Circularly polarized optical spatial solitons

Xiao Sheng Wang and Wei Long She
State Key Laboratory of Optoelectronic Materials and Technologies, Sun Yat-Sen (Zhongshan) University, Guangzhou 510275, China

Shui Zhu Wu and Fang Zeng
Department of Polymer Science and Engineering, South China University of Technology, Guangzhou 510640, China

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We present, experimentally and theoretically, a polymer material system that supports optical spatial solitons of circular polarization. We demonstrate one-dimensional circularly polarized dark solitons supported by photoisomerization nonlinearity in a bulk polymer. © 2005 Optical Society of America

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The optical spatial soliton (SS) is one of the most intriguing phenomena of nonlinear optics. The formation of optical SSs, which is possible because of the Kerr effect, was predicted more than 30 years ago. In the past decade, SSs supported by the photorefractive effect have stimulated much research. Some interesting discoveries relative to this type of SS, such as the interaction of SSs, rotating SSs, multiple composite SSs, and photorefractive SSs in organic materials, have been reported.

Photoisomerization is another interesting phenomenon of nonlinear optics. The reversible transition of trans and cis isomerization of the photochromic process in polymers, which is different from another photosensitive process (photopolymerization) and is used to form spontaneous waveguides in the polymers, can lead to photoinduced birefringence, dichroism, mass transport, and intensity-dependent changes in the refractive index. This intensity-dependent change in refractive index is capable of supporting SSs. We have predicted theoretically that, assisted by an appropriate background beam, dark or bright one-dimensional SSs can be formed in bulk polymer with photoisomerization nonlinearity.

Poly(methyl methacrylate) (PMMA) doped with the azo dye 4′-(2-hydroxyethyl)ethylamino-4-nitroazobenzene (Disperse Red 1 (DR1)) is one of the most popular materials used by many researchers to study photoisomerization nonlinearity. It has been confirmed that, when a light beam with a wavelength in the photoisomerization-sensitive range propagates in this material, the photoinduced change in refractive index will come chiefly from the photoisomerization nonlinearity of the DR1. Poly(methyl methacrylate) (PMMA) doped with the azo dye 4′-(2-hydroxyethyl)ethylamino-4-nitroazobenzene (Disperse Red 1 (DR1)) is one of the most popular materials used by many researchers to study photoisomerization nonlinearity. It has been confirmed that, when a light beam with a wavelength in the photoisomerization-sensitive range propagates in this material, the photoinduced change in refractive index will come chiefly from the photoisomerization nonlinearity of the DR1.

Recently, dark SSs were induced in DR1-doped PMMA by Bian and Kuzyk. All the SSs mentioned above were formed by a linearly polarized light beam. As far as we know, SSs formed by a circularly polarized (CP) light beam have not yet been reported. In this Letter we demonstrate experimentally and theoretically that a CP beam with a dark notch can spontaneously form optical dark SSs supported by photoisomerization nonlinearity in a bulk polymer material of DR1-doped PMMA.

The experimental setup is similar to that for the formation of photorefractive SSs but without an additional background beam or external field. The signal beam is 514.5-nm CP radiation through a quarter-wave plate irradiated from an argon-ion laser. The power of the signal beam is 32 mW, and the average intensity in the center area of its cross section is ~23 W/cm^2. A dark notch, which arises from a π-step phase jump across it, is introduced by a thin glass coverslip inserted halfway into the center of the cross section of the signal beam. This signal beam is focused onto the front surface of a 2.4-mm-thick sample and detected by a CCD behind the sample. The sample is bulk PMMA doped with 1% DR1. The preparation, absorption spectra, and chemical structure of the sample were reported in Refs. 23 and 24. It was found that, when the signal beam is turned on, the dark notch narrows and then spontaneously goes to self-trapping after ~1-s exposure. The image and intensity profiles of the signal beam on the input face, and on the output face of the sample when self-trapping and diffraction happen, are shown in Figs. 1(a)–1(c), respectively. It is clear from Fig. 1(b) that the dark notch self-traps and forms a dark SS with a full width of ~15.8 µm. All these self-trappings are reversible, and we have determined that left and right circular polarization results in the same formation of solitons. The experimental results are explained by the theory given below.

![Fig. 1](image-url)
When a CP signal beam of intensity \( I_s \) is turned on, the reaction kinetics of the photoisomerization photochromic process in the polymer can be described by

\[
\frac{dT}{dt} = -\frac{1}{2}q_{T}\sigma_{T}I_{s}T \sin^{2} \theta + q_{C}\sigma_{C}I_{s}(T_{0} - T)
\]

\[+ K_{C}(T_{0} - T), \]

(1)

where \( T \) and \( T_0 \) are the concentrations of molecules in the trans form under illumination and in the dark, respectively; \( \theta \) is the angle between the molecular orientation and the direction of the wave vector of the signal beam; \( q_{T} \) and \( q_{C} \) are the quantum yields of the signal beam for trans-to-cis and cis-to-trans transitions and \( \sigma_{T} \) and \( \sigma_{C} \) are the absorption cross section of the signal beam in the trans-to-cis and cis-to-trans transitions, respectively; and \( K_{C} \) is the thermal relaxation rate of the cis-to-trans transition. For the steady state, one can get

\[T = T_{0}(1 + 1)/(\beta I \sin^{2} \theta/2 + 1 + 1),\]

(2)

where \( I = I_{s}/I_{D}, I_{D} = K_{C}/(q_{C}\sigma_{C}) \), and \( \beta = (q_{T}\sigma_{T})/(q_{C}\sigma_{C}) \). Neglecting linear absorption, the wave equation is \( \nabla^{2}E - c^{2}\partial^{2}(E + P)/\partial t^{2} = 0 \), where \( E \) is the electric field of the beam, \( P \) is the polarization, and \( c \) is the velocity of light in vacuum. We can rewrite this equation in scalar form. For the CP beam we have

\[\nabla^{2}E_{j} - c^{2}\partial^{2}(E_{j} + P_{j})/\partial t^{2} = 0,\]

(3)

where \( j = 1, 2, E_{1} \) and \( E_{2} \) are the two perpendicular components of \( E \) along the \( x \) and \( y \) axes (the wave vector is set in the \( z \) axis), respectively, which have a \( \pi/2 \) phase difference, and \( P_{j} \) are the components of \( P \) in the direction \( E_{j} \).

According to the symmetry of the signal beam, we set up a coordinate as shown in Fig. 2. In a solid angle, \( d\Omega \), the number of the molecules is \( T d\Omega \). With a rodlike assumption, the polarization induced in \( d\Omega \) is \( T d\Omega \chi_{33}(E_{1} \cos \Psi + E_{2} \cos \Phi)\hat{e}_{a} \), where \( \hat{e}_{a} \) is a unit vector along the direction of the molecular axis and \( \chi_{33} \) is the component of the linear dielectric tensor in the molecular coordinate. Then we get

\[P_{1} = \int T\chi_{33}(E_{1} \cos^{2} \Psi + E_{2} \cos \Phi \cos \Psi)d\Omega,\]

\[P_{2} = \int T\chi_{33}(E_{1} \cos \Psi \cos \Phi + E_{2} \cos^{2} \Phi)d\Omega.\]

(4a)

(4b)

\( P_{1} \) and \( P_{2} \) can be divided into a linear part, \( P_{1}^{L} \) and \( P_{2}^{L} \), and a nonlinear part, \( P_{1}^{N} \) and \( P_{2}^{N} \), where

\[P_{1}^{L} = \int(T_{0}\chi_{33}(E_{1} \cos^{2} \Psi + E_{2} \cos \Phi \cos \Psi)d\Omega, \quad P_{1}^{N} = \int(T - T_{0})\chi_{33}(E_{1} \cos^{2} \Psi + E_{2} \cos \Phi \cos \Psi)d\Omega, \quad P_{2}^{L} = \int T\chi_{33}(E_{1} \cos \Psi \cos \Phi + E_{2} \cos^{2} \Phi)d\Omega, \quad P_{2}^{N} = \int(T - T_{0})\chi_{33}(E_{1} \cos \Psi \cos \Phi + E_{2} \cos^{2} \Phi)d\Omega.\]

The integrals give

\[P_{1}^{L} = 4\pi T_{0}\chi_{33}I_{1}/3 = \chi^{L}(I_{1}), \quad P_{2}^{L} = 4\pi T_{0}\chi_{33}E_{2}/3 = \chi^{L}(I_{2}), \quad P_{1}^{N} = \chi^{N}(I_{1}), \quad \text{and} \quad P_{2}^{N} = \chi^{N}(I_{2}),\]

(5)

where \( \chi^{N}(I) = 4\pi T_{0}\chi_{33} \left[ I + 1 \left( 1 + \frac{(I + 1)/\beta I}{[2(I + 1)/\beta I + 1]^{1/2}} \right) \right] \frac{1}{3}.\]

(6a)

Obviously \( P_{j} \) are functions of \( E_{1} \) and \( E_{2} \) because they are functions of \( I \) and \( I = (E_{1}^{2} + E_{2}^{2})/I_{D}. \)

For the one-dimensional SSs we assume that \( E_{1} = A_{1}(x) \exp(i(kz - wt)) \) along the \( x \) axis and \( E_{2} = A_{2}(x) \exp(i(kz - wt) \pm \pi/2) \) along the \( y \) axis, where \( A_{j}(x) \) is the slowly varying amplitude of the \( j \)th component and \( + \) and \( - \) correspond to left- and right-hand circular polarization. Then we get the Schrödinger equations

\[\frac{\partial^{2}A_{1}}{\partial x^{2}} + k_{0}^{2}(n_{0}^{2} - n_{0}^{2})A_{1} + 2ik \frac{\partial A_{1}}{\partial z} = 0,\]

(6a)

\[\frac{\partial^{2}A_{2}}{\partial x^{2}} + k_{0}^{2}(n_{0}^{2} - n_{0}^{2})A_{2} + 2ik \frac{\partial A_{2}}{\partial z} = 0,\]

(6b)

where \( k = n_{0}k_{0} \), where \( k_{0} \) is the wave number of light in free space, \( n_{0} \) is the unperturbed refractive index, \( n_{0}^{2} = 1 + \chi^{L} + \chi^{N}, \) and \( n_{0}^{2} = 1 + \chi^{L} \). \( A_{1} \) and \( A_{2} \) satisfy the Schrödinger equations of the same form, so we can set \( A_{1} = A_{2} = A. \)

The intensity-dependent change in refractive index is \( \Delta(n^{2}) = \chi^{N}(I) \) for each of the two perpendicular components of the CP beam. Numerical calculations tell us that this change in refractive index is always negative and saturable and decreases monotonically relative to the intensity, which implies that only dark spontaneous SSs can be formed \( \text{in bulk material.} \)

Let \( A = u(x) \sqrt{2I_{D}} \exp(\sqrt{I}x)/2, \) where \( \sqrt{I} \) is the propagation constant of the SSs; then the soliton equation in dimensionless form deduced from Eqs. (6) is
a wavelength of 514.5 nm, b stils02@zsu.edu.cn. 001192 and 031567). W. L. She's e-mail address is foundation of Guangdong Province, China (grants 10374121, and 50173007). The formation of solitons is spontaneously and the photoisomerization nonlinearity is saturable. This research was supported by the National Natural Science Foundation of China (grants 10074082, 10374121, and 50173007) and the Natural Science Foundation of Guangdong Province, China (grants 001192 and 031567). W. L. She's e-mail address is stils02@zsu.edu.cn.

\[ \frac{\partial^2 u(\xi)}{\partial \xi^2} = u \left( b - \frac{u^2 + 1}{\beta u^2} \left( 1 + \frac{(u^2 + 1)/\beta u^2}{(2u^2 + 1)/\beta u^2 + 1} \right)^{1/2} \times \ln \left( \frac{[2(u^2 + 1)/\beta u^2 + 1]^{1/2}}{[2(u^2 + 1)/\beta u^2 + 1]^{1/2} + 1} \right) \right), \]  

where \( u^2(\xi) = 1, \, \xi = x/a_0, \, a_0 = (8n_0k_0^2\pi ST_0)^{-1/2}, \) and \( b = 1/(4k_0\pi ST_0). \) The dark SS solution obtained is shown in Fig. 3 for \( u_x = 1.0 \) and \( \beta = 1/2 \) (for light with a wavelength of 514.5 nm, \( \beta \) is \( \sim 1/2 \), corresponding to the parameters given in Ref. 23). The curve for the existence of a soliton is shown in the inset of Fig. 3.

The results above are not surprising. As the isomerization nonlinearity is axisymmetric along the propagation direction of the CP light [Eq. (2)], two components of the CP beam will satisfy the same form of the propagation equation and then experience the same evolution. In conclusion, we have shown experimentally and theoretically that a circularly polarized beam with a dark notch can self-trap and form dark spatial solitons supported by photoisomerization nonlinearity in a bulk polymer. The formation of solitons is spontaneous and the photoisomerization nonlinearity is saturable.

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Fig. 3. Intensity profile of a dark SS for \( u_x = 1.0 \) and \( \beta = 1/2 \). The existence curve is shown in the inset.

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