Self-protecting semiconductor optical limiters

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We present a detailed characterization of passive, picosecond optical-power-limiting devices using tightly focused beams in thick semiconductor samples. This study of limiting in ZnSe with 30-psec, 532-nm pulses shows that the resulting internal self-action (two-photon absorption plus free-carrier self-defocusing) protects the bulk material from optical damage. Simple scaling relations were determined from our results that link the limiting energy and the dynamic range to the focusing geometry and sample dimensions. These relations were used to design a monolithic optical limiter, optimized to have maximum dynamic range and minimum limiting energy. This device limits at an input energy of 10 nJ (300 W) and has a dynamic range greater than 10^4.

An optical power limiter (OPL) is a device that exhibits a high linear transmittance for low incident-light irradiance (fluence) and low transmittance at high incident irradiance (fluence). Ideally, the output should reach a constant limited irradiance (fluence) that is never exceeded, regardless of how large the input may become.

Passive limiting by self-defocusing was first demonstrated in 1967.[1] However, a slow thermal effect produces this response. A much faster effect, self-focusing in liquid CS_2, was used to build an OPL.[2] Because of the self-focusing nature of that device, the limiting always occurs at a fixed power, the critical power for self-focusing,[3] regardless of focusing geometry, and this process results in optical breakdown.

More recently, limiting experiments using semiconductors have been performed.[4] The value of using semiconductors is the potential for having larger optical nonlinearities[5–7] (as much as 10^9 times that of CS_2). The dominant source of the nonlinear refraction in these experiments is the large defocusing contribution to the linear refractive index from the two-photon-absorption (2PA) generated carriers through free-carrier[8] (Drude) and interband blocking[9] (Moss–Burstein). However, a major difficulty with using semiconductor OPL's is that they incur irreversible optical damage. For example, in GaAs,[4,7] it was found that the single-shot melting threshold was less than 2 orders of magnitude above the limiting energy, the figure for multiple-shot damage being considerably lower. For this reason we have designed and fabricated a new type of semiconductor limiting device that protects itself from damage. In this Letter we describe the operation and performance of these self-protecting optical limiter (SPROL) devices using single 30-psec FWHM pulses at a wavelength of 532 nm.

The SPROL device combines the designs of the liquid self-focusing-based thick OPL with the self-defocusing-based thin semiconductor OPL. Here "thick" and "thin" refer to the relative propagation length in the sample with respect to the depth of focus of the input beam (see Fig. 1). The limiting process may be outlined as follows. As the input energy is increased, the combination of 2PA and self-defocusing cause depletion and spreading of the transmitted beam and hence a reduction of on-axis irradiance in the far field. This is the basic limiting mechanism seen in previous semiconductor limiters. However, in this device the defocusing also occurs inside the nonlinear material, thus causing the internally focused beam to expand. Provided that the fractional expansion of the focused beam area is always greater than the fractional increase in input power, the device protects itself from damage. This was verified in that only front-surface damage was observed. As the front surface may be arbitrarily distant from the focus, the damage power is limited in practice only by constraints on the size of focusing optics and on sample thickness.

The initial experiments were performed using the

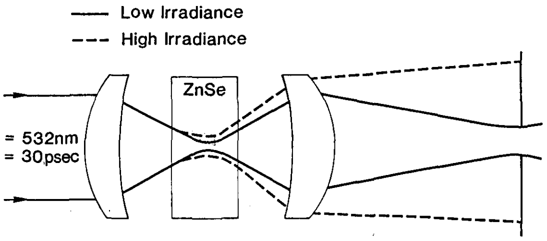

Fig. 1. Configuration for a SPROL. The 30-psec frequency-doubled Nd:YAG laser pulse is focused into the bulk of the semiconductor. The transmitted beam is then imaged onto a pinhole such that the low-energy transmittance is ~90%. To measure the total transmitted energy, rather than on-axis fluence, the pinhole and the imaging lens are removed, and the transmission detector is placed immediately behind the sample to avoid any probability of aperturing by the detector because of the self-defocusing.

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arrangement depicted in Fig. 1. The second lens was used to refocus the transmitted beam through a pinhole, such that the low-energy pinhole transmittance was approximately 90%. The energy transmitted through the pinhole was measured on a large-area Si photodiode placed immediately behind the pinhole. The input energy and pulse width were simultaneously monitored for each pulse.[10] The incident energy was continuously variable without beam distortion or deviation by using a half-wave plate and polarizer. As the laser repetition rate was 0.5 Hz, the experiments were effectively single shot. The total energy transmittance could be measured by removing the pinhole, thus showing the contribution of nonlinear absorption to the limiting. At high input levels, this was found to be less significant than the fluence limiting caused by self-defocusing. The device showed a linear transmittance for input energies much less than the limiting energy (E_L) and a constant transmitted fluence for input energies much greater than E_L. E_L is defined as the input energy at which the transmittance falls to one half of the low-energy transmittance. It should be noted that E_L was not particularly sensitive to the choice or position either of the pinhole or of the refocusing lens.

The limiting energy and the damage energy, E_D, were measured for various distances ΔZ between the sample front surface and the beam waist. This was done for two sample thicknesses L (L = 10 and 3 mm) and two focusing lenses (f = 37 and 75 mm, producing measured focused spot radii in air of 8 and 14 μm half-width $1/e^2$ maximum, respectively). Figure 2(a) shows the limiting energy as a function of ΔZ for both samples with the f = 37 mm lens. A minimum limiting energy of 14 nJ was observed for the 10-mm sample, and 32 nJ for the 3-mm sample. The limiting energies when focused on the rear surface are similar for both samples. The data for the f = 75 mm lens showed a similar response but with limiting energies between 3 and 5 times greater. For each position ΔZ, the device transmission was measured for increasing energy until the front surface was damaged.

It is useful to define the dynamic range (DR) of the limiter as the ratio of E_DE_L. Single-shot damage occurred at a wide range of fluences attributed to variations in surface quality, as the general condition of the surfaces was poor. Assuming that a well-prepared surface would give a constant damage fluence (or irradiance), we can show the variation of the DR with ΔZ by using the fact that E_D is directly proportional to the beam area on the front surface of the sample. In Fig. 2(b) we show this version of the dynamic range plotted versus ΔZ for the 10-mm-thick sample and 37-mm focal-length lens. This shows that the optimum condition for a large DR is when the focus is as far into the sample as possible (i.e., in this case on the rear face of the sample). Using a previously measured damage threshold, we estimate that with carefully prepared surfaces the maximum dynamic range would be $>10^4$. The dynamic range was also measured for the 3-mm-thick sample with the same lens and the 10-mm-thick sample with a 75-mm focal-length lens. The behavior was similar for all configurations. However, the absolute value of the DR was found to be strongly dependent on the configuration. The 3-mm sample gave a maximum DR that was a factor of 20 smaller than for the 10-mm sample with the same lens. The focal length (f/no.) used is an even more important factor in determining the DR. The maximum DR for the 10-mm sample with a 75-mm focusing lens was almost 10^2 smaller than for the 37-mm lens with the same sample.

We have empirically deduced the following approximate scaling relations, which we have used to assist us in the design of limiters with both a large dynamic range and low limiting energy. The relations have been constructed from data for which the dynamic range was largest. However, they would appear to hold for any fixed position of the beam waist. They are (1) E_L nearly independent of the sample length L; (2) $E_L \propto (f/\text{no.})^2$; (3) DR $\propto L^2/(f/\text{no.})^4$. Of course, these relations will break down unless the depth of focus is much less than the sample thickness, and there is no guarantee that they will hold if f/no. is

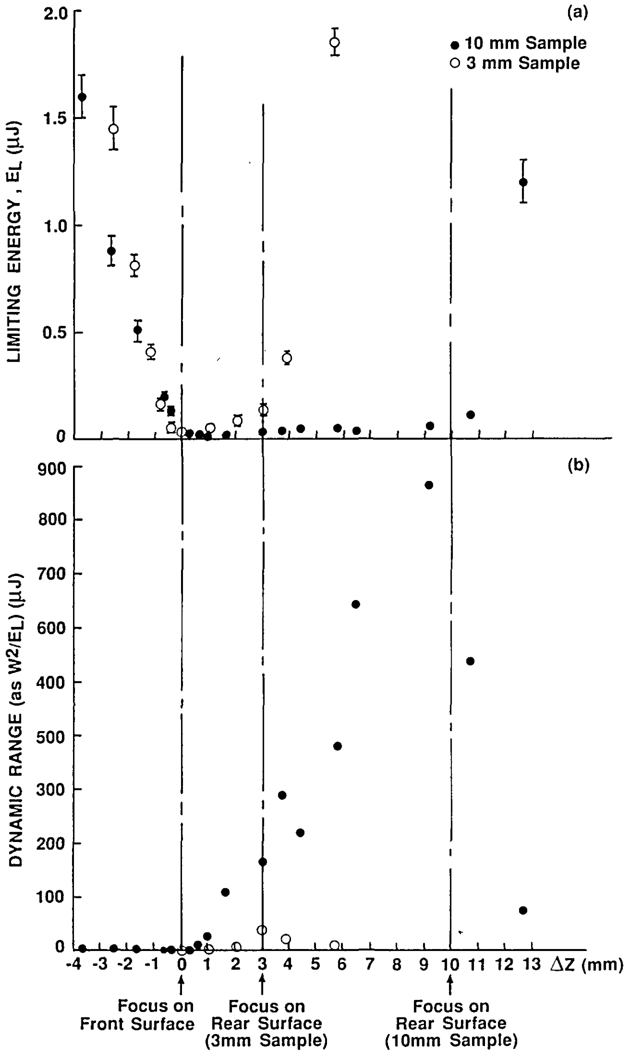

Fig. 2. (a) Plot of limiting energy versus position of beam waist relative to the front surface of the sample, ΔZ. (b) Dynamic range, plotted as W^2/E_L, where W is the spot size on the front surface of the sample. The true dynamic range (E_D/E_L) is approximately 1.3 × this number.

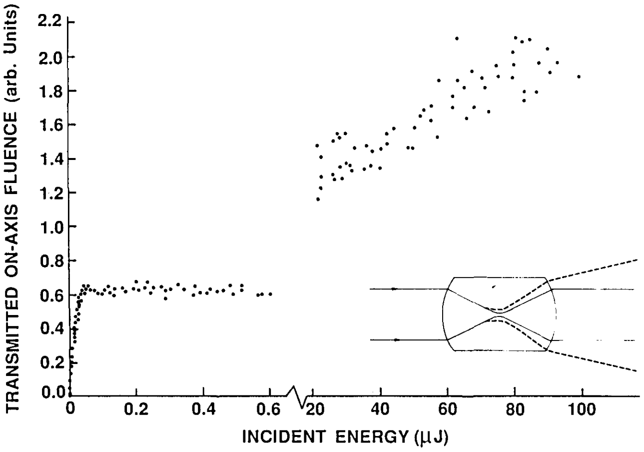

Fig. 3. Input–output characteristic for the ZnSe MONOPOL. The transmission changes by a factor of 3 between the turnover energy and the maximum tested energy. This corresponds to an average slope $dE_T/dE_{in} \simeq 3 \times 10^{-4}$. Inset: Schematic of the MONOPOL. The beam focuses in the center.

decreased or L is increased beyond the experimental values. Nevertheless, tight focusing and longer sample lengths are clearly advantageous in a low-energy, large-dynamic-range limiter.

On the basis of these results, we have designed and constructed a monolithic optical power limiter (MONOPOL). This device is fabricated from a single piece of semiconductor with spherically polished ends, so that a collimated input beam focuses inside the medium and is recollimated on leaving it for low input. In choosing this design, we have optimized the dynamic range of the device for the given *f*/no., in that the front surface is as far from the beam waist as is possible.

The MONOPOL was fabricated from chemical-vapor-deposition-grown polycrystalline ZnSe. The ZnSe device had a length of 32 mm and diameter of 12 mm. The performance was determined by placing it in the path of the beam. A further 100-mm focal-length lens was placed at the output of the limiter to focus the output onto a pinhole–detector arrangement as in the previous experiments. In this case, the low-energy (1-nJ) pinhole transmittance was ~65%. Thus we are monitoring primarily the output fluence. The resulting input–output characteristic for the ZnSe MONOPOL is shown in Fig. 3. The limiting input energy, E_L, is 10 nJ, which is within a factor of 2 of the predicted scaling.

We have calculated the DR of the ZnSe MONOPOL to be $\sim 5 \times 10^5$, using a conservative estimate for the surface-damage threshold of ~10 GW/cm^2. The device was not tested to destruction, but it was successfully tested up to input energies of 100 μJ, so that a minimum DR of $>10^4$ may be confidently stated for 30-psec pulses. From the input energy where the input–output curve first becomes horizontal, up to the maximum tested energy, the transmitted on-axis fluence changed by only a factor of 3. This corresponds to an average slope $dE_T/dE_{in} \simeq 3 \times 10^{-4}$. The maximum energy transmitted was 3 nJ, while the low-energy transmission was 10%.

To conclude, we have characterized a number of semiconductor limiting devices and have shown that, for single 30-psec pulses, the devices are self-protecting. The MONOPOL device shows a dramatic improvement over previous picosecond passive OPL's in that the limiting power has been reduced to ~300 W. Also, the problem of laser-induced damage has been virtually eliminated. As the 2PA coefficient (5.5 cm/GW in ZnSe) is essentially constant for $E_g/2 < \hbar\omega \leq E_g$,[11] the devices are broadband devices (for ZnSe the range is $\lambda \sim 500$–930 nm). Also, since the wavelength dependence of nonlinear refraction induced by 2PA, for a fixed band gap, is much less strongly varying than the band-gap-energy dependence for a fixed wavelength, we do not expect that the characteristics of a given limiter would change much over this wavelength range. It is probable that lower limiting powers (but not energies) should be observed for longer pulse widths, since the nonlinear refraction is proportional to carrier density. However, thermal self-focusing effects may be a problem. We expect that for long-wavelength–small-band-gap combinations, such as HgCdTe and CO$_2$ laser radiation, greatly reduced limiting energies will be seen. This is expected since the 2PA coefficient varies as E_g^{-3}, and for a given ratio of $\hbar\omega/E_g$ the nonlinear refraction varies as ω^{-2}.

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