Optical switch phenomenon in a self-defocusing medium

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A spatial optical switch phenomenon caused by the induced focusing of a weak probe beam occurring in self-defocusing nonlinear media is discussed theoretically. A weak beam is induced to focus when it copropagates with an intense pump beam under the conditions that the probe and pump beams peak at different positions and propagate in different directions. Due to the effect of cross-phase modulation, the weak beam can not only be focused but also be deflected. The phenomenon is discussed by numerically solving the coupled amplitude equations.

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The effects of Kerr nonlinearity have been well studied. The nonlinear Schrödinger equation describes a rich set of physical phenomena that have been so thoroughly investigated, and self-focusing and self-defocusing are well-known nonlinear optical processes. It has been predicted theoretically[1−6] and demonstrated experimentally[7,8] that the presence of a strong pump beam can induce focusing and deflection of a weak probe beam even in a self-defocusing medium. In this letter, we report a spatial optical switch phenomenon caused by the deflection of the induced focusing in a self-defocusing medium.

We assume that three beams copropagate at the frequencies ω_1, ω_2, and ω_3, and they are linearly polarized, having two coplanar angular separations. The mathematical description of the cross-phase modulation induced interaction among these three copropagating continuous-wave (CW) or quasi-CW beams is provided by the coupled amplitude equations which, in the paraxial approximation, take the form

$$\frac{\partial A_1}{\partial z} - \frac{\mathrm{i}}{2k_1}\left(\frac{\partial^2 A_1}{\partial x^2} + \frac{\partial^2 A_1}{\partial y^2}\right) = \frac{\mathrm{i}k_1 n_2}{n_{01}}\left(|A_1|^2 + 2|A_2|^2 + 2|A_3|^2\right)A_1, \quad (1)$$

$$\frac{\partial A_2}{\partial z} + \mathrm{tg}\theta_{12}\frac{\partial A_2}{\partial x} - \frac{\mathrm{i}}{2k_2}\left(\frac{\partial^2 A_2}{\partial x^2} + \frac{\partial^2 A_2}{\partial y^2}\right) = \frac{\mathrm{i}k_2 n_2}{n_{02}}\left(|A_2|^2 + 2|A_1|^2 + 2|A_3|^2\right)A_2, \quad (2)$$

$$\frac{\partial A_3}{\partial z} - \mathrm{tg}\theta_{13}\frac{\partial A_3}{\partial x} - \frac{\mathrm{i}}{2k_3}\left(\frac{\partial^2 A_3}{\partial x^2} + \frac{\partial^2 A_3}{\partial y^2}\right) = \frac{\mathrm{i}k_3 n_2}{n_{03}}\left(|A_3|^2 + 2|A_1|^2 + 2|A_2|^2\right)A_3, \quad (3)$$

where A_j $(j = 1, 2, 3)$ is the slowly varying envelope amplitude, $k_j = 2\pi n_{0j}/\lambda_j$, and n_{0j} is the linear refractive index at the carrier wavelength λ_j. The nonlinearity coefficient n_2 is negative for a self-defocusing medium, while θ_{12} and θ_{13} are the angles made by Beam 1 with Beam 2 and Beam 1 with Beam 3, respectively.

It is difficult to solve Eqs. (1)–(3) analytically, so a numerical approach is often necessary. The insight can be gained by limiting the diffractive coupling to one transverse dimension by setting $\partial A_j/\partial y = 0$ for $j = 1, 2, 3$. This is justified for nonlinear interaction in planar optical waveguides. We introduce the normalized variables

$$X = \frac{x}{w_0}, \quad \xi = \frac{z}{L_D}, \quad U_j = \frac{A_j k_1 w_0 |n_2|^{\frac{1}{2}}}{n_{01}^{\frac{1}{2}}}, \quad (4)$$

where $L_D = k_1 w_0^2$, w_0 is the spot size, and write Eqs. (1)–(3) in the form

$$\frac{\partial U_1}{\partial \xi} - \frac{\mathrm{i}}{2}\frac{\partial^2 U_1}{\partial X^2} = \mathrm{sgn}(n_2)\mathrm{i}\left(|U_1|^2 + 2|U_2|^2 + 2|U_3|^2\right)U_1, \quad (5)$$

$$\frac{\partial U_2}{\partial \xi} + \frac{\sigma_1 \partial U_2}{\partial X} - \frac{\mathrm{i}}{2}\frac{\lambda_2}{\lambda_1}\frac{\partial^2 U_2}{\partial X^2} = \mathrm{sgn}(n_2)\mathrm{i}\frac{\lambda_2}{\lambda_1}\left(|U_2|^2 + 2|U_1|^2 + 2|U_3|^2\right)U_2, \quad (6)$$

$$\frac{\partial U_3}{\partial \xi} - \frac{\sigma_2 \partial U_3}{\partial X} - \frac{\mathrm{i}}{2}\frac{\lambda_3}{\lambda_1}\frac{\partial^2 U_3}{\partial X^2} = \mathrm{sgn}(n_2)\mathrm{i}\frac{\lambda_1}{\lambda_3}\left(|U_3|^2 + 2|U_1|^2 + 2|U_2|^2\right)U_3. \quad (7)$$

The nonlinear interaction is described in terms of two parameters σ_1 and σ_2, defined by

$$\sigma_1 = \mathrm{tg}\theta_{12} k_1 w_0, \quad \sigma_2 = \mathrm{tg}\theta_{13} k_1 w_0. \quad (8)$$

Equations (5)–(7) are solved numerically by using the split-step Fourier method. The initial field distribution at $\xi = 0$ depends on the spatial profiles of the three beams. If we assume that the three beams are initially Gaussian with the same 1/e half-width, the initial conditions are

$$U_1(0, x) = a_1 \exp\left(-\frac{X^2}{2}\right), \quad (9)$$

$$U_2(0,x) = a_2 \exp\left(-\frac{(X - X_0)^2}{2}\right),$$

$$U_3(0,x) = a_3 \exp\left(-\frac{(X + X_0)^2}{2}\right), \qquad (10)$$

where $X_0 = x_0/w_0$, x_0 is the physical distance between the beam centers for the general case in which Beam 1 and Beam 2 or Beam 1 and Beam 3 do not overlap completely. In the following discussion, we consider a three-beam configuration by assuming that the probe beams at wavelengths λ_2 and λ_3 have the same intensity ($a_2 = a_3 = 1$). The wavelength ratio is $\lambda_2/\lambda_1 = \lambda_3/\lambda_1 = 1.3$, the parameter for nonlinear interaction is $\sigma_1 = \sigma_2 = 18$, and X_0 is 2.

Consider firstly the case that only the probe beams are copropagating. Numerical solutions of Eqs. (6) and (7) show that both beams defocus as they propagate inside the nonlinear medium. Figure 1 shows that the probe beams are too weak to influence each other, and their propagations are cross because of the oblique incidences.

The situation changes completely when the probe beams are induced focusing. Figure 2 shows the evolution of the probe beams over the range $\xi = 0 - 0.5$ in the case where the probe beams are much less intense than the pump beam which is at the wavelength $\lambda_1(a_1/a_2 = 10)$. The probe beams focus initially in the form of narrow beams before they begin to defocus, and synchronously they deflect their propagating directions so as to arrive at the other's destination. It is quite clear that optical switch phenomenon occurs due to the induced focusing caused by the strong pump through the effect of cross-phase modulation.

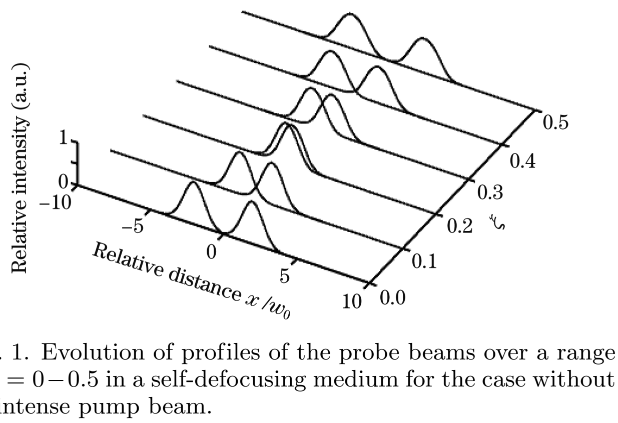

Fig. 1. Evolution of profiles of the probe beams over a range of $\xi = 0-0.5$ in a self-defocusing medium for the case without an intense pump beam.

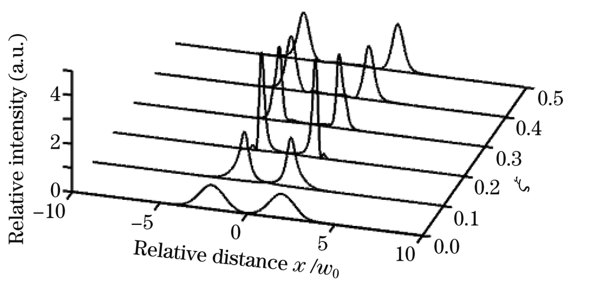

Fig. 2. Evolution of profiles of the probe beams over a range of $\xi = 0 - 0.5$ in a self-defocusing medium for the case with an intense pump beam of the initial amplitude such that $a_1/a_2 = 10$. Other parameters are the same as those in Fig. 1.

The profiles of the probe beams in Figs. 1 and 2 are compared in Fig. 3, with the propagating distance $\xi = 0.5$. One can see that the probe beams are one another transposition in the situation of Fig. 2, and their full widths at half maximum (FWHMs) are smaller than in the situation of Fig. 1, where the pump beam is absent. That means the probe beams can be compressed and reshaped in the optical switch phenomenon. The origin of this optical switch phenomenon is that the center of the probe beam and the center of the wavefront mismatch[1] and the wavefront asymmetry in both sides of the probe beam leads to the induced deflection.

Figure 4 shows the influence of the pump intensity on the optical switch phenomenon. When the amplitude of the pump beam is $a_1 > 1.5$, the center position of the probe beam at the end is linearly growing and the optical switch phenomenon occurs when $a_1 > 6$. So we can control the deflection of the probe beams by changing the intensity of the pump beam.

Optical switch phenomenon described here should be observable experimentally by using common self-defocusing media. The conditions demanded should be the same as that in the induced focusing experiments, but the incidence of the probe beams must be oblique. For a 100-μm spot-size pump beam, the diffraction length is $L_D \approx 10$ cm, and the optical switch phenomenon can be observed by using samples only a few centimeters long by properly controlling the incidence angle of the probe beams.

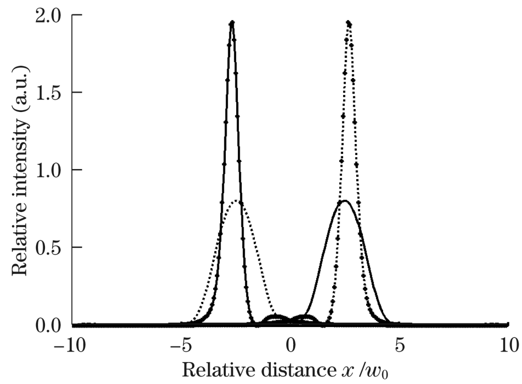

Fig. 3. Comparison of profiles of the probe beams at $\xi = 0.5$ in Fig. 2 and Fig. 1, where the solid lines are for probe Beam 2, the dotted lines are for probe Beam 3, and the marked lines are for the probe beams in Fig. 2.

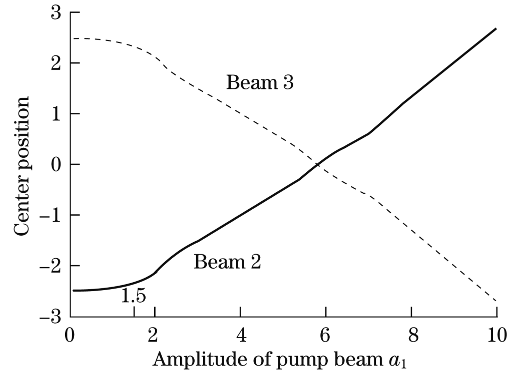

Fig. 4. Influence of the pump beam intensity on the center positions of the probe beams at the end. Other parameters are the same as those in Fig. 2.

In conclusion, we have discussed the optical switch phenomenon in self-defocusing nonlinear media as a result of induced focusing. When the weak probe beams are oblique incident and copropagate with an intense pump beam, the interaction of the cross-phase modulation in the three beams can make the weak probe beams focused, deflected, and also reshaped, which shows that the optical switch phenomenon comes up. This phenomenon is important for the field of light transmission.

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