All-optical deflection induced by cross-phase modulation in solutions of beta-carotene with CW lasers

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Abstract -All-optical deflection has been obtained with a CW laser and hexane solution of beta-carotene. The mechanism exploited to obtain angular deflection was theoretically proposed by Agrawal and is based on the cross-phase modulation between two beams propagating in a nonlinear medium in the self-defocusing regime. The pump laser intensity is 510 W/cm^2 and the maximum ratio of angular deflection obtained was approximately 1mrad. This material may find applications in optical communications as in ultrafast optical deflectors or space division all-optical switches.

1-INTRODUCTION

The deflection of an optical beam is a basic operation necessary to carry out more complex optical processing and optical computing. To accomplish this, a number of schemes have been developed based on electro-optic and acoustic-optic effects. A diffraction-based deflection method is also available with optically induced dynamic gratings in a nonlinear optical material [1].

An optical deflector consists of a light switch, transporting the information to new space region. Agrawal [2] suggested, theoretically, the control mechanism of a light beam across the cross-phase modulation (CPM) in the self-defocusing regime: one intense beam light moves across a sample, altering its refractive index. Another light beam, traveling through the sample, experiences the refractive index variation caused to the first beam and changes its propagation direction. The refractive index variation caused to first light beam is:

$$\Delta n = n' - n = n_2 I \qquad (1)$$

Where n_2 is the nonlinearity coefficient, sometimes called the Kerr coefficient, and I is the laser beam intensity. n′(n) denotes the material refractive index under (without) the presence of the pump beam. The mathematical description of the CPM-induced interaction between the two copropaganting cw or quasi-cw beams is provided by the coupled amplitude equations which, in the paraxial approximation, take the form:

$$\frac{\partial A_1}{\partial z} - \frac{i}{2k_1}\left[\frac{\partial^2 A_1}{\partial z^2} + \frac{\partial^2 A_1}{\partial y^2}\right] = \frac{ik_1 n_2}{n_{01}}\left(|A_1|^2 + 2|A_2|^2\right) A_1, \qquad (2)$$

$$\frac{\partial A_2}{\partial z} - \frac{i}{2k_2}\left[\frac{\partial^2 A_2}{\partial z^2} + \frac{\partial^2 A_2}{\partial y^2}\right] = \frac{ik_2 n_2}{n_{02}}\left(|A_2|^2 + 2|A_1|^2\right) A_2, \qquad (3)$$

Where A_j is the slowly varying envelope amplitude, $k_j = 2\pi n_{0j}/\lambda_j$, and n_{oj} is the linear refractive index at the carrier wavelength λ_j (j = 1 and 2). The sign of the nonlinearity depends on whether the pump photon energy is above or below the energy corresponding to the absorption peak of the sample. In the first case occurs a self-focusing ($n_2 > 0$) and in the second case a self-defocusing ($n_2 < 0$).

In this work, an all-optical beam deflector with CW laser and hexane solutions of beta-carotene (βC) was mounted. This compound, which belongs to the polyene family (lycopene, vitamin A, retinene, lutein, rhodoxantin, etc.), is responsible for the coloring of the carrots and consists of an 18-carbon conjugated chain terminated at both ends by a six-member carbon ring, each of which adds another double bond to the conjugated system [3], [4]. The third-order optical nonlinearity in beta-carotene is due to photochromic changes. When the system is excited by a sudden influx of energy, which can be in the form of heat or light, the double-bond character of molecules is relaxed, so that a trans configuration can change to a cis. This ability to change form is the key element in our all-optical beam deflector. The Kerr coefficient of βC is approximately 10^{-11} e.s.u [5].

2-EXPERIMENTAL

Figure 1 shows the absorption spectrum of the beta-carotene and the wavelengths of the laser used in our experiment. The Kerr solution was placed in a 10mm long cuvette and the measurements were

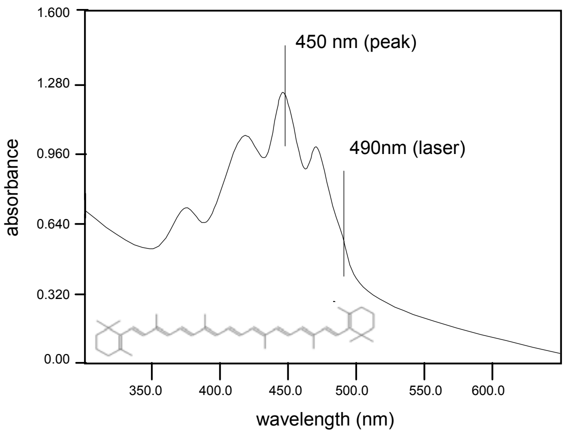

FIG. 1. Beta-carotene molecule: structure and spectrum of the hexane solution. It is important to notice that the laser operates in regimen of auto-defocusing because its energy is below the corresponding energy of the absorption peak .

performed at 28^0 C. The concentration of samples is not relevant and was kept in the order of 10^{-5}g/liter. The setup for the all-optical deflector is showed in figure 2.

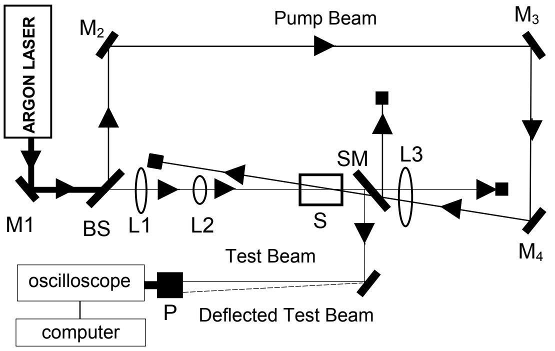

FIG. 2. Experimental array of the all-optical beam deflector. The mirrors M2, M3 and M4 direct the pump beam through a 15cm focal length converging lens (L3). L1 (f = +100cm) and L2 (f = +10cm) reduce the test beam diameter to 200□m. L3 reduces the diameter of the pump beam to 100□m. Semi-mirror (SM) diverts the light deflected to the photodiode (P).

In the system shown in figure 2, an argon laser was used, operating at λ= 490nm. Beam powers were varied from 10 to 35mW in the region of the sample. The original laser beam was divided into two beams by a beam splitter (BS). The mirrors M2, M3 and M4 guide the pump beam to a convergent lens (L3) of 15cm of focal length. The pump beam, focused on the sample, had a 100□m beam waist in the region of the sample. On the other hand, the test beam had a diameter of 200□m in the region of the sample. The test beam, after crossing the sample, was deviated of its original passage by the semi-mirror SM (80% of refraction). This was projected in a bulkhead situated 5 meters of SM2. When the pump beam was blocked, the test beam reached the bulkhead at another point. To study the temporal behavior of our optical beam deflector the test beam was detected by a photodiode and displayed on a digital oscilloscope linked to a computer for data acquisition. The response time of our optical deflector in the CW mode is of the order of 12ms, verified using a chopped beam and detecting the deflection with a fast photodiode.

The results of our experiments are summarized in figures 3 and 4. Figure 5 compares our results with those reported previously in the pulsed regime.

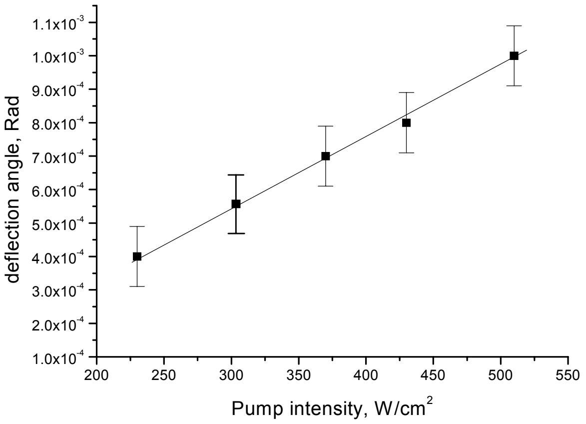

FIG. 3. Pump intensity dependence of the deflection angle in solutions of □C. The solid line is the linear fit of the experimental data. Maximum ratio of angular deflection obtained was 1mrad.

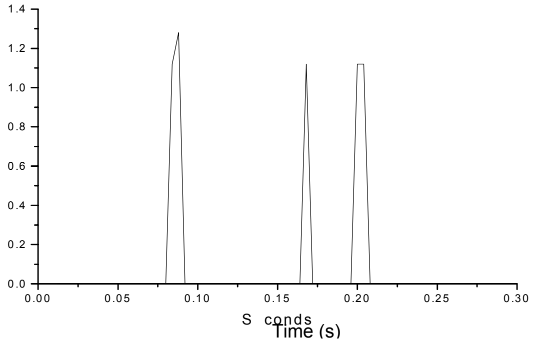

FIG.4. Temporal response of all-optical beam deflector of □C.

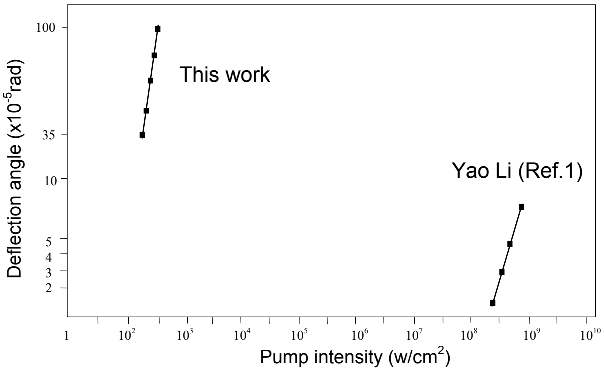

FIG. 5. Comparing the results of CW (βC, n_2=10^{-11}e.s.u), and pulsed mode of operation (CS2, n_2=10^{-11}e.s.u).

Table 1 shows a survey of all-optical deflectors found in the literature, for comparisons with the results obtained here. We note that different nonlinear materials are employed [6].

TABLE I - Survey of all-optical deflectors including nonlinear medium employed, sample length, nonlinear coefficient (n_2), maximum intensity employed (I), response time and maximum ratio of angular deflection (□).

Nonlinear medium (Length – cm)	n_2 (cm^2/w)	$I_{max.}$ (w/cm^2)	Response time	$\theta_{max.}$ (rad)
CS2 (0.2)	10^{-16}	2.6×10^9	2ps	2.6×10^{-10}
Corning CS 3-69 (5)	10^{-14}	5.6×10^7	100ps	1.4×10^{-9}
Na (5)	10^{-10}	2.5×10^5	16ns	0.2×10^{-4}
CS2 (10)	10^{-16}	4.0×10^9	2ps	5.0×10^{-10}
Ruby (7)	10^{-8}	8.0×10^4	3ms	1.25×10^{-4}
Corning CS 3-63 (0.3)	10^{-14}	5.6×10^6	100ps	1.8×10^{-6}
TPPH2 (0.2)	10^{-7}	3.8	200ms	3.9×10^{-1}
bR (2)	10^{-4}	9.3×10^2	6ms	1.0×10^{-3}
βC (1)	**10^{-11}**	**5.1×10^2**	**12ms**	**1.0×10^{-3}**

In summary, we presented a CW version of an all-optical refractive deflector based on the cross-phase modulation (CPM) in an organic Kerr solution of βC. The beta-carotene is also potentially useful in large bandwidth applications under pulsed illumination. The high nonlinear polarizabilities associated with conjugated chains may have practical implications. Nonlinear electronic distortion, a non-resonant mechanism, is known to have short relaxation time, in the order of femtoseconds [7]. This mechanism contributes predominantly to the refractive index change under pulsed illumination in liquids and disordered systems, particularly in the case of highly symmetric molecules, as is the case of the βC structure. Kerr media incorporating βC as dopants in solid matrices can be potentially useful in a short time scale. This is supported by the fact that all microscopic theoretical models predict large non-resonant third-order optical nonlinearities derived from π-electrons. Specially in a highly conjugated polymeric structure which provides effective π-electron delocalization.

Thus, βC glass with a nonlinear index $n_2 = 10^{-11}$ e.s.u and a linear index n = 1.53 can be of interest for fast all-optical deflectors in the red and near infrared or even space division all-optical switches, substituting for thermo-optical switches, which are widely required devices for cross-connect and add-drop systems in wavelength division multiplexing optical networks. The test and pump beam need not to be necessarily mutually coherent.

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