Optical Power Limiter with Picosecond Response Time

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Abstract—Optical self-action in CS_2 and other liquids was used to make a power-limiting device having a picosecond response time. This device uses self-focusing in liquids to produce phase aberrations and laser-induced breakdown, which in turn limit the transmitted power. This device has near-unity transmission for input power below P_C, which is on the order of the critical power for self-focusing, and limits the transmitted power to a nearly constant value for input power greater than P_C. The onset of nonlinear transmission was adjusted by mixing various liquids to adjust the nonlinear refractive index. Experimental results using linearly and circularly polarized 40 ps (FWHM) pulses at 1.06 μm are presented.

I. INTRODUCTION

WE describe a technique by which self-focusing and laser-induced breakdown are used to make an optical power limiter. The basic concept is to use intensity-dependent refraction (self-focusing) and intensity-dependent absorption (associated with laser-induced breakdown) to make a passive optical device which has *high* transmission for *low* input power, but *low* transmission for *high* input power. Such a device can be considered an optical power limiter or a nonlinear optical switch. We have demonstrated a device with picosecond response time. Possible uses of this device include the protection of detectors used to study pre-lasing in large oscillator–amplifier laser systems, the optical isolation of sensitive oscillator components from back propagating high-power beams, and as a limiter in various integrated optics applications.

II. PASSIVE NONLINEAR POWER LIMITER CONCEPT

Fig. 1 is a schematic of the device which we call an optical power limiter (OPL). The solid lines schematically trace the input beam for low input power. The beam is focused by lens L_1 into a material with high nonlinear refractive index n_2. For low input powers, the light is imaged by lens L_2 through a pinhole onto detector D_4. As the input power is increased to approximately P_2, the critical power for self-focusing [1], the beam undergoes severe phase aberrations (i.e., nonlinear refraction) and, consequently, the waist from lens L_1 is no longer in the proper location to be reimaged by L_2 onto de-
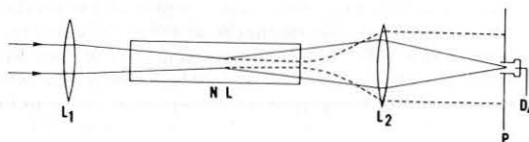
NONLINEAR OPTICAL SWITCH

Fig. 1. Nonlinear optical switch (OPL) concept. Lens L_1 was a single element lens of "best form" design. The input beam radius (to the $1/e^2$ points of irradiance) was 2.35 mm, and the focal length of lens L_1 was 37 mm. L_1 was located so as to produce a focal spot in the middle of the nonlinear cell. L_2 was an 80 mm focal length microscope objective placed approximately 68 mm behind the 12 mm thick cell. This arrangement produced a focal spot of approximately 100 μm diameter, which matched the 100 μm diameter aperture located 525 mm behind lens L_2.

tector D_4. The high-power situation is shown schematically by the dotted lines.

The OPL shown in Fig. 1 has been previously demonstrated by Soileau [2] using nanosecond pulses at 1.06 μm with CS_2 as the nonlinear medium, and is similar to an arrangement used by Bjorkholm et al. [3] to make a passive bistable device and the arrangement used by Teite et al. [4] to make a power-limiting device for CW lasers. In this work, we demonstrated the power-limiting feature of this concept for picosecond pulses at 1.06 μm. Various nonlinear media were investigated, including CS_2, nitrobenzene, and mixtures of these liquids in ethanol. The laser source used in this work was a mode-locked Nd:YAG laser operated at 1.06 μm with Gaussian spatial profiles. The single pulse energy was variable up to approximately 10 mJ. The temporal pulse width was variable from 40 to 300 ps; however, all data presented in this paper correspond to pulse widths of 40 ps (FWHM). The laser system and associated diagnostic equipment is described in greater detail in [5].

Fig. 2 shows the power-limiting capability of the OPL, using CS_2 as the nonlinear medium and linearly polarized light. Note that the output of the device (D_4) is effectively clamped, even for the maximum input of approximately 4×10^6 W. The "step-function"-like transmission for low input power is the region of linear response. The linear response for low input power and the onset of the nonlinear response are shown more clearly in Fig. 3. Note that the device transmission is linear for input power lower than approximately 26 kW, and is clamped for higher input powers. CS_2 is highly transparent at 1.06 μm, so, with the exception of Fresnel reflection losses at the cell windows (which can be avoided with antire-
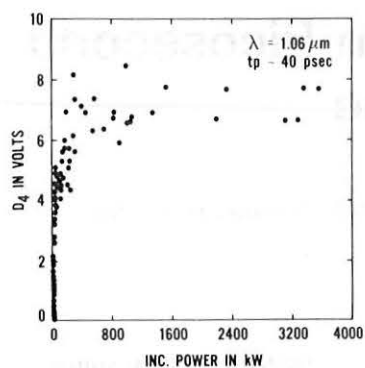
Fig. 2. Intensity limiter response. This is a plot of the results of measurements using CS_2 as the nonlinear medium (NL) in Fig. 1. The laser source was a Nd:YAG laser operating at 1.06 μm with pulse width of 40 ps. The region of linear response (the nearly vertical line on the extreme left of this graph) is shown in more detail in Fig. 3.
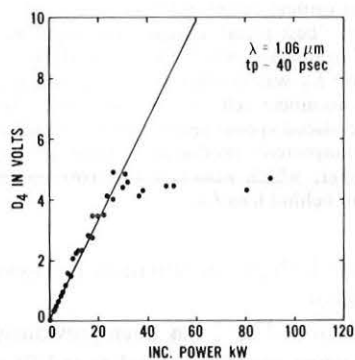

Fig. 3. The onset of nonlinear transmission. This plot is for the same material (CS_2) and laser source as used for the data in Fig. 2. Here, the horizontal scale has been expanded to show the region of linear response and the onset of nonlinear transmission ($P_c = 26 \pm 3$ kW).

flection coatings), the device transmits *all* the incident power until the cutoff power is reached.

III. POWER-LIMITING MECHANISMS

The mechanisms for the limiting action shown in Figs. 2 and 3 were investigated by measurements of the threshold for nonlinear transmission (P_c) as a function of n_2 (nonlinear refractive index), the f/number of lens L_1, and of the polarization of the incident laser radiation. These measurements were conducted with and without the limiting aperture in front of detector D_4. The results of these measurements indicate that the mechanisms which limit the transmission of the OPL are intensity-dependent refraction (self-focusing) and intensity-dependent absorption associated with laser-induced breakdown (initiated by self-focusing).

Analysis of the data shown in Fig. 3 and two additional experiments under identical conditions indicate that the critical power for the onset of nonlinear transmission (P_c) is 26 ± 3 kW for CS_2 for linearly polarized light. The data points shown in Fig. 3 and the other plots in this paper are the averages of the reading on detector D_4 for five laser shots. P_c was determined from the ratio of the reading on D_4 to the input power in accordance with the following procedures. The standard deviation of this ratio for a group of five shots was relatively small for powers significantly above or below P_c.

The standard deviation of this ratio increases by as much as an order of magnitude at P_c, and becomes small again for powers greater than P_c. Thus, monitoring the standard deviation in the ratio of the reading on detector D_4 to the input power was a sensitive and reliable method of determining P_c. The large standard deviation in the ratio is expected near P_c since the device fluctuates from the nonlimiting mode to the limiting mode with small shot-to-shot fluctuations in laser output power.

Marburger [1] has solved the nonlinear wave equation for the case of a focused Gaussian beam. He determines the least critical power for a self-trapped mode to be $P_{c1} = 3.72 P_1$, where

$$P_1 = \frac{c\lambda^2}{32\pi^2 n_2}$$

and where n_2 is the nonlinear index of refraction, λ is the laser wavelength, and c is the speed of light. The beam will self-focus for powers greater than P_{c1} for Gaussian beams [1]. (P_{c1} is sometimes referred to as P_2 for Gaussian beams.) Assuming that our measured value of P_c corresponds to P_{c1}, we then calculate n_2 for CS_2 at 1.06 μm to be $1.5 \pm 0.3 \times 10^{-11}$ ESU. The $\pm 0.3 \times 10^{-11}$ ESU total uncertainty includes the 15 percent absolute uncertainty in the power measurement and the 13 percent relative uncertainty in P_c. The total uncertainty is calculated assuming the absolute errors in power measurement and relative error in determining P_c are uncorrelated. This value of n_2 is in excellent agreement with the value of $1.3 \pm 0.3 \times 10^{-11}$ ESU for CS_2 at 1.06 μm deduced from direct interferometric measurements by Witte et al. [6] at 1.32 μm using 700 ps pulses.

The measurements by Witte et al. [6] are the only known direct measurement of n_2 in CS_2 at optical frequencies. Moran et al. [7] inferred a value of $1.10 \pm 0.33 \times 10^{-11}$ ESU for CS_2 at 1.06 μm by comparing their direct measurement of n_2 for ED-2 glass with independent measurements of n_2 for ED-2 glass by Bliss et al. [8] and relative measurements of n_2 for ED-2 glass and CS_2 by Owyoung [9]. Shen [10] and Owyoung [9] used the dc Kerr constant for CS_2 to calculate n_2 for CS_2 at 0.67 and 0.694 μm. When extrapolated to 1.06 μm, Shen and Owyoung's values give n_2 at 1.06 μm of 2×10^{-11} ESU and 2.55×10^{-11} ESU, respectively.

The n_2 value for CS_2 at 1.06 μm deduced from the measurements of P_c in this work and the n_2 values determined by direct interferometric measurements have overlapping error bars, and are therefore in agreement. However, there are several tests for self-focusing which do not depend upon knowing the absolute value of n_2, and are independent of absolute errors in the input power measurements. In the paragraphs that follow, we describe the results of several of these tests, which confirm that self-focusing was the primary mechanism for the limiting action shown in Figs. 2 and 3.

Self-focusing theory [1] predicts that $P_{c1} \propto 1/n_2$. Prior work [11] has shown that one can vary n_2 by mixing CS_2 with ethanol (which has a very low n_2). A 50-50 mixture of CS_2 and ethanol has an n_2 equal to approximately one-half that of neat CS_2. Therefore, for self-focusing in a 50-50 mixture, one would expect that the onset of the power limiting would occur at a power approximately twice as high as

required for neat CS_2. Measurements using this mixture show that the onset of limiting occurs at 58 ± 7 kW, which is in good agreement with the predictions of self-focusing theory. Note that this result means that one can adjust the output of the OPL by simply mixing a high n_2 material with a low n_2 material to adjust P_c to the desired level.

The data shown in Figs. 2 and 3 were taken using a 37 mm focal length lens (L_1) used at $f/7.9$ to focus the light into the nonlinear medium. A critical test for self-focusing is to vary the focal length of L_1. The onset of self-focusing is dependent upon the *power*, rather than the input intensity; therefore, the onset of nonlinear transmission will be independent of the focal length of L_1 if self-focusing is the critical mechanism. The cutoff power was measured in neat CS_2 with the 37 mm focal length lens replaced by a 75 mm focal length lens (used at $f/16$). The cutoff power for this case is approximately the same as that shown in Fig. 3 (26 ± 3 kW). An intensity-dependent process would have required a factor of 4 increase in input power, and our measurements show that the critical power is independent of the focal lengths of lens L_1 within the experimental uncertainty.

The relatively large n_2 values for materials such as CS_2 are due to the orientational dependence of the polarizability of these molecules. Thus, the self-focusing observed in these materials is due to optically induced ordering of the molecules, i.e., the ac Kerr effect. Therefore, self-focusing in these materials should be critically dependent upon the polarization of the incident light [10]. The measured value of the cutoff power for circularly polarized light P_{cc} is 47 ± 4 kW for neat CS_2. The cutoff power measured for a 50-50 mixture of ethanol and CS_2 is 125 ± 10 kW for circularly polarized light, as compared to 58 ± 7 kW for linear polarized light for the same mixture. Similar measurements in neat nitrobenzene yielded $P_c = 72 \pm 7$ kW and $P_{cc} = 133 \pm 13$ for linear and circular polarization, respectively. The average ratio of P_{cc} to P_c for the various measurements was 1.9 ± 0.2. This compares favorably with the value of 2.0 found by Close et al. [12] and Wang [13] for the ratio of the critical power for self-focusing in CS_2, using completely different techniques and nanosecond ruby laser pulses ($\lambda = 0.694$ μm). However, theoretical calculations by Shen [10] predict that the ratio of n_2 for circular polarization to the n_2 for linear polarization should be 4 for self-focusing which is due to molecular reorientation. The approximate factor of 2 difference between the measured ratio in this work and in [12] and [13] and the theoretical value is not understood at this time. Feldman et al. [14] measured a ratio of approximately 1.1–1.3 for various solids for which electrostriction and electronic self-focusing are thought to be important. Hellwarth [15] and Wang [13] have pointed out that the circular-to-linear polarization ratio should be related to the ratios of the various components of $\chi^{(3)}$, the third-order optical susceptibility. While there is considerable debate in the literature as to what the exact ratio of n_2 for circular and linear polarization should be, there is agreement that n_2 for circular polarization is less than that for linear polarization.

The dependence of P_c upon n_2, the beam polarization, and the focal length of lens L_1 are all consistent with the idea that the observed nonlinear transmission is due to the onset of self-
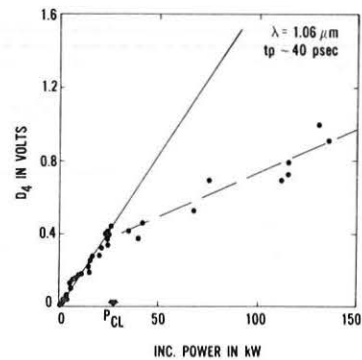

Fig. 4. OPL response for CS_2 using linearly polarized light and a 37 mm focal length lens for L_1. The aperture in front of D_4 was removed and the reading on D_4 was measured as a function of input power. Note that the change in slope occurs at $P_c = 26$ kW, as in Fig. 3. The change in slope is due to absorption in the laser-induced breakdown that results from the self-focusing.

focusing. Additionally, we observed bright "streamers" of flashes (due to laser-induced breakdown) for input power substantially above P_c, which suggests self-trapping or a moving self-focus position [16]. These "streamers" are evidence that self-focusing is the mechanism for the self-limiting action of the OPL; however, they also suggest that the observed limiting behavior may be due to the absorption in the laser-induced plasma (initiated by self-focusing). The effects of laser-induced breakdown were investigated by removing the pinhole in front of the detector (D_4 in Fig. 1), so that all the light transmitted through the cell was intercepted by the detector. The results are shown in Fig. 4.

The onset of the nonlinear transmission is associated with the same input power as observed in Fig. 3 for the onset of nonlinear transmission. The tests previously described for self-focusing were repeated without the pinhole in place, and the onset of nonlinear behavior varied as predicted by self-focusing theory. We conclude that the observed clamping of the output of the OPL is due to both nonlinear refraction and nonlinear absorption in the laser-induced plasma, and that both mechanisms are associated with self-focusing.

The above results indicate that P_c, the critical power for the onset of nonlinear transmission, has the polarization, focal length, and n_2 dependence consistent with self-focusing. These experiments were repeated with neat ethanol and CCl_4 (materials for which self-focusing was expected to be negligable) substituted for the high n_2 material. P_c and P_{cc} for the various materials and configurations examined are summarized in Table I. The average ratio of P_c and P_{cc} for the 37 and 75 mm focal length lenses is 4.1 ± 0.4 for ethanol, whereas the square of the focal lengths of the lenses is 4.11. Therefore, the onset of nonlinear behavior is intensity dependent, instead of power dependent, as in the Kerr liquids. The data in Table I indicate that the critical power for linear (P_c) and circular (P_{cc}) polarization are approximately equal for ethanol and CCl_4. The lack of polarization dependence of P_c and the dependence of P_c upon the focal length of lens L_1 confirms that self-focusing in these media is not the dominant mechanism for producing laser-induced breakdown. The nonlinear transmission in ethanol and CCl_4 is due to absorption in the laser-induced plasma which accompanies dielectric breakdown

TABLE I

P_c AND P_{cc} FOR VARIOUS MATERIALS AND FOCAL LENGTHS OF LENS L_1.
NOTE THAT THE AVERAGE RATIO OF P_{cc} TO P_c IS 1.9 ± 0.2 FOR CS_2 AND
THE KERR LIQUIDS, AND IS 1.2 ± 0.1 FOR THE ETHANOL AND CCl_4.
P_c AND P_{cc} ARE INDEPENDENT OF THE L_1 FOCAL LENGTH FOR THE KERR
LIQUIDS AND SCALE AS THE RATIO OF THE FOCAL LENGTH SQUARED
FOR ETHANOL AND CCl_4.

Material	L_1 Focal Length	Linear Polarization P_c in kW	Circular Polarization P_{cc} in kW
CS_2	37 mm	26 ± 3	50 ± 7
CS_2	75 mm	26 ± 3	43 ± 3
CS_2:Ethanol	37 mm	58 ± 7	125 ± 10
Nitrobenzene	37 mm	72 ± 7	133 ± 13
Ethanol	37 mm	350 ± 30	380 ± 20
Ethanol	75 mm	1300 ± 200	1700 ± 200
CCl_4	37 mm	410 ± 40	466 ± 40

in these materials. Hellwarth *et al.* [17] determined that the ratio of the n_2 for CS_2 to that of CCl_4 is 56 ± 6 at 0.694 μm, indicating that P_c (CCl_4) = 56 P_c (CS_2). This implies that P_c (CCL_4) due to self-focusing should be approximately 1460 kW, which is more than a factor of 3.5 greater than the value required to induce breakdown in this material for these pulse widths. The ratio of the optical Kerr constant for CS_2 to that of ethanol is 156 [10], which implies that P_c (ethanol) due to self-focusing should be approximately 4060 kW, a factor of 3.1 greater than that required to induce breakdown. Thus, one would expect that self-focusing was not a factor in the observed nonlinear transmission of these two materials.

IV. PULSE WIDTH DEPENDENCE OF THE OPL

The molecular reorientational relaxation time for CS_2 is approximately 2.1 ps [18], [19], and is therefore much shorter than the pulse width used in this work. P_c and P_{cc} for CS_2 are expected to be independent of pulse width for pulse widths substantially longer than 2 ps. P_c for similar measurements at 1.06 μm with 9 ns pulses was 29 ± 3 kW [20], which indicates that P_c is independent of pulse width over the 40 ps–9 ns range.

The ratio of P_c (nitrobenzene) to P_c (CS_2) from Table I is 2.8 ± 0.4, and the corresponding ratio of P_{cc}'s is 2.7 ± 0.4. The ratio predicted by the optical Kerr constant [10] for these materials is 1.23, and the measured ratio for P_c for nanosecond pulses [11] is 1.8 ± 0.3. Since the molecular relaxation time for nitrobenzene is 44 ps [21] (the same order as the laser pulse width in this work), the contribution of molecular reorientation to the n_2 of nitrobenzene should be diminished. The ratio of n_2 for CS_2 to n_2^e, the nonlinear index of nitrobenzene due to electronic self-focusing, is 2.74 [21]. We conclude that the P_c and P_{cc} measured for nitrobenzene using picosecond pulses is primarily due to electronic self-focusing. Thus, while P_c and P_{cc} for CS_2 are expected to be much larger for subpicosecond pulses than the values reported here, the corresponding values for nitrobenzene are expected to be nearly independent of pulse width for pulse widths from 40 ps to the order of 10^{-14} s, unless other mechanisms become important. Limiting characteristics using nitrobenzene as the nonlinear medium are given elsewhere [22].

V. SUMMARY

We have demonstrated a device that can be used as a power limiter for picosecond laser pulses. The mechanisms which limit the transmission of this device are intensity-dependent refraction (self-focusing) and intensity-dependent absorption associated with laser-induced breakdown (initiated by self-focusing). This device, which we call an optical power limiter, has been shown to work for 1.06 μm pulses of 40 ps duration. The ultimate response time for this device is determined by the response time of the nonlinear medium, e.g., 2 ps for CS_2. A medium in which the dominant nonlinear refraction is electronic is expected to have a response time on the order of 10^{-14} s. The advantages of this power-limiting technique include rapid response and recovery, completely passive operation, and a relatively low limiting power P_c (26 kW for CS_2 at 1.06 μm). Additionally, P_c can be adjusted by varying n_2.

It is important to note that substantial temporal fluctuations, frequency shifts, and self-phase modulation may be imposed on the beam which is transmitted through the OPL [23]–[26]. Such effects should not result in severe problems when low bandwidth nondispersive detectors are employed with the OPL. If the OPL is used with an optical streak camera or a spectrometer, highly modified signals due to propagation through the nonlinear medium could result.

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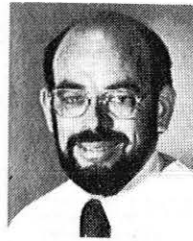
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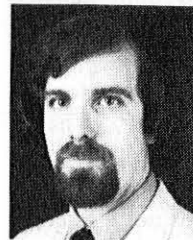
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Eric W. Van Stryland, photograph and biography not available at the time of publication.