recombination factors of the CB-VB and IL-VB, s_2 is photo-excitation crosses, $I_{2d}=\beta_2/s_2$ is the dark irradiance. β_1 and β_2 are the thermo-ionization probability constants for the transitions of VB-IL and IL-CB, D is diffusion coefficient, I_1 is the intensity of the gating beam, which can be considered as a constant, $I=I(x,z)$ is the total intensity of the two optical beams. According to Poynting's theorem, the total intensity of the two mutually incoherent optical beams can be obtained by:

$$I=I_A+I_B=(n_e/2\eta_0)(|\phi|^2+|\psi|^2) \quad (4)$$

where $\eta_0=(\mu_0/\varepsilon_0)^{1/2}$ and $I_\infty=I(s\to\pm\infty,z)$.

Note that the values of the fields in two crystal in this case depend on the parameters of both crystals and are not independent [22] and we investigate the interaction of the two bright soliton in one of the crystals in this circuit.

For convenience, the following dimensionless coordinates and appropriate normalization variables are adopted i.e. $s=x/x_0$, $\xi=z/(kx_0^2)$, $\phi=(2\eta_0I_{2d}/n_e)^{1/2}U$ and $\psi=(2\eta_0I_{2d}/n_e)^{1/2}V$, where x_0 is an arbitrary spatial width for scaling. Under these conditions, we obtained the normalized envelopes U and V of the two optical beams that satisfy the following dynamical evolution equations [22,23]:

$$iU_\xi+\frac{1}{2}U_{ss}-\frac{\beta(1+\rho)}{(1+\rho+\sigma)}\left(1+\frac{\sigma}{1+|U|^2+|V|^2}\right)U-\alpha\eta\frac{(\rho-|U|^2+|V|^2)(1+|U|^2+|V|^2+\sigma)}{1+|U|^2+|V|^2}U+\delta\frac{\sigma(|U|^2+|V|^2)_s}{(|U|^2+|V|^2+1)(|U|^2+|V|^2+1+\sigma)}U=0 \quad (5)$$

$$iV_\xi+\frac{1}{2}V_{ss}-\frac{\beta(1+\rho)}{(1+\rho+\sigma)}\left(1+\frac{\sigma}{1+|U|^2+|V|^2}\right)V-\alpha\eta\frac{(\rho-|U|^2+|V|^2)(1+|U|^2+|V|^2+\sigma)}{1+|U|^2+|V|^2}V+\delta\frac{\sigma(|U|^2+|V|^2)_s}{(|U|^2+|V|^2+1)(|U|^2+|V|^2+1+\sigma)}V=0 \quad (6)$$

where $\sigma=\gamma_1N_A/\beta_2$, $\alpha=(k_0x_0)^2(n_e^4r_{33}/2)E_P$, $\delta=(k_0x_0)^2(n_e^4r_{33}/2)D/(x_0\mu)$, $\eta=\beta_2/(s_1I_1+\beta_1)$ $\beta=(k_0x_0)^2(n_e^4r_{33}/2)E_0$.

We consider bright–bright soliton pairs. In this case, where bright optical beams are involved in both components, the intensity is expected to vanish at infinity ($s\to\pm\infty$) and thus $I_\infty=\rho=0$. Soliton solutions can, then, be readily obtained by expressing the normalized envelopes U and V as $U=r^{1/2}y(s)\exp(i\nu\xi)$ and $V=r^{1/2}y(s)\exp(i\nu\xi)$ respectively where ν represents a nonlinear shift of the propagation constant, $y(s)$ is a normalized real function bounded as $0\le y(s)\le 1$. After the same algebra, direct substitution of these forms of U and V in Eqs. (5) and (6) and applying boundary condition $y(0)=1$, $y(s\to\pm\infty)=0$ and $\dot{y}(0)=0$ leads to the following differential equation:

$$\left(\frac{dy}{ds}\right)^2=\left[\ln(1+ry^2)-y^2\ln(1+r)\right]\left[\frac{2\beta\sigma}{r(1+\sigma)}+2\alpha\eta\frac{\sigma}{r}\right]+\alpha r\eta y^2(1-y^2) \quad (7)$$

By integrating once we found that:

$$s=\pm\int_y^1\left\{\left[\frac{2\beta\sigma}{r(1+\sigma)}+2\alpha\eta\frac{\sigma}{r}\right]\left[\ln(1+r\tilde{y}^2)-\tilde{y}^2\ln(1+r)\right]+\alpha r\eta\tilde{y}^2(1-\tilde{y}^2)\right\}^{-1/2}d\tilde{y} \quad (8)$$

We will discuss the incoherently interaction of the bright–bright photovoltaic soliton pairs solutions due to two-photon photorefractive media in the next section.

3. Numerical simulations

In this paper we have used the numerical method for simulation of propagation of soliton pairs and solved the differential equations by using some modification of Crank-Nicholson iteration and Runge-Kutta methods by taking boundary conditions into account [24].

A relevant example is provided for the bright–bright soliton pairs formed in $LiNbO_3$ crystal that used with the parameters that mentioned in [22,23]. Where $\beta=21.7580$, $\alpha=-2.22$, $\sigma=10^4$, and $\eta=1.5\times10^{-4}$. We have taken incoherent interaction of this pair by changing the distance between the two soliton without changing another parameters also the diffusion term δ is ignored. The results are in Fig. 2 for $\Delta s=0.2,0.4,0.8,1.2,1.8,2$. As it can be seen in Fig. 2(a) and (b) solitons overlap with each other completely and they propagate as a beam with periodical and slightly changes in amplitude. Fig. 2c–e indicate that by increasing the length of separation, solitons attract each other but the attraction is decreased by increasing the separation. Also in Fig. 2(f), the attraction goes to zero. Solitons have greater tendency to preserve their profiles and period of attraction occurs in further distance. It can be seen that the strength of attraction