Self-bending of a cw laser beam in sodium vapor

G. A. Swartzlander, Jr., H. Yin, and A. E. Kaplan

Department of Electrical and Computer Engineering, The Johns Hopkins University, Baltimore, Maryland 21218

Received June 24, 1988; accepted August 16, 1988

Continuous-wave self-deflection of an asymmetrical laser beam, with a deflection angle up to eight diffraction widths, and strong attenuation of the on-axis radiation were achieved in a short sodium-vapor cell. We determined that the nonlinear refractive index Δn varied almost linearly with intensity I, $\Delta n \approx n_2 I$, with $n_2 \sim -10^{-7}$ cm^2/W at ~200°C and intensities less than 220 W/cm^2.

Self-bending (or self-deflection) of a laser beam, proposed in Ref. 1 and experimentally observed in Ref. 2, occurs when a light beam with an asymmetrical spatial intensity profile propagates through a nonlinear refractive material, causing a nonlinear prism to be induced in the beam path. Various applications utilizing this effect are possible, including optical switching and interconnecting, resonatorless optical bistability,[3] radiation protection, and power limiting.[4,5] The effect can also be used to measure the intensity-dependent refractive index $\Delta n(I)$, which, on comparison with theory, can yield spectroscopic information, e.g., at near-resonance frequencies.[6–8] Since the first observation of self-bending[2] in a NaCl crystal, experiments have been limited to the use of pulsed lasers, resulting in time-integrated observations and other complications that prohibited a complete study of the effect. Recently some indication of steady-state self-bending has been reported in liquid crystals,[9] and long pulses have been used to achieve self-bending in CS_2 using a powerful CO_2 laser in the infrared range (at 10.6 μm).[10] On the other hand, the large nonlinearity in the vicinity of the D resonances of sodium vapor permitted the first investigation of a cw self-action effect (self-focusing),[11] as well as the effects of resonatorless optical bistability based on self-focusing.[12]

Here we present the first detailed study, to our knowledge, of visible cw self-bending in sodium vapor. Self-bending angles as large as eight times the diffraction width and strong attenuation of the on-axis radiation were observed. When the laser frequency was tuned just below the D_2 resonance (589.0 nm) and the vapor temperature was 202°C, the refractive index was predominantly Kerr-like, i.e., $\Delta n = n_2 I$, with $n_2 \sim -10^{-7}$ cm^2/W. This result was not expected because a calculation of the saturation of the anomalous dispersion of a two-level system, based on the power-broadened hole-burning model,[7,8] predicts that $\Delta n(I)$ should be appreciably saturated under our experimental conditions.

An ideal case of self-bending occurs when a slab beam, with a spatial intensity profile that is right triangular [$I(x) = I_0(1 - x/w_0)$, $0 < x < w_0$, where x is the coordinate across the slab beam], propagates through a thin Kerr-like nonlinear medium,[1,4,5] inducing a nonlinear prism. The beam will be self-deflected in the far-field region by the angle θ_{NL} (Ref. 5):

$$\theta_{NL}/\theta_D = -n_2 k L I_0/2, \qquad (1)$$

where k is the wave number, $\theta_D = 2/kw_0$ is the (half-) diffraction angle, and L is the thickness of the medium. The self-deflection angle of a slab two-dimensional semi-Gaussian beam [$I(x) = I_0 \exp(-2x^2/w^2)$, $x > 0$] is nearly equivalent to Eq. (1).[5] Since slab beams are not the most suitable for experiments, we formed a quasi-triangular beam profile in the self-deflection plane by covering half of a three-dimensional TEM_{00} Gaussian beam (of power P_{in}) with a razor blade, as in Fig. 1, where the peak intensity is given by $I_0 = 2P_{in}/\pi w_0^2$. In such a case, Eq. (1) still gives a good approximation for the far-field self-bending angle.[13]

Our experiment partially satisfied the thinness requirement because the length of the nonlinear medium (L = 18 mm) was much less than the diffraction length, $R_D = kw_0^2/2$. Typically our experiment was done on the self-defocusing side of the resonance in sodium vapor, which allowed us to avoid complications related to self-focusing. For the largest product $n_2 I_0$ in our experiment, the self-defocusing length $R_{NL} = w_0/2(|n_2|I_0)^{1/2}$ was of the same order as the cell length L, which should have resulted in somewhat underestimated values of n_2 at large intensities. Meanwhile, the condition of weak absorption across the beam was satisfied because the absorption saturates at an intensity three to four orders of magnitude smaller than those in this experiment.[6–8,11] The saturation intensity $I_{sat} = 2\pi h\nu_0^3/c^2\tau_N$, where τ_N is the

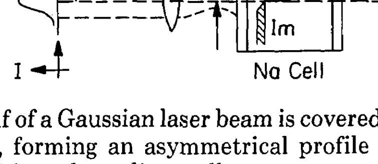

Fig. 1. Half of a Gaussian laser beam is covered with a razor blade (RB), forming an asymmetrical profile that is then imaged (Im) into the sodium cell.

0146-9592/88/111011-03$2.00/0

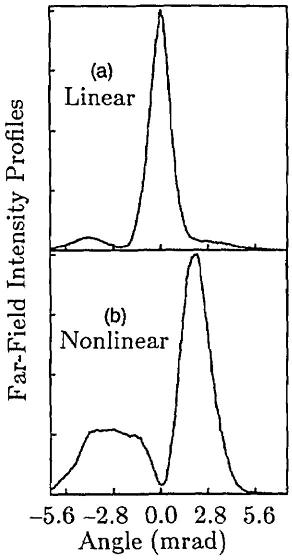

Fig. 2. Far-field profiles for (a) linear and (b) nonlinear propagation of an asymmetrical beam through a short sodium cell, demonstrating self-deflection of the intensity peak in (b).

natural lifetime of the transition and $\nu_0 = c/\lambda_0$ is the resonance frequency, was 37.5 mW/cm^2.

We used two methods to verify whether the medium was Kerr-like. According to Eq. (1), if a linear relationship is found between θ_{NL} and P_{in}, then $\Delta n = n_2 I$ will be verified. Another method is to record the far-field intensity at a point on the optical axis as the input power is increased. If the medium is thin, transparent, and Kerr-like and if the beam has a half-TEM_{00} profile, then the far-field on-axis intensity, $I_{\text{on-axis}}$, can be found analytically:

$$I_{\text{on-axis}} \propto [C^2(\eta_{NL}) + S^2(\eta_{NL})] w_0^4/n_2 kL,$$
$$\eta_{NL} = \sqrt{2 n_2 k L I_0/\pi}, \qquad (2)$$

where C and S are the Fresnel integral functions.

An argon-pumped ring dye laser was used to achieve a frequency-stabilized single-mode beam. The beam was focused on the razor blade in front of the input face of the cell and then imaged into the cell (Fig. 1). The beam waist had a $(1/e^2)$ size of 220 μm ±15% (without the razor blade). The laser was detuned until the maximum self-bending was observed: −1.9 GHz from the point in the D_2 line that produced the brightest resonance radiation. Far-field beam profiles were measured 95 cm $\simeq 5R_D$ from the cell. Figure 2 shows the far-field intensity profiles measured at 202°C (with the vapor density $N = 3.6 \times 10^{12}$ cm^{-3}). At 170 mW the beam was deflected by 2.1 mrad ($\simeq 3.0\theta_D$). The linear relation $\theta_{NL}/P_{in} = 12.6$ mrad/W ±5% shown in Fig. 3, which plots the self-deflection angle against the input beam power, indicates that Δn is Kerr-like. We calculate that $n_2 = -(\theta_{NL}/\theta_D P_{in})(\pi w_0^2/kL) = -1.4 \times 10^{-7}$ cm^2/W (±30%). On comparison with similar data obtained at 197°C, we found a linear dependence of n_2 on the vapor density N, as expected from expressions in Ref. 7.

At higher temperatures θ_{NL} was not only larger but also saturated—presumably because either Δn saturated or beam distortions limited the effective interaction length. At 214°C ($N = 7.0 \times 10^{12}$ cm^{-3}) we measured a self-deflection angle of 5.9 mrad, which is eight times the diffraction angle θ_D, when the input beam power was 170 mW. This is a substantial accomplishment for a cw experiment, e.g., compared with Ref. 9; even in pulsed experiments[10] with a laser power up to 400 MW/cm^2 the deflection did not exceed the diffraction angle. Self-bending was also observed on the self-focusing side of the resonance (where $n_2 >$ 0), but measurements were difficult because the beam damaged the output window.

In the far-field on-axis observation, we measured the intensity of radiation at the point that corresponds to the center of the linear beam (Fig. 4). The solid curve corresponds to relation (2), in which the amplitude and n_2 (= -1.7×10^{-7} cm^2/W) are the fitting parameters. The vapor temperature was 195°C ($N = 2.5 \times 10^{12}$ cm^{-3}), with beam powers up to 170 mW and a −2.0-GHz detuning. Extrapolating the previous experimental value of $n_2 \simeq -1.4 \times 10^{-7}$ cm^2/W to the lower vapor density, we expected a value of $n_2 \simeq -1.0 \times 10^{-7}$ cm^2/W. The factor-of-1.7 discrepancy can be attributed to several sources of error, including the underestimation of n_2 when Eq. (1) is applied to a half-TEM_{00} beam and the neglect of absorption and self-defocusing.

Treating dilute sodium vapor as a two-level system, $\Delta n(I)$ was calculated in Ref. 7 under cw and uniform

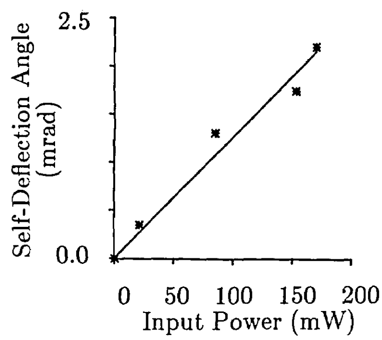

Fig. 3. Self-deflection angle plotted against the input beam power.

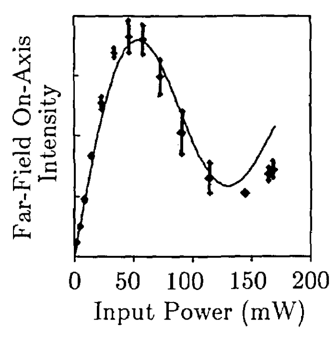

Fig. 4. Far-field on-axis intensity (in arbitrary units) versus the input power. The solid curve is a fit to relation (2).

excitation, where the effects due to power-broadened hole burning of an inhomogeneously broadened transition are included. Our numerical calculations show that this model predicts significant saturation of $\Delta n(I)$ under the experimental conditions. When the detuning of the laser frequency ν from the resonance frequency is large compared with the Doppler width $\Delta\nu_D$, such that the normalized detuning $\Delta = 2\sqrt{\ln 2}(\nu - \nu_0)/\Delta\nu_D$ is large ($|\Delta| \gg 1$), and when the normalized power-broadened hole width $y = \sqrt{(\ln 2)(1 + I/I_s)}/\pi\tau_N\Delta\nu_D$ is relatively small ($y \ll |\Delta|$), then the series expansion $\Delta n(I) \approx n_2 I + \ldots$ results in[8]

$$n_2 = (\ln 2)^{3/2} c^5 N/32\pi^6\Delta^3 h\nu_0{}^6 \Delta\nu_D{}^3 \tau_N{}^2. \quad (3)$$

For example, at 202°C and $\Delta = -1.0$ (or -1.9 GHz from the middle of the F lines), this approximation gives $n_2 = -1.2 \times 10^{-7}$ cm^2/W, which agrees surprisingly well with the experimentally determined value, in spite of the violation of the inequalities ($|\Delta| \simeq y \simeq 1.0$). At higher temperatures, however, the agreement was poor.

There are a few possible reasons for the seemingly weak manifestation of saturation in the refractive index. Since the D_2 resonance is actually a three-level system (the $^2S_{1/2}$ ground state is hyperfine split by 1.77 GHz), some incongruity with the two-level theory is expected[11,13] since optical pumping of the ground states was not included. In future experiments this effect may be reduced by using circular polarization. Other complications may also arise, such as nonlocal effects due to the drift of excited atoms[11] and the long-range light–light interaction[14] mediated by atoms moving under the action of a gradient force in the beam. The drift displacement l_d for the former mechanism [estimated by $l_d \sim \tau_N(3KT/m_a)^{1/2}$, where K_β is the Boltzmann constant and m_a is the mass of the atom] is relatively small (~10 μm in our case); the latter mechamism, however, may be effective at a distance of up to 100 μm.[14] This distance is comparable with the beam size in our experiment and can be considerably larger than the size of the sharp beam edge.

In conclusion, we observed cw self-bending of a laser beam in sodium vapor, measuring deflection angles up to eight times the diffraction angle of the input beam. We also observed the strong attenuation of the on-axis radiation resulting from the self-bending effect. These results suggest a strong potential for applications such as radiation protection, optical switching and limiting, optical bistability, and nonlinear coupling. As expected, the measured self-deflected profiles revealed a main self-deflected peak and smaller counter-self-deflected subpeak(s). From data obtained at ~200°C, we determined that the nonlinear refractive index in sodium vapor was Kerr-like, with $n_2 \simeq -10^{-7}$ cm^2/W for near-resonance tuning on the self-defocusing side of the resonance.

We thank D. Elliott for his expert help with developing the laboratory, C. Harrington for lending his craftsmanship, and the Purdue University School of Electrical Engineering, where this experiment was conducted. We are indebted to J. E. Bjorkholm for his insights on sodium-vapor experiments. This research was supported by the U.S. Air Force Office of Scientific Research and the Indiana Corporation for Science and Technology.

References

1. A. E. Kaplan, Pis'ma Zh. Eksp. Teor. Fiz. **9**, 58 (1969)[JETP Lett. **9**, 33 (1969)].
2. M. S. Brodin and A. M. Kamuz, Pis'ma Zh. Eksp. Teor. Fiz. **9**, 577 (1969)[JETP Lett. **9**, 351 (1969)].
3. A. E. Kaplan, Opt. Lett. **6**, 360 (1981).
4. J. A. Hermann, Opt. Commun. **62**, 367 (1987); Opt. Quantum Electron. **19**, 169 (1987).
5. G. A. Swartzlander, Jr., and A. E. Kaplan, J. Opt. Soc. Am. B **5**, 765 (1988); G. A. Swartzlander, Jr., M.S. thesis (Purdue University, West Lafayette, Ind., 1985).
6. A. Javan and P. L. Kelley, IEEE J. Quantum Electron. **QE-2**, 470 (1966).
7. D. H. Close, Phys. Rev. **153**, 360 (1967).
8. J. E. Bjorkholm, AT&T Bell Laboratories, Holmdel, N.J. 07733 (communication).
9. I. C. Khoo, R. R. Michael, T. H. Liu, G. Finn, and A. E. Kaplan, Proc. Soc. Photo-Opt. Instrum. Eng. **613**, 43 (1986); I. C. Khoo, G. M. Finn, R. R. Michael, and T. H. Liu, Opt. Lett. **11**, 227 (1986).
10. I. Golub, Y. Beaudoin, and S. L. Chin, Opt. Lett. **13**, 488 (1988); "Self-bending of a spatially asymmetric carbon dioxide laser beam in a nonlinear medium" (to be published).
11. J. E. Bjorkholm and A. Ashkin, Phys. Rev. Lett. **32**, 129 (1974).
12. J. E. Bjorkholm, P. W. Smith, W. J. Tomlinson, and A. E. Kaplan, Opt. Lett. **6**, 345 (1981).
13. H. M. Gibbs, S. L. McCall, and T. N. C. Venkatesan, Phys. Rev. Lett. **36**, 1135 (1976).
14. A. C. Tam and W. Happer, Phys. Rev. Lett. **38**, 278 (1977).