High-dynamic-range cascaded-focus optical limiter

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We report experimental results of using an $f/5$, cascaded-focus optical geometry for a high-dynamic-range optical limiter. The device consists of a 2-cm-thick CS_2 cell at the first focus and a reverse saturable-absorber dye in a thin cell (0.1 mm) at the second focus. The strong self-focusing in the CS_2 that is due to the ac Kerr effect and electrostriction keeps the energy at the second cell below its damage threshold. Using lead phthalocyanine in chloroform as the reverse saturable-absorption material, we clamped the maximum output energy below 1 μJ for input energies up to 14.5 mJ without damage. We used a frequency-doubled, Q-switched 5-ns (FWHM) Nd:YAG laser operating at a 10-Hz repetition rate. The measured dynamic range of the device is at least 7500. © 2000 Optical Society of America

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Optical limiters are devices that have high transmittance for low inputs and low transmittance for high inputs. They can, for example, be used to protect sensitive detection components such as optical sensors and human eyes from damage. In the case of human eyes the damage threshold for nanosecond visible pulses is of the order of 1 μJ.[1,2]

Nonlinear optical limiting processes, such as nonlinear scattering,[3,4] polarization changes,[5,6] multiphoton absorption,[2,7,8] and reverse saturable absorption[9,10] (RSA), have been studied in various materials including particle suspensions, organics, inorganics, organometallics, and liquid crystals. In recent years, molecules that exhibit RSA have been the subject of intense study because of their large nonlinear response, which is essentially a resonant two-photon absorption process.[10–14] As first described by Giuliano and Hess,[10] this kind of process occurs in materials in which the excited-state absorption cross section σ_{ex} is greater than that of the ground state σ_{gr}. For a single element of RSA material, the figure of merit (FOM), defined as the ratio of linear transmittance to minimum transmittance at high energy (T_L/T_{min}), could be theoretically large, depending on the ratio σ_{ex}/σ_{gr}. However, the input energy at which the limiting device suffers damage is what determines T_{min} and hence the performance of the optical limiter.[15] Another measure of limiter performance is the dynamic range, defined as the ratio of damage energy to limiting threshold energy. For most limiters, this number is the same as the FOM. Multiple RSA elements can be positioned in a converging beam geometry to greatly increase the FOM.[12] This geometry was referred to as a tandem limiter, and this idea was extended by Miles,[16] who showed that the absolute optimum performance of a RSA limiter could be achieved by use of a graded molecular concentration. Experimentally, three-element tandem limiters were shown to have FOM's of the order of 400.[12,13] In the research reported in Ref. 13 the output energy was 12 μJ for an input value of 7 mJ, approximately 1 order of magnitude better than for a single-element device. Here we present what is, to our knowledge, the highest dynamic range optical limiter ever reported, which uses the $f/5$, cascaded-focus, optical geometry shown in Fig. 1.

The experimental setup consists of a 1-cm-thick CS_2 cell at the first focus and a RSA cell of 0.1-mm thickness at the second focus. A half-wave plate and a polarizer are used in combination to control the input energy. Lenses L1 and L3 focus the beam into the samples. Apertures A1 (2-cm diameter), A2, and A3 define the $f/5$ focusing and the collection apertures through the limiter, respectively. L2 and L4 recollimate the beams after the first and second cells. L5 collects the beam into detector D1 to measure the transmitted energy. A small aperture (A4) is placed in the focal plane of L5 and in front of D1 to measure the encircled energy, E_{en}. E_{en} is defined as the energy

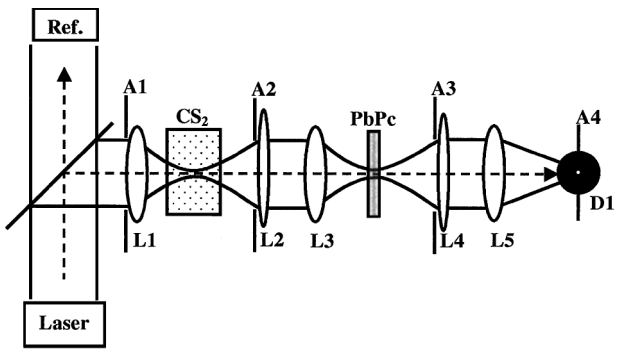

Fig. 1. Experimental setup for the high-dynamic-range optical limiter with an $f/5$ cascaded-focus optical geometry.

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passing through a 1.5-mrad-diameter focal-plane aperture.[2] In our case, the focal length of L5 is 1 m, and hence the aperture diameter is 1.5 mm.

For the RSA material, we used a solution of lead phthalocyanine (PbPc, 90%; Aldrich) in chloroform. This solution had previously been filtered with a 0.22-μm syringe filter to eliminate small particles in the solution. PbPc is known as a good optical limiter.[17] The low-irradiance transmittance for the resultant dye solution was measured to be 60% at the operating wavelength of 532 nm; the total linear transmittance for the whole system, including Fresnel losses, was 21% (no antireflection coatings were used on the several optical surfaces). With antireflection coatings the total linear transmittance should be 60%. We used a frequency-doubled, Q-switched 5-ns FWHM single-longitudinal-mode Nd:YAG laser operating at a 10-Hz repetition rate. The input beam overfills aperture A1 to produce a flat-topped beam at the input of the system. In both focal planes, the low-irradiance spot size was measured by the thin-sample Z-scan technique to be 6 μm half-width $1/e^2$ maximum (HW1/e^2M).[18]

In Fig. 2 we show the normalized E_{en} versus input energy E_i for three experiments. The open triangles show the transmittance with the CS_2 cell far from the first focus and the PbPc–chloroform cell positioned in the second focal plane. In this case, only the PbPc contributes to the limiting, as the irradiance in the CS_2 is too small. At the maximum input energy of 47 μJ the PbPc cell is damaged. The open circles show the situation with the CS_2 cell positioned with the first focus inside (3 mm from the rear window) the CS_2 cell while the PbPc is far from the second focus. In this case, only the CS_2 contributes to the limiting, which occurs at a sharp threshold of $\cong$14 μJ. Such a sharp limiting threshold is expected for a self-focusing medium in which limiting is due to strong scattering from the laser-induced breakdown produced above the critical power, P_c.[19] As the CS_2 is a liquid, it is not permanently damaged by this breakdown. The crosses in Fig. 2 show the case in which the two cells are placed at their respective foci. As expected, the CS_2 protects the PbPc cell, extending the damage threshold of the device. No damage was observed up to the maximum incident energy for this set of experiments at 1 mJ. In Fig. 3 we show data taken for incident energies up to 14.5 mJ. The measured value of P_c is smaller than predicted from the ac Kerr effect ($n_2 = 3.1 \times 10^{-14}$ cm^2/W, to yield $P_c = 8.2$ kW at 532 nm).[19] This value would correspond to an energy of 43.5 μJ for our pulse width. However, for the tight focusing geometry and the laser pulse width in this experiment the refractive-index change that is due to electrostriction can contribute significantly to the nonlinear index change in CS_2.[20] Using a nonlinear optical beam propagation code developed for optical limiting,[21] we modeled the beam propagation through CS_2 with and without electrostriction for various beam radii. We found that for a 5-ns (FWHM) pulse and a $1/e^2$ beam radius of 6 μm, the nonlinear index change in CS_2 including electrostriction is three times that with molecular reorientation alone. The measured effective critical power of 2.6 kW is in good agreement with this calculation. For similar focused spot sizes electrostriction should provide lower critical powers for longer pulses.[21]

We repeated the experiment for higher input energies to determine the dynamic range. During this experiment we used a 2-cm-thick CS_2 cell, and the linear transmittance of the PbPc solution was 50%. Figure 3 shows the output energy as a function of input energy, up to 14.5 mJ, for the second cell at two positions. The

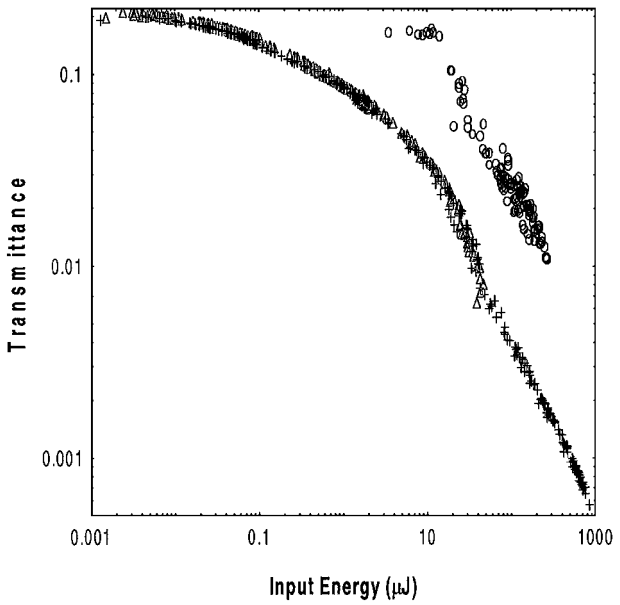

Fig. 2. Normalized encircled energy versus input energy: open triangles, CS_2 cell far from the first focus and PbPc cell at the second focus; open circles, CS_2 cell at the focus and PbPc cell far from the second focus; crosses, both cells placed at their respective foci.

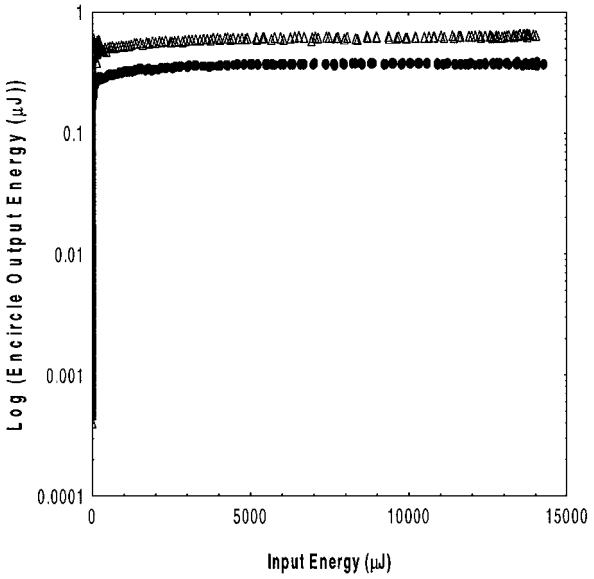

Fig. 3. Output encircled energy versus input energy for the high-dynamic-range optical limiter with an $f/5$ cascaded-focus optical geometry. Open triangles, the second cell placed exactly at the focus; filed circles, cell positioned 400 μm before the focus.

two positions of the PbPc cell correspond to the minima of Z scans[18] of this sample at low (0.073-μJ) and high (8.4-mJ) energies. These two positions correspond to the linear focus (open triangles) and 400 μm before the focus (filled circles), respectively. Whereas the behavior is very good in both cases, the output energy is clamped to a lower value when the cell is positioned before the focus.

Clamping the transmitted encircled energy below 1 μJ enables this device to provide a sufficient limiting effect to protect human eyes from catastrophic damage.[2] The corresponding measured FOM is at least 7500, because the device did not cause damage up to the maximum input energy of this system. In principle the output energy should remain clamped for considerably higher input energies.

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