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Letter

Induced deflection of optical beams in an off-axis geometry

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Abstract. The induced deflection of a probe beam, only partially overlapping with a pumping beam, is analysed theoretically. The physical mechanism of this phenomenon is induced phase modulation. It is shown that the conditions under which induced deflection can occur depend on the magnitude and the sign of the nonlinear susceptibility, as well as on the beam radii and their initial physical separation.

1. Introduction

In the last few years there has been significant progress in the study of induced-phase modulation (IPM) (for a review see [1, 2]). Since the first experimental observation of induced focusing (IF) [3], the spatial effects of IPM have become attractive with respect to ultrafast switching, scanning, streaking, deflection, focusing and logic operations in various signal-processing systems [4]. Recently, the novel phenomenon of induced focusing, occurring in self-defocusing nonlinear media, has been discussed theoretically [5]. In this Letter we show that in a cubic nonlinear medium a weak signal beam copropagating off-axially with a pump beam can be deflected significantly. The conditions for induced deflection of the probe beam depend simultaneously on the sign of the nonlinear susceptibility, the physical distance between the beam centres and their radii.

2. Theoretical model

The nonlinear medium considered is taken to be homogeneous, stationary and with a resonant structure. Choosing the probe and pump frequencies ω_s and ω_p, respectively, in the vicinity of a $\omega_s+\omega_p$ two-photon resonance, one can obtain a high value of the nonlinear susceptibility for IPM ($\chi^{(3)}_{IPM}$). If ω_s and ω_p are far from single-photon and two-photon resonances, the self-phase modulation (SPM) is negligible compared with the IPM ($\chi^{(3)}_{SPM}(\omega_{s,p}) \ll \chi^{(3)}_{IPM}$). These assumptions are made to retain the possibility of studying the pure effect of pump-induced deflection, although they are not obligatory for observing it experimentally [5]. It should be noted, that in a resonant nonlinear medium $\chi^{(3)}_{IPM}$ becomes negative on the high-frequency side of the resonance.

Under these assumptions, in the plane-wave approximation, the spatial evolution of a c.w. or a quasi-c.w. probe beam, copropagating with a pump beam, has the form

$$\mathrm{i}\,\frac{\partial \psi_s}{\partial x} + \alpha\,\frac{\partial^2 \psi_s}{\partial r^2} + k^{\mathrm{IPM}}(\omega_s)|\psi_p|^2\psi_s = 0, \tag{1}$$

where ψ_s and ψ_p are the slowly varying envelope amplitudes, $\alpha = 1/(2k_s)$, k_s is the wavenumber for the probe beam

$$k^{IPM}(\omega_s) = \frac{n_2^{IPM}(\omega_s)k_s}{2n_0(\omega_s)} = \frac{k_s}{2n_0(\omega_s)} \times \frac{6\pi N \chi_{IPM}^{(3)}}{n_0(\omega_s)},$$

is the nonlinear coefficient, N is the particle density, $n_0(\omega_s)$ is the refractive index for the probe-wave and r denotes the transversal coordinate. We assume, that the beams are Gaussian

$$\psi_s(r, x) = \frac{A_s(x)}{\xi_s(x)} \exp\left\{ -\frac{(r - r_0)^2}{a_s^2 \xi_s^2(x)} - \mathrm{i}\, \frac{k_s \rho_s(x) r^2}{2} \right\}, \tag{2 a}$$

$$\psi_p(r, x) = \frac{A_p(x)}{\xi_p(x)} \exp\left\{ -\frac{r^2}{a_p^2 \xi_p^2(x)} \right\}, \tag{2 b}$$

where A_s and A_p are the electric field amplitudes, ξ_s and ξ_p are the normalized beam radii, a_s and a_p are the physical beam radii at the entrance of the nonlinear medium, r_0 is the distance between the beam centres and ρ_s is a function of the inverse radius of curvature of the probe-beam wavefront.

According to the above mentioned assumptions, the initial conditions are $\xi_s(x=0) = 1$, $\xi_p(x) = 1$, $\rho_s(x=0) = 0$. The mathematical description of the induced deflection is based on the variational approach for solving equation (1) [6]. The analytical representation of the results is the main advantage of this method, which results in a set of ordinary differential equations for the corresponding variational parameters:

$$\frac{\mathrm{d}\xi_s}{\mathrm{d}x} = -\xi_s \rho_s, \tag{3 a}$$

$$\frac{\mathrm{d}r_0}{\mathrm{d}x} = 2r_0 \rho_s, \tag{3 b}$$

$$\frac{\mathrm{d}\rho_s}{\mathrm{d}x} = \rho_s^2 - \frac{4}{k_s^2 a_s^4 \xi_s^4} + \frac{4k^{IPM}(\omega_s)|A_p|^2 a_p}{\xi_p k_s (a_s^2 \xi_s^2 + a_p^2 \xi_p^2)^{3/2}} \times \left\{ 1 - \frac{4r_0^2}{a_s^2 \xi_s^2 + a_p^2 \xi_p^2} \right\} \exp\left\{ -\frac{2r_0^2}{a_s^2 \xi_s^2 + a_p^2 \xi_p^2} \right\}. \tag{3 c}$$

According to equation (3 *b*), the rate at which the physical distance r_0 between the beam centres changes near the entrance of the nonlinear medium depends on ρ_s, and hence (from equation (3 *c*)) on the rate of development of probe-beam phase distortions induced by IPM. In this process the nonlinear term in equation (3 *c*) is the dominating one and its sign determines the induced focusing ($\mathrm{d}r_0/\mathrm{d}x < 0$) or defocusing ($\mathrm{d}r_0/\mathrm{d}x > 0$). The sign of the nonlinear term in equation (3 *c*) is a product of the sign of the nonlinear coefficient (i.e. $\chi_{IPM}^{(3)}$) and the sign of the function

$$F = (\gamma^2 + 1)^{-3/2} \left\{ 1 - \frac{4\beta^2}{\gamma^2 + 1} \right\} \exp\left\{ -\frac{2\beta^2}{\gamma^2 + 1} \right\}, \tag{4}$$

where $\beta = r_0(x=0)/a_p$ and $\gamma = a_s(x=0)/a_p$.

Figure 1 plots the dependence $F(\beta, \gamma)$. There are two characteristic areas on this surface. The first one, the peak near $r_0 = 0$, corresponds to an induced focusing/defocusing of a probe beam in an on-axis geometry (i.e. fully overlapping beams).

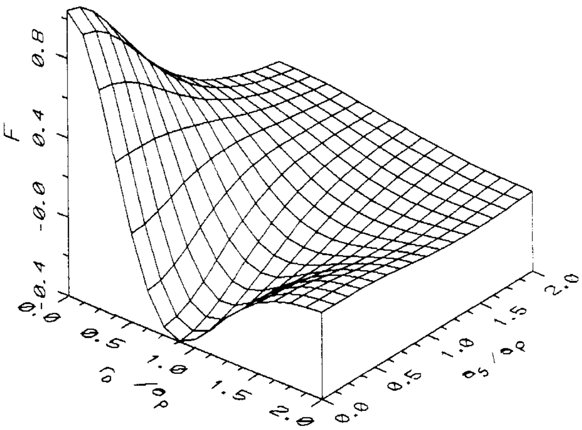

Figure 1. Plot of the dependence $F(\beta, \gamma)$ with $\beta = r_0(x=0)/a_p$ and $\gamma = a_s(x=0)/a_p$. When the condition sign $(\chi_{IPM}^{(3)})$ sign $(F) > 0$, this corresponds to an induced focusing, and when it is <0 to an induced defocusing.

List of the possible sign-combinations of $\chi_{IPM}^{(3)}$ and F and the spatial effect expected.

	Sign $(\chi_{IPM}^{(3)})$	
Sign F	-1	1
-1	induced focusing	induced defocusing
1	induced defocusing	induced focusing

This effect is studied theoretically in [8, 9]. The second characteristic area, the valley near $r_0/a_p \approx 0{\cdot}9$, corresponds to an induced deflection of a probe beam in an off-axis geometry (i.e. partially overlapping beams). The possible sign-combinations of $\chi_{IPM}^{(3)}$ and F and the spatial effect expected are listed in the table. It should be noticed, that the sign of equation (4) can reverse in the medium to the opposite one, since F depends on $r_0(x)$ and $a_s(x)$. This simple model does not account for the energy redistribution within the cross-section of the probe beam [4], but it can be very useful in optimizing the initial conditions for achieving a maximum induced deflection of the probe beam.

Figure 2 shows the evolution of the off-axis distance $r_0(x)$ in the nonlinear medium in the case of $\chi_{IPM}^{(3)} > 0$ for different values of the parameter $\gamma = a_s(x=0)/a_p$. In the generation of the figure the initial conditions are chosen to correspond to the induced-focusing condition sign $(\chi_{IPM}^{(3)})$ sign $(F) > 0$, and the maximum value of the nonlinear correction to the refractive index at the probe-beam frequency (assumed to be equal to unity) was chosen to be $|\Delta n| = |n_2^{IPM} \langle E_p \rangle^2| = 2{\cdot}3 \times 10^{-4}$. As seen, the induced deflection of the probe beam becomes stronger with the reduction of the ratio $(a_s/a_p)_{x=0}$. This result shows that IF of an off-axis probe beam may be observed even if $\chi_{IPM}^{(3)}$ is positive (figure 2). This is not unexpected in view of the spatial-temporal analogy in the description of the nonlinear beam/pulse propagation [5, 9]. It is shown experimentally, that a negative chirp can be induced on a probe pulse even in a medium with positive nonlinearity for IPM as a consequence of the initial time delay and pulse walk-off [9].

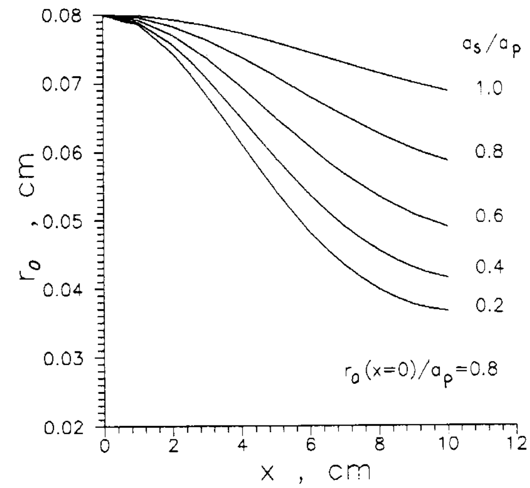

Figure 2. Off-axis distance evolution in the nonlinear medium for $\chi^{(3)}_{\rm IPM}>0$ with $\gamma=a_s(x=0)/a_p$ as a parameter $(r_0(x=0)/a_p=0{\cdot}8, |\Delta n|=|n_2^{\rm IPM}\langle E_p\rangle^2|=2{\cdot}3\times10^{-4})$.

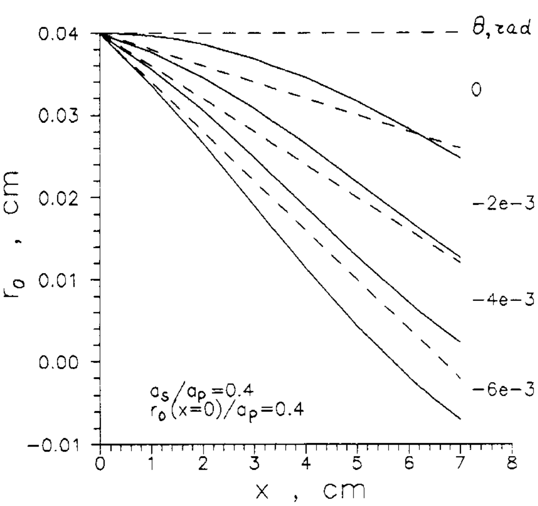

Figure 3. Evolution of the beam centres distance $r_0(x)$ along the nonlinear medium for different values of the initial angular displacement of the beams $\theta=(dr_0/dx)_{x=0}$ (solid lines). The dashed lines represent the linear propagation regime for the probe beam $(\chi^{(3)}_{\rm IPM}>0)$.

To achieve a linear deflection of the probe beam, the length of the nonlinear medium should be restricted to the region of nearly linear reduction of the off-axis distance r_0 along the x-axis. The spatial separation of the pump and probe beam can be performed by introducing a small initial angular displacement $\theta=(dr_0/dx)_{x=0}$. Figure 3 plots the dependence $r_0(x)$ for different values of the parameter θ (solid lines). The dashed lines represent the off-axis distance evolution when the pump beam is turned off. As seen from the figure, an increase in the initial angular displacement θ reduces the differences between the corresponding pairs of curves. Therefore, θ should be kept reasonably small to retain a greater contrast between the linear and nonlinear propagation regimes.

3. Conclusions

In this Letter we have shown that the conditions under which the induced deflection of an off-axis probe beam can occur depend simultaneously on the magnitude and the sign of the medium nonlinearity and on the initial distance between the beam centres and their radii. This result is important for increasing the number of nonlinear media that are applicable for constructing ultrafast all-optical switches. The introduction of a variable initial time delay between the pulses may allow an all-optical streak camera to be constructed.

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