Photorefractive Polymeric Solitons

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Abstract— **We show the existence of photorefractive polymeric solitons in a bulk photorefractive polymer. We also show the existence of incoherently coupled two dimensional soliton pairs under steady state condition. The soliton pairs can exist under the condition that the two beams are mutually incoherent and have the same wavelength and polarization. The system was studied using the variational method and the result so obtained was analyzed using the finite-difference Beam Propagation method. Stable propagation of the soliton beam through the medium was observed.**

Keywords— **finite difference beam propagation method, incoherent solitons, polymeric solitons, spatial solitons, variational method**

I. Introduction

There has been tremendous growth in the field of optical spatial solitons since the first observation of self-trapping of light[1]. When an optical beam propagates in a suitable nonlinear medium, solitons can be formed and can be propagated without any diffraction effect. Spatial solitons with various dimensionality have been observed in various nonlinear media. The study of spatial solitons is considered to be important because of its possible applications in optical switching and routing. Segev et.al proposed a new kind of spatial soliton, the Photorefractive Soliton (PR) in the year 1992 [2]. When illuminated, a space-charge field is formed in the photorefractive material which induces nonlinear changes in the refractive index of the material by the electro-optic (Pockels) effect. This change in refractive index can counter the effect of beam diffraction forming a PR soliton. The light beam effectively traps itself in a self-written waveguide. As compared to the Kerr-type solitons, these solitons exist in two dimensions and can be generated at low power levels of the order of several microwatts. The PR soliton has been investigated extensively by various groups as it has potential applications in all-optical switching, beam steering, optical interconnects. At present, three different kinds of PR solitons have been proposed; quasi-steady state solitons [2], screening solitons [3]-[4] and screening photovoltaic solitons [5]. The screening PR solitons are one of the most extensively studied solitons. They are possible in steady state when an external bias voltage is applied to a non-photovoltaic PR crystal. This field is partially screened by space charges induced by the soliton beam. The combined effect of the balance between the beam diffraction and the PR focussing effect results in the formation of a screening soliton.

Recently, a new kind of PR soliton, the photorefractive polymeric soliton, has been proposed and observed [6]-[7]in a photorefractive polymer. The PR polymer was discovered in 1991 [8]. Since then it has attracted much research interest owing to the possibility of using them as highly efficient active optical elements for data transmission and controlling coherent radiation in various electro-optical and optical communication devices when compared to PR cystals. Pioneering works in incoherently coupled solitons were done by Christodoulides et al [9]. They theoretically and experimentally showed that an incoherently coupled soliton pair can propagate in a biased photorefractive crystal if the pairing beams experience roughly the same refractive index and electro-optic coefficients. The two beams are incoherent in the sense that their path difference is larger than the coherence length of the laser from which they are derived. The coupled soliton beams can exist in bright-bright, dark-bright and dark-dark form. Later the concept of incoherent solitons was extended to multibeam or multicomponent solitons. It has been shown that several beams can be combined to form multicomponent self trapped states, also known as vector solitons. When the soliton-induced waveguide traps one or several higher-order modes, the corresponding vector soliton may have a complex internal structure with several humps in the intensity profile. Such solitons have already been studied in the $(1+1)$-dimensional [10] and $(2+1)$ -dimensional [11] case in which some of the soliton components may carry an angular momentum.

In this work, we show the existence of PR polymeric solitons in the bulk geometry. We also show the existence of incoherently coupled solitons in this medium. We extend the concept of incoherently coupled solitons to two transverse dimensions. First we discuss our analytical model for the soliton propagation through the PR polymer. We use the variational method for the analytical study. We have considered an isotropic model for the PR nonlinear medium. Then we discuss the interaction of two mutually incoherent laser beams launched into the medium.

II. $(2+1)D$ polymeric solitons

The envelope evolution equation for a 1D polymeric soliton is given by,

$$i\phi_\zeta + \phi_{\xi\xi} + \beta\left(\frac{\gamma+1}{1+|\phi|^2}\right)^{2/m+1}\phi = 0. \qquad (1)$$

where ϕ is the amplitude of the slowly varying envelope, ζ is the normalized propagation direction of the beam, ξ is the normalized direction of diffraction of the beam, m is a material parameter that ranges from less than 1.0 to greater than 3.0, γ is the intensity ratio for the dark soliton, $\gamma = 0$ for the bright soliton.

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The optical beam passing through a bulk photorefractive material obeys the following envelope equation.

$$i\phi_\zeta + \nabla^2\phi + \beta\left(\frac{\gamma+1}{1+|\phi|^2}\right)^{2/m+1}\phi = 0. \qquad (2)$$

Variational method, which is a semi-analytical method, is used to analyze (1). We will consider cylindrical coordinates for our analysis. In the variational approach (1) is first reformulated as a variational problem in terms of a Lagrangian density

$$L = r\tfrac{i}{2}\left(\phi\phi^*_\zeta - \phi^*\phi_\zeta\right) + r\tfrac{\partial\phi}{\partial r}\tfrac{\partial\phi^*}{\partial r} + r\beta\tfrac{(1+m)(1+\gamma)}{(1-m)}\left[\left(\tfrac{\gamma+1}{|\phi|^2}\right)^{(1-m)/(1+m)} - 1\right]. \qquad (3)$$

The variational analysis proceeds by forming the reduced lagrangian, which is defined as

$$\langle L\rangle = \int_0^\infty L(\phi) r dr \qquad (4)$$

where ϕ is the trial function. The success of the variational approach depends upon the choice of the trial function. We assume a Gaussian trial solution of the form,

$$\phi(\zeta, r) = A(\zeta)\exp[-\frac{r^2}{2a(\zeta)^2} + ib(\zeta)r^2 + i\Phi(\zeta)] \qquad (5)$$

where A is the amplitude, a is the beam width, b is the curvature of the beam and Φ is the phase. After some algebra, we get the following set of ordinary differential equations.

$$a^2|A|^2 = constant \qquad (6)$$

$$b = \frac{1}{4}\frac{d\ln a}{d\zeta} \qquad (7)$$

$$\frac{d^2a}{d\zeta^2} = \frac{-5}{a^3} + \frac{(4+3m)Cr^5}{3a^6} - \frac{5C(1-m)r^3}{3(1+m)a^4} \qquad (8)$$

where,

$$C = \frac{64\beta(1+m)^2(1+\gamma)^{-2m/(1-m)}}{5\sqrt{\pi}(1-m)^2}. \qquad (9)$$

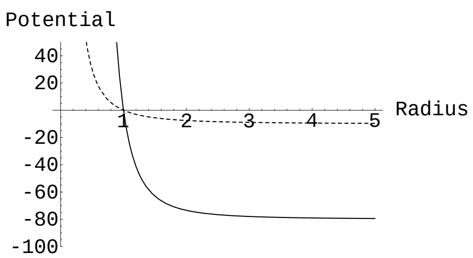

Fig. 1. Qualitative plot of the potential function showing the unbounded motion of the beam. The diffraction in linear regime is given by dotted line.

The evolution of the beam in the PR polymeric medium is determined by the competition between two factors: diffraction (given by the first term on the right-hand side of (8)) and the nonlinear self-focusing (net effect of the second and third term). In our calculations we have assumed that r is sufficiently large.

Integration of (8) using (6) and introducing the normalized variables, $a(\zeta)/a_0 = y(\zeta)$, gives an equation of the form,

$$\frac{1}{2}\left(\frac{dy}{d\zeta}\right)^2 + \Pi(y) = 0 \qquad (10)$$

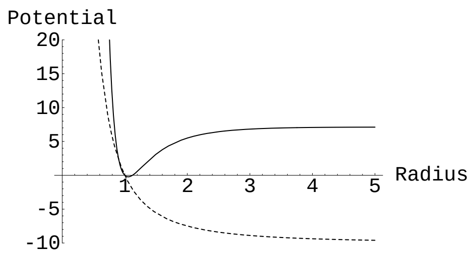

Fig. 2. Qualitative plot of the potential function showing trapping of the beam.

This equation is analogous to the equation of a particle moving in a potential well. The potential function, $\Pi(y) = \mu/y^2 + \alpha/y^3 + \nu/y^5 + K$ with $\mu = 5/(2a_o^5)$, $\alpha = -5C(1-m)/(9(1+m)a_o^5)$, $\nu = (4+3m)\,C/\left(15a_0^7\right)$.

The beam is self trapped when the diffraction of the beam is completely compensated by the self-focussing of the beam. The beam diffracts even more than the linear case if we change the sign of the nonlinearity (Fig.1). But the beam is self-trapped when the nonlinearity is of focussing nature (Fig.2). The result so obtained is taken as the initial condition for our numerical simulation. We solve (2) using a finite-difference Beam Propagation method. The Crank-Nicholson implicit method is used to write the approximate derivatives in the propagation direction and the transverse Laplacian. We get a tridiagonal matrix which is then easily solved using Thomas algorithm [12]. The material parameters for the simulation are taken as $\beta = 10.6$, $m = 2$ and $\gamma = 0$. The two-dimensional spatial soliton propagates through the medium without any change in its shape. The output profile of the beam after a propagation of $3mm$ through the medium is shown in Fig.3.

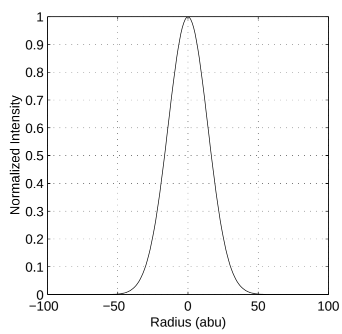

Fig. 3. Output profile of the beam after a propagation of $3mm$ through through the medium.

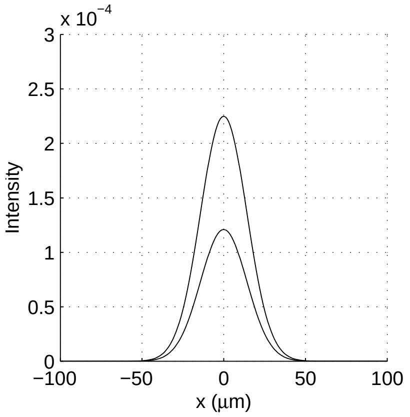

Fig. 4. Soliton components, $|\phi|^2$ and $|\psi|^2$ for bright-bright polymeric soliton pair.

III. Incoherently coupled solitons

Now we consider the propagation of incoherently coupled soliton pairs through the photorefractive polymeric medium. To study the incoherently coupled soliton pairs, we have to consider two mutually incoherent soliton beams which have the same wavelength and polarization and propagates collinearly in a biased PR polymer. The two beams propagate along the z direction and are allowed to diffract along the two transverse dimensions x and y. Using the standard procedure we get the following coupled equations in the dimensionless form for the two incoherently coupled beam.

$$i\phi_\zeta + \nabla^2\phi + \beta \left(\frac{\gamma + 1}{1 + |\phi|^2 + |\psi|^2} \right)^{2/m+1} \phi = 0, \qquad (11)$$

$$i\psi_\zeta + \nabla^2\psi + \beta \left(\frac{\gamma + 1}{1 + |\phi|^2 + |\psi|^2} \right)^{2/m+1} \psi = 0, \qquad (12)$$

where ϕ and ψ are the amplitudes of the slowly varying envelopes of the two beams.

We look for possible soliton pair solutions of the two equations. For this we take the variational solution of (2) as the initial solution for the numerical simulation of the two coupled equations. The coupled equations are solved using the finite-difference beam propagation method. First the two equations are written in the finite-difference form using the Crank-Nicholson scheme and then they are simultaneously solved using the Thomas algorithm. The result of the numerical simulation for bright-bright incoherently coupled solitons is shown in Fig(4).

IV. Conclusion

We have studied the propagation of two-dimensional spatial solitons in a photorefractive polymer medium. We considered an isotropic model for our system. Existence of stable bright solitons was established in the PR polymer medium. We have also considered the propagation of two mutually incoherent beams through the nonlinear medium. We could show that two mutually incoherent beams of the same polarization and wavelength can form a coupled steady-state spatial soliton pair in a biased photorefractive polymeric medium under steady-state conditions.

References

[1] R. Y. Chiao, E. Garmire and C. H. Townes , “Self-Trapping of Optical Beams” Phys. Rev. Lett. **13**, No.15 (1964)pp 479-482.
[2] M. Segev, B. Crosignani, A. Yariv, and B. Fischer, Phys. Rev. Lett. **68**, 923 (1992).
[3] M. Segev, G. C. Valley, B. Crosignani, P. DiPorto and A. Yariv, Phys. Rev. Lett. **73**, 3211 (1994).
[4] D. N. Christodoulides and M. J. Caravalho, J. Opt. Soc. Am. B **12**, 1628 (1995).
[5] G. C. Valley, M. Segev, B. Crosignani, A. Yariv, M. M. Fejer and M. C. Bashaw, Phys. Rev. A **50**, R4457 (1994).
[6] Ming-Feng Shih and Fang-Wen Sheu, Opt. Lett. **24**, 1853 (1999).
[7] Zhigang Chen, Marcus Asaro, Oksana Ostroverkhova, W. E. Moerner, Meng He and R. J. Twieg, Opt. Lett. **24**, 2509 (2003).
[8] S. Ducharme, J. C. Scott, R. J. Twieg, and W. E. Moerner, Phys. Rev. Lett. **66**, 1846 (1991).
[9] D. N. Christodoulides, S. R. Singh and M. I. Carvalho, Appl. Phys. Lett. **68**, 1763(1996).
[10] M. Haelterman and A. P. Sheppard, Phys. Rev. E 49, 3376 (1994).
[11] Z. H. Musslimani, M. Segev, D. N. Christodoulides, and M. Soljacic, Phys. Rev. Lett. 84, 1164 (2000).
[12] C. P. Jisha, V. C. Kuriakose and K. Porsezian, Phys. Rev. E **71**, 056615 (2005).