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Beam deflection in a pulsed chemical laser amplifier

J. Munch, L. W. Casperson, and E. C. Rea

Analyses and experiments have been performed to investigate deflection of a Gaussian beam propagating through an amplifying medium possessing a strong transverse gain gradient. The analysis includes effects due to dispersion and gain steering. The experiments were performed in a high power pulsed chemical laser amplifier using a cw frequency stabilized laser as a source. Time dependent beam deflection due to the interaction of the gain gradient with the finite radius of curvature of the propagating beam was observed.

I. Introduction

The output beam from a laser amplifier may be deflected due to the transverse gain gradients necessarily present in every real laser medium. Such a deflection may have important consequences in applications requiring high spatial coherence and pointing accuracy. In the case of a pulsed laser amplifier, the deflection will be time dependent and cannot be corrected by subsequent beam pointing optics since the slew rate of such devices is slow compared with the pulse length of typical lasers. It is therefore important that the nature and magnitude of the deflection be properly understood so that its effects can be minimized.

The present work arose from the possibility of using the chemical laser in a laser radar application, where a pointing accuracy of 50 μrad, or better, is required. During the initial theoretical work, we found that under certain conditions, the deflection was dominated by gain steering rather than by dispersion effects, and in subsequent experimental measurements, this prediction was verified. In the following paragraphs we shall present the theory of beam deflection and the experimental verifications of some of the predictions.

II. Theory

The theory governing the propagation of a beam in an inhomogeneous laser medium has been developed in detail by several authors.[1-3] For a real laser it is often a good approximation to describe the distribution of gain and index of refraction by functions which are at most linear and quadratic in space. In this case the propagation of the beam can be described in terms of Hermite-Gaussian or Laguerre-Gaussian eigenmodes, and an analytical solution can be found.[4]

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Specifically, we assume that the complex propagation constant k has the spatial dependence

$$k(x,y,z) = k_0(z) - \frac{k_{1x}(z)x}{2} - \frac{k_{1y}(z)y}{2} - \frac{k_{2x}(z)x^2}{2} - \frac{k_{2y}(z)y^2}{2}, \quad (1)$$

and the components of k can be separated into their real and imaginary parts according to $k = \beta + i\alpha$. In a medium described by Eq. (1) the electric field amplitude of the fundamental Gaussian mode can be written

$$E(x,y,z) = E_0 \exp\left\{-i\left[\int k_0(z)dz + \frac{Q_x(z)x^2}{2} + \frac{Q_y(z)y^2}{2} + \frac{S_x(z)x}{2} + \frac{S_y(z)y}{2} + P(z)\right]\right\}, \quad (2)$$

where $Q_x(z)$ is related to the phase front curvature $R_x(z)$ and the $1/e$ amplitude spot size $w_x(z)$ by

$$Q_x(z) = k_0/R_x(z) - 2i/w_x^2(z). \quad (3)$$

The parameter $S_x(z)$ is related to the displacement of the amplitude and phase centers of the beam by

$$d_{xa}(z) = -S_{xi}(z)/Q_{xi}(z), \quad (4)$$

$$d_{xp}(z) = -S_{xr}(z)/Q_{xr}(z), \quad (5)$$

where the subscripts i and r denote, respectively, the imaginary and real parts of the parameters. The complex phase is characterized by $P(z)$.

The deflection angle can be found as the normal to the phase fronts evaluated at the displacement d_{xa}, and the result is[5]

$$\theta_x(z) = \frac{\lambda}{2\pi}\left[S_{xr}(z) - S_{xi}(z)\frac{Q_{xr}(z)}{Q_{xi}(z)}\right] = \frac{d_{xa}(z) - d_{xp}(z)}{R(z)}. \quad (6)$$

Thus the displacement and deflection angle of the beam would be completely characterized if the z dependences of the Q and S parameters were known. When Eq. (2) is substituted into the wave equation with the propagation constant of Eq. (1), one obtains a set of ordinary differential equations in the variable z.[4] If the propagation constant is independent of z these equations may be solved to yield

$$\frac{Q_x(z)}{k_0} = \frac{-(k_{2x}/k_0)^{1/2}\sin[(k_{2x}/k_0)^{1/2}z] + [Q_x(0)/k_0]\cos[(k_{2x}/k_0)^{1/2}z]}{\cos[(k_{2x}/k_0)^{1/2}z] + [Q_x(0)/k_0](k_0/k_{2x})^{1/2}\sin[(k_{2x}/k_0)^{1/2}z]}, \quad (7)$$

$$S'_x(z) = \frac{S'_x(0)}{\cos[(k_{2x}/k_0)^{1/2}z] + [Q_x(0)/k_0](k_0/k_{2x})^{1/2}\sin[(k_{2x}/k_0)^{1/2}z]}, \quad (8)$$

where we have substituted $S'_x = S_x - k_{1x}Q_x/2k_{2x}$. Similar results hold for the y parameters. With the definitions of Eq. (3), Eq. (7) is an explicit expression for the propagation of the spot size and phase front curvature. Also, Eqs. (4)–(8) describe completely the propagation of the beam center and deflection angle.

For practical applications the remaining problem is to determine the real and imaginary parts of the components of the propagation constant indicated in Eq. (1). In short amplifiers, where beam distortion and deflection effects are not severe, the gain profile can be most easily determined by scanning the amplifier with a probe laser beam. The index of refraction may also have a spatial profile, and this profile may in general have two components. The first component is due to spatial variations of the background permittivity of the host material caused by imperfections, strain and thermal effects in solid lasers, or plasma nonuniformity and turbulence in gas lasers. The other, more interesting component of the index of refraction in the present study is due to the intrinsic dispersion of the amplifying atoms themselves.

The dispersion of a laser medium can be obtained from a semiclassical analysis, and the results are well known. These results are particularly simple for unsaturated lasers, and one finds that the index of refraction of a homogeneously broadened medium is

$$n = n_0 + \frac{cg_h}{4\pi\nu}\frac{u}{1+u^2}, \quad (9)$$

where n_0 is the background index of refraction, c is the speed of light, g_h is the line center incremental gain coefficient, ν is the frequency, and $u = 2(\nu - \nu_0)/\Delta\nu_h$ is the frequency shift from line center normalized in units of the homogeneous linewidth $\Delta\nu_h$. Similarly, for an inhomogeneously broadened gas laser medium the index of refraction is

$$n = n_0 + [(cg_D)/(2\pi^{3/2}\nu)]F(v), \quad (10)$$

where g_D is the line center incremental gain coefficient of the Doppler profile, $v = 2(\nu - \nu_0)(\ln 2)^{1/2}/\Delta\nu_D$ is the frequency shift normalized in units of the Doppler width $\Delta\nu_D$, and $F(v)$ is Dawson's integral

$$F(v) = \exp(-v^2)\int_0^v \exp(t^2)dt. \quad (11)$$

From Eqs. (9) or (10) it is clear that spatial variations in the gain will always be accompanied by spatial variations in the index of refraction. The amount of the index variations depends on the laser frequency with respect to line center, and at $\nu = \nu_0$ dispersion effects vanish. In the following section the implications of these results are explored using numbers appropriate to our experiments with HF lasers.

III. Simplification to Linear Gain Gradient

The above theory predicts the behavior of a beam propagating through an inhomogeneous laser medium. Different parts of the beam will experience different deflections depending on the local gain gradient and frequency of the beam, and the output beam will be deflected and defocused in a complex manner, which does not lend itself to simple measurements for experimental verification of the theory. However, if the transverse dimensions of the probing beam are small compared with those of the gain region, it may be reasonable to approximate the gain gradient by a local linear function. In this case the beam would be expected to deflect, rather than defocus, and a simple experiment can be conducted to test the predictions.

In a medium with only linear gain and index profiles ($k_{2x} = 0$), Eqs. (7) and (8) simplify to

$$\frac{Q_x(z)}{k_0} = \frac{Q_x(0)/k_0}{1 + Q_x(0)z/k_0}, \quad (12)$$

$$S_x(z) = \frac{S_x(0) - k_{1x}Q_x(0)z^2/4k_0 - k_{1x}z/2}{1 + Q_x(0)z/k_0}. \quad (13)$$

For small gain per wavelength ($k_0 \simeq \beta_0$) and an incident beam along the z axis [$S_{xr}(0) = S_{xi}(0) = 0$], Eqs. (12) and (13) may be separated into their real and imaginary parts:

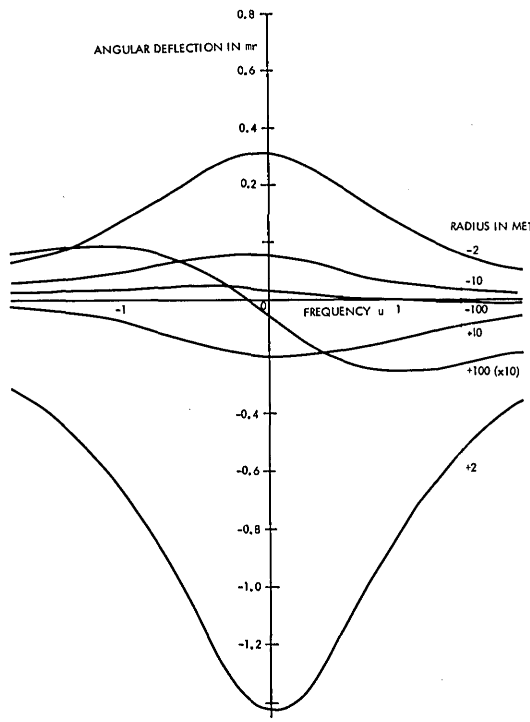

Fig. 1. Theoretical prediction of the laser beam deflection angle in milliradians, calculated as a function of frequency u and the radius of curvature of the wavefront at the entrance to the amplifier. For the exact value of the parameters chosen, see text.

$$\frac{Q_{xr}(z)}{\beta_0} = \frac{\beta_0 Q_{xr}(0) + [Q_{xr}^2(0) + Q_{xi}^2(0)]z}{[\beta_0 + Q_{xr}(0)z]^2 + Q_{xi}^2(0)z^2}; \tag{14}$$

$$\frac{Q_{xi}(z)}{\beta_0} = \frac{\beta_0 Q_{xi}(0)}{[\beta_0 + Q_{xr}(0)z]^2 + Q_{xi}^2(0)z^2}; \tag{15}$$

$$S_{xr}(z) = \frac{-2\beta_0^2\beta_1 z - [3\beta_0\beta_1 Q_{xr}(0) + \beta_0\alpha_1 Q_{xi}(0)]z^2 - \beta_1[Q_{xr}^2(0) + Q_{xi}^2(0)]z^3}{4[\beta_0 + Q_{xr}(0)z]^2 + 4Q_{xi}^2(0)z^2}; \tag{16}$$

$$S_{xi}(z) = \frac{-2\alpha_1\beta_0^2 z - [3\alpha_1\beta_0 Q_{xr}(0) - \beta_0\beta_1 Q_{xi}(0)]z^2 - \alpha_1[Q_{xr}^2(0) + Q_{xi}^2(0)]z^3}{4[\beta_0 + Q_{xr}(0)z]^2 + 4Q_{xi}^2(0)z^2}. \tag{17}$$

Equations (14)–(17) can be substituted directly into Eq. (5) to obtain the beam displacement or into Eq. (6) to obtain an explicit expression for the deflection angle $\theta_x(z)$. It only remains to summarize the formulas for the parameters that enter into these results. If the gain and background index of refraction vary linearly in the x direction, they may be expressed in the form

$$n(x) = n_0 - n_{1x}x/2, \tag{18}$$

$$g(x) = g_0 - g_{1x}x/2. \tag{19}$$

Now the linear components of the propagation constant, including frequency effects, for a homogeneously broadened medium are

$$\beta_1 = \frac{2\pi}{\lambda}\left(n_{1x} + \frac{\lambda g_{h1x}}{4\pi}\frac{u}{1+u^2}\right), \tag{20}$$

$$\alpha_1 = \frac{g_{h1x}}{2(1+u)^2}. \tag{21}$$

For a Doppler broadened medium they are

$$\beta_1 = \frac{2\pi}{\lambda}\left[n_{1x} + \frac{\lambda g_{D1x}}{2\pi^{3/2}}F(v)\right], \tag{22}$$

$$\alpha_1 = \frac{g_{D1x}}{2}\exp(-v^2). \tag{23}$$

The other parameters include the propagation constant $\beta_0 = 2\pi n_0/\lambda$ and the input values $Q_{xr}(0) = \beta_0/R(0)$, $Q_{xi}(0) = -2/w_x^2(0)$.

If the above substitutions are used in Eq. (6), the deflection angle for a laser amplifier exhibiting a linear gain gradient can be evaluated. It is only necessary to introduce the properties of the amplifier and input beam.

The amplifier will be described in detail in the next chapter, but for the purpose of this preliminary calculation, we shall briefly state some of its characteristics. The medium is approximately homogeneously broadened at the pressure of 125 Torr used in the experiment.[6] With this approximation the gain profile is Lorentzian, and the index of refraction is given by Eq. (9). The experiments are done on $P_2(5)$ and $P_2(6)$ where a gain of $g_h = 10\ \mathrm{m}^{-1}$ has been measured at line center.[7] The length of the gain medium is 0.4 m, and the input spot size is $w_x(0_0) = 3 \times 10^{-3}$ m.

In previous interferometric measurements, it has been shown that the background index of refraction is nearly uniform,[7] so we assume $n_{1x} = 0$. For the purpose of this initial calculation we assume the gain to vary linearly from its maximum value of $10\ \mathrm{m}^{-1}$ to zero in a distance of 0.02 m across the amplifier aperture, resulting in the linear gain coefficient $g_{h1x} = 10^3\ \mathrm{m}^{-2}$. The actual experimental measurement of the gain profile is described later. Using these values, we have calculated the deflection angle, and the results are shown in Fig. 1. An interesting consequence of these results is the strong dependence of the deflection angle on the radius of curvature of the input phase fronts. If the phase front curvature is positive (convex in the direction of propagation), the beam tends to be deflected in the negative x direction toward the region of highest gain. If the phase front curvature is negative, the beam is deflected away from the region with the highest gain. This behavior can be understood intuitively by considering the array of vectors or light rays normal to the wave surface. These rays have slightly different propagation directions, and the gain profile tends to augment the rays on the negative x side of the beam. With a convex wave surface these rays tend toward the negative x direction, and the opposite behavior results for a concave surface.

Another consequence of Fig. 5 is that the asymmetric dispersion effects are negligible for most reasonable values of the input phase front curvature. Only if the phase fronts are extremely flat at the input ($R \sim 100$ m) does the deflection due to the gradient of the real index of refraction (dispersion) become comparable to the deflection caused by the gain profile.

IV. Experiment

A. Description of Equipment

In this section we shall describe the laser amplifier and the measurements performed on it. The amplifier is a double discharge uv preionized HF laser, similar in design to the CO_2 laser of Judd.[8] It uses premixed hydrogen and fluorine gas as fuel, with helium diluent,

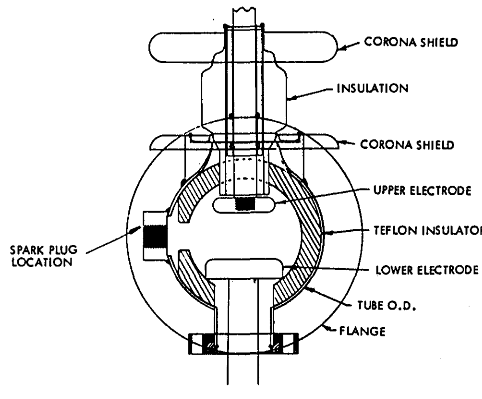

Fig. 2. Cross section of laser amplifier.

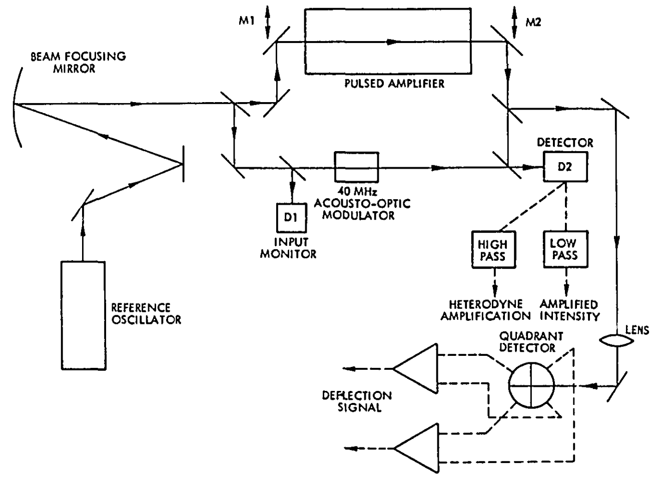

Fig. 3. Experimental arrangement. Beam deflection is measured on the quadrant detector. The gain is measured both by a heterodyne system making use of a Mach-Zehnder interferometer and by comparing the output and input intensities. By translating mirrors $M1$ and $M2$ the gain at different positions is measured. By moving the beam focusing mirror, the radius of curvature of the beam at the amplifier is changed.

and a trace of oxygen to inhibit premature reaction of the H_2 with F_2. The detailed performance of this laser medium, both as an oscillator and as an amplifier, has been described elsewhere.[7] However, we include a diagram of the cross section of the laser, Fig. 2, to help clarify the presence of the gain gradient.

The laser is filled with gas in the following ratio: F_2:H_2:He:O_2 = 5%, 2.5%, 92%, ½% at 125 Torr. The capacitors are charged to 12 kV. When the trigger is activated, the discharge current first flows to the spark plugs, which have the lowest initial impedance. When these fire, they ionize the gas mixture in the laser by the uv radiation emitted, and this lowers the impedance of the main gap, causing it to discharge. During this discharge the fluorine molecules are dissociated, and the free F atoms react with the hydrogen to produce the lasing species:

$$F_2 + h\nu \rightarrow 2F,$$

$$F + H_2 \rightarrow HF^* + H,$$

$$H + F_2 \rightarrow HF^* + F.$$

However, since the spark plugs are situated along one side of the laser, the deposition of uv radiation is strongly nonuniform, resulting in a nonuniform F_2 dissociation fraction and hence a transverse gain gradient (see below).

The apparatus was arranged as shown in Fig. 3. A beam from a frequency stabilized HF probe laser[9] was passed through the amplifier and the output beam analyzed with a number of detectors. Figure 3 is a composite diagram, showing all the measurements done, even though not all of them were done simultaneously.

B. Measurement of the Gain Gradient

The transverse gain profile was measured by passing the probe beam through the amplifier and observing the input and output intensities at detectors D_1 and D_2 as functions of time. As a check we also measured the gain as an amplitude modulation of the beat frequency produced by the interference of the output beam with part of the frequency shifted input beam in a Mach-Zehnder interferometer. The purpose of this check was also to observe the beam deflection interferometrically, but this was unsuccessful due to the significant deformation of the wavefront of the reference beam by the acoustooptic modulator.

By translating the mirrors M_1 and M_2 as shown, the probing beam was moved across the amplifier aperture, and the gain as a function of time and transverse position measured. Some typical results for three different positions are shown in Fig. 4. For $x = 0$, the gain is measured on the geometrical center axis of the amplifier, and positive values of x are toward the side with the spark plugs. It can be seen that close to the spark plugs, very high values of the gain are reached, while the pulse length is quite short. In this region, much uv preionization occurs, and as a result the initial F_2 dissociation rate is high. This leads to high gains and rapid reactions, with the converse holding farther away from the spark plugs.

If we assume the gain to be approximately linear in between the measured values, we can reconstruct the gain gradient as a function of time at $x = +7.5$ mm. At this position, the gradient is initially toward the spark plugs, as indicated by the dotted arrows in Fig. 4. At 7 μsec, the gradient is zero since the gains at +10 mm and +5 mm are the same at this instant; and for later times, the gradient is away from the spark plugs. The behavior of the gain gradient as a function of time was measured from the data in Fig. 4 and plotted in Fig. 5.

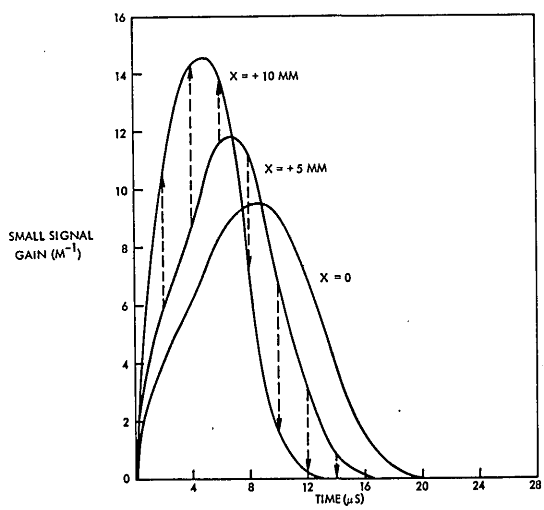

Fig. 4. Small signal gain on $P_2(5)$ as a function of time at three different transverse positions. $X = 0$ is on the centerline, and positive x is toward the preionizers. Dashed lines indicate direction of gain gradient.

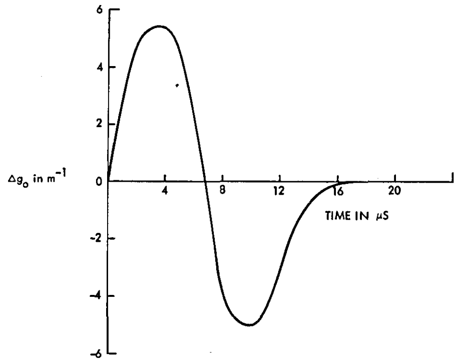

Fig. 5. Transverse gain gradient as a function of time at the position $x = +5$ mm, extracted from results in Fig. 4. The peak gain gradient is $1.1 \times 10^3\ m^{-2}$.

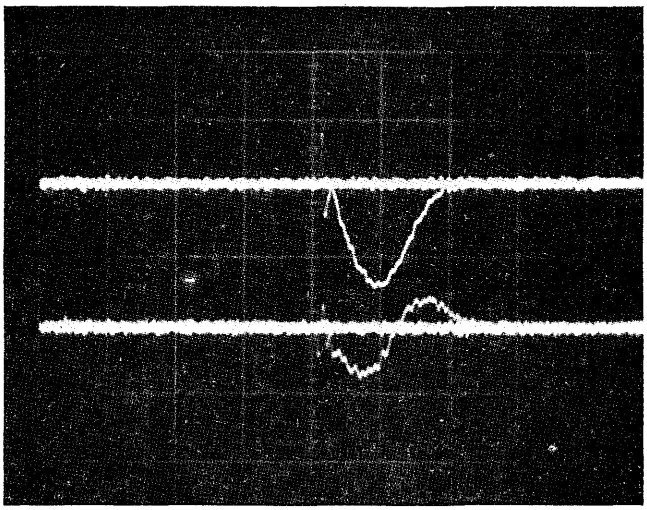

Fig. 6. Transverse beam deflection; vertical scale: 500 μR/cm; horizontal scale: 5 μsec/cm. The lower trace shows the deflection first to one side and then to the other.

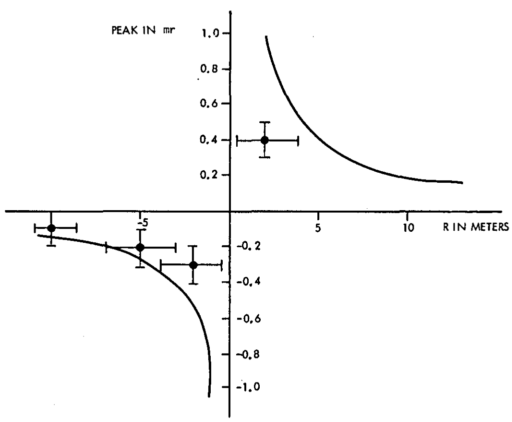

Fig. 7. Comparison between measured values of beam deflection and calculated predictions. The observed beam deflection angle is plotted as a function of the radius of curvature of the beam.

C. Measurement of Beam Deflection

To confirm the theoretical calculations of Sec. III, it is necessary to measure the beam deflection as a function of frequency and radius of curvature of the input wavefront. The beam deflection was observed by imaging the output beam on a quadrant detector with opposing quadrants connected differentially as shown in Fig. 3. In this arrangement a beam deflection will be measurable as a deviation from a null balance of opposing quadrants, and this deviation can easily be calibrated as an angle by shifting the beam across the detector a known distance. When the amplifier was fired, a deflection was observed, with the beam first steering in one direction, and then in the other, as expected from the measurement of the gain gradient. A typical result is shown in Fig. 6.

The radius of curvature of the wavefront at the entrance to the amplifier was deduced from the following measurement. From the length of the probe laser cavity and the curvature of its mirrors, the beam spot size could be calculated from the well known equations[10]

$$w_0^2 = [\lambda/(2\pi)][d(2R-d)]^{1/2}, \tag{24}$$

$$w^2(z) = w_0^2\left[1 + \left(\frac{\lambda z}{\pi w_0^2}\right)^2\right], \tag{25}$$

where w_0 is the $1/e$ radius of the spot size at the waist of the laser, R is the radius of curvature of the outcoupling mirrors, d is the separation of the mirrors, and $w(z)$ is the $1/e$ radius of the propagating beam at a distance z from the waist. Using a rotating mirror, sweeping the beam across a small detector, we measured $w(z)$ as a function z and found it to be in excellent agreement with the values calculated. We were therefore confident that the propagating beam was well characterized by this formalism for the propagation of a Gaussian beam and felt justified in calculating the radius of curvature of the beam from

$$R(z) = z\left[1 + \left(\frac{\pi w_0^2}{\lambda z}\right)^2\right]. \tag{26}$$

To vary the radius of curvature of the beam propagating through the amplifier, we simply varied the distance from the probe laser to the concave beam focusing mirror, shown in Fig. 3 and the distance from this mirror to the amplifier. After each change, we measured $w(z)$ for several values of z on either side of the amplifier, as well as the value of z, to check on the continued agreement. This measurement also provided the value of $w(0)$ at the entrance to the amplifier, required in the calculation. The uncertainty in $R(z)$ is still quite large due to the difficulties in measuring $w(z)$ accurately. We measured $\theta(z_{\rm out})$ for several different values of $R(0)$, and the results are shown in Fig. 7 with the calculated values of $\theta(z_{\rm out})$. These measurements represent the maximum values of $\theta(z_{\rm out})$ at line center of the laser. The reversal of the deflection angle with radius of curvature was observed as shown.

The frequency dependence of the deflection angle, especially the predicted asymmetry due to anomalous dispersion for large radii of curvature wavefronts, was not observed. This was due to a limitation to the smallest deflection angle measurable: the probe laser was on one optical table, the amplifier on another, and the detectors on a third, in a shielded enclosure required to protect the detectors from electrical noise due to the laser discharge. With this arrangement, the individual vibrations of the tables limited the minimum angle measurable as beam deflection to 50 μrad. For this reason, effects due to anomalous dispersion could not be seen. We verified this to be the case by observing the same sign of $\theta(z)$ for two input frequencies at either side of line center with $R(z)$ sufficiently short to observe a repeatable beam steering signal. This test confirms that the deflection observed was due to gain deflection rather than anomalous dispersion, as predicted in Fig. 3. From the comparison of experimental results with the theoretical predictions shown in Fig. 7, we conclude that the linear theory of beam deflection developed above adequately describes the effects observed. The agreement is semiquantitative since both the sign and approximate magnitude predicted are close to the observed values, but not quite within the experimental errors.

V. Conclusion

We have developed a theoretical description for beam deflection in a chemical laser amplifier and have demonstrated by experiments that the theory is semiquantitatively correct. With this understanding of beam deflection, amplifier systems can be designed to minimize the effect. Deflection can be minimized by using plane waves and large Fresnel numbers, ensuring that the radius of curvature of the wavefronts will remain large. Furthermore, in the saturated region of the laser, the magnitude of the deflection will decrease with the saturated gain. The effect of anomalous dispersion is also very small in most laser amplifier designs.

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