Optical Limiting in GaAs

THOMAS F. BOGGESS, JR., MEMBER, IEEE, ARTHUR L. SMIRL, SENIOR MEMBER, IEEE, STEVEN C. MOSS, MEMBER, IEEE, IAN W. BOYD, AND ERIC W. VAN STRYLAND

Abstract—We have used two-photon absorption, self-defocusing, and optically-induced melting in GaAs to limit 1 μm picosecond pulsed radiation. The contribution to the limiting action from each of these mechanisms is discussed and demonstrated. Additionally, we measure a two-photon absorption coefficient of 26 cm/GW, which is in good agreement with the smallest values reported in the literature. A pulsewidth study of the nonlinear absorption was conducted to isolate the effects of two-photon-generated free-carrier absorption. Results indicate that, even though the number of free-carriers is sufficient to severely defocus the incident beam, free-carrier absorption does not measurably contribute to the nonlinear absorption.

INTRODUCTION

PASSIVE nonlinear optical power limiters (OPL) have tremendous potential as simple yet effective devices for protecting sensitive optical components from high-power laser radiation and optical transients. These devices have a high transmission for weak input beams but utilize material nonlinearities to effectively block more intense signals that may damage some critical component. Interest in these devices dates back to the late 1960's when two-photon absorption (TPA) was demonstrated as a means of optical limiting in semiconductors [1], [2]. Nonlinear refraction combined with spatial filtering has since been used to achieve OPL in thick liquid [3], [4] and gas filled cells [5]. Self-focusing in the amplifiers of large Nd:glass laser systems has been shown to result in OPL at the spatial filters [6]. Here, we have combined the effects of TPA, nonlinear refraction, and laser-induced phase transitions in GaAs to construct an effective optical limiter for 1 μm picosecond radiation. Although TPA has been previously used to demonstrate OPL in GaAs [1], [2], we show that nonlinear refraction can be used to greatly enhance the limiting capability of the device. The device is completely passive in operation and, since it is switched by electronic transitions, it has a subpicosecond turn-on time. Additionally, we find that the device continues to function even at input fluences more than a factor of 12 above the single-shot melting threshold of the GaAs.

The interest in identifying and demonstrating optical limiters for 1 μm radiation arises in part from the large number of high-power Nd:YAG and Nd:glass lasers presently in use and the necessity of being capable of protecting sensitive and often extremely expensive optical components from these intense sources. In addition, it may be possible to adapt devices that operate at 1 μm to even more interesting and useful spectral regions by a judicious choice of material. We have previously demonstrated a Si optical limiter that utilizes indirect absorption, free-carrier absorption, and nonlinear refraction to limit energetic pulses of 1 μm radiation [7]. The nonlinearities in this device are strictly fluence dependent and the device is functional for all pulsewidths shorter than the carrier relaxation time. The present device is considerably more complicated. The nonlinear absorption, which is dominated by TPA, is intensity dependent, while the nonlinear refractive index that arises from the TPA-generated free-carriers is a time integrated effect that persists for the duration of the carrier lifetime. Nevertheless, the carriers cannot be generated without a sufficiently intense pulse, which in practice restricts this device to operation with nanosecond and subnanosecond pulses. An advantage of the present device (and TPA-based optical limiters in general) over the Si device is its higher linear transmission at 1 μm. Another more important advantage of TPA-based limiters is the broader band-pass that they offer. For example, the GaAs device should function for wavelengths between approximately 0.9 and 1.7 μm where TPA is the dominant absorption process.

In order to understand the limiting action and to separate the contributions of nonlinear absorption and nonlinear refraction, we have measured the TPA coefficient β of our sample. We found this necessary because of the wide disparity in the reported values of β. An accurate knowledge of this parameter is crucial to any model of the limiting action in this device. We obtain a TPA coefficient of 26 ± 8 cm/GW, a value in excellent agreement with the smallest values reported in the literature [1], [8]–[11]. In obtaining this value, we have used a broad range of optical pulsewidths. This procedure, which has not been used in previous TPA measurements in GaAs, is necessary to ensure that two-photon-generated free-carrier absorption does not influence the extracted value of β. If free-carrier absorption (FCA) is important, it would be more evident for longer pulses than shorter pulses of equal intensity. We find that free-carrier absorption is not significant for the pulsewidths and intensities used in this study. This is an interesting result in that, even though the free-carriers do not measurably affect the absorption, they modify the refractive index sufficiently to cause severe self-defocusing and beam break-up. In fact, self-defocusing is shown to be even more important than nonlinear absorption in determining the device characteristics.

NONLINEAR OPTICAL LIMITER

The geometry used for optical limiting in GaAs is similar to that used for Si [7] and is shown in Fig. 1. A single 40 ps

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The authors are with the Center for Applied Quantum Electronics, Department of Physics, North Texas State University, Denton, TX 76203.

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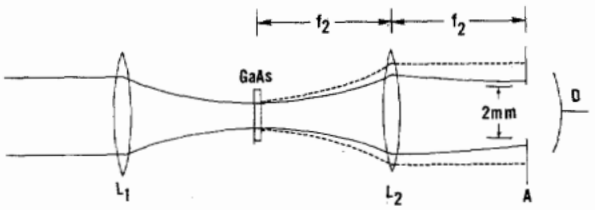

Fig. 1. Schematic of GaAs optical limiter.

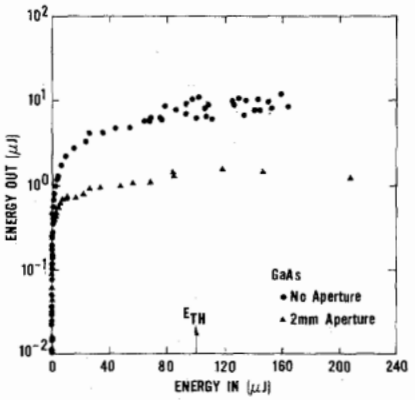

Fig. 2. Device response with (triangles) and without (circles) the 2 mm aperture in place. E_{TH} represents the single-shot melting threshold.

(FWHM) pulse from a passively mode locked Nd:YAG laser was focused to a 100 μm (FWHM) spot at the surface of the GaAs with an $f = 465$ mm "best form" lens L_1. This lens was designed for minimum spherical aberrations. The spot size at the sample was measured by pinhole scans and the spatial profile of the pulse was found to be Gaussian. The transmitted beam was collected by an $f = 381$ mm "best form" lens L_2 placed one focal length from the sample. This lens recollimated the beam, which then passed through a 2 mm diameter aperture placed one focal length beyond L_2 and directly in front of a silicon p-i-n-photodiode D. In this configuration, the detector D represents the component that we wish to protect. For low input energies, the device has little effect on the incident beam. At higher input energies, however, the nonlinearities in the GaAs reduce the overall system transmission such that the energy density incident on D is clamped at a value below the damage threshold.

The sample used in these studies was a 1.75 mm thick, optically-polished wafer of high purity, high resistivity, undoped, Czochralski grown, single crystal GaAs. The sample orientation was [1, 1, 1] and was chosen for its isotropic TPA response [12]. The sample temperature was 300 K.

The initial system transmission, i.e., the pinhole transmission and Beer's law transmission of the GaAs, was 33 percent. As the input energy was increased, the GaAs transmission was reduced by TPA, and the accompanying nonlinear refraction reduced the pinhole transmission. The result of these combined effects is illustrated by the triangles in Fig. 2, where we show the output energy of the system as a function of input energy. The initial response, though not resolved in Fig. 2, is linear with a corresponding transmission of 33 percent as mentioned above. Deviations from linearity are observed for input energies above 0.5 μJ, while above 10 μJ the output energy is essentially clamped at 1 μJ. Although not shown in Fig. 2, the device continued to limit for input energies as large as 1.2 mJ. We emphasize that this upper fluence was limited by the geometry and the maximum output energy of the laser. The device will continue to limit at still higher energies. Over the full range of operation, the system transmission is reduced from 33 to 0.1 percent. Notice that regulation continues for input energies far above the GaAs single shot melting threshold of ≈ 0.9 J/cm^2 or about 100 μJ of input energy. As we have said, nonlinear refraction is partially responsible for the limiting action observed in Fig. 2. Since the GaAs is much thinner ($l = 0.175$ cm) than a Rayleigh range (2.2 cm), the effect is similar to the "external" self-focusing described by Kaplan [13]. This is in contrast to the thick media used in the literature [3]-[5], where significant self-focusing occurs within the material.

The contribution of nonlinear refraction can be canceled by repeating the measurement with the aperture removed and by carefully collecting the transmitted light to avoid overfilling the detector D. The results are shown by the circles in Fig. 2. For input energies below that required for surface damage after 5 pulses (≈ 80 μJ), these data represent the average of 5 shots, while above this value they represent single-shot events, each incident on a new spot on the sample. This same procedure was used in obtaining the data represented by the triangles in Fig. 1. Clearly, there are two regions of interest in this measurement: 1) the region below the melting threshold E_{TH} and 2) the region above E_{TH}. Below E_{TH}, TPA dominates the nonlinear transmission which can be successfully modeled, as we show below. Above E_{TH}, the problem becomes much more complicated and is beyond the scope of this paper. In this region, the portion of the pulse that arrives after melting occurs is heavily attenuated by the molten GaAs. In addition, the reflectivity of the molten layer is quite high and provides additional loss. It is clear, however, that there is a smooth transition between the two regions, i.e., there is no discontinuity in the data at E_{TH} in either measurement.

It is interesting to compare the contributions of TPA and nonlinear refraction. The linear transmission of the GaAs was measured to be 45 percent. At an input energy of 80 μJ TPA alone has reduced the transmission by a factor of 5. On the other hand, the combined effects of TPA and nonlinear refraction have reduced the transmission by a factor of 30. The present configuration is, therefore, a considerable improvement over GaAs limiters that utilize TPA exclusively [1], [2].

We emphasize that we have made no attempt here to optimize the device geometry for a particular application. The specific parameters of the device are not unique but are in fact strongly geometry dependent, i.e., the f-number of the focusing lens, the aperture size, etc., determine the device characteristics. Since both the TPA and nonlinear refraction are clearly dependent upon the input irradiance, the linear response region can be adjusted by varying the f-number of the focusing lens (i.e., the spot size at the sample) and/or the pulsewidth. The regulated output energy can be reduced with optical filters, by decreasing the aperture size, or by decreasing the f-number of L_1. In the present device we have an f-number of ~ 230. Clearly, to minimize the transmission of the system we would need as small an f-number as possible. The output energy can

be substantially increased by using much more energetic pulses and a larger spot size at the sample. As with Si [7] and HgCdTe [14], there is a strong dependence of the nonlinear refraction on the position of the GaAs with respect to the focus of L_1. This results in considerably more defocusing for a given irradiance when the sample is slightly beyond focus, a behavior that can be qualitatively understood by considering the GaAs as a thin negative lens. In addition, for this geometry, the incident spot size is increased and the fluence, for a given input energy, is decreased. Under these conditions it may be possible to achieve limiting at a lower input energy and single shot damage at a higher input energy.

The application of this OPL as a protective device for sensitive components such as detectors is apparent, but a number of other applications may be found. Examination of Fig. 2 shows that this OPL is essentially the optical equivalent of a Zener diode and could be used as such in an optical circuit. That is, this device can be used to smooth intense optical transients. Additionally, if the device is operated at input energies where the output is regulated, it can be used to stabilize the output of a high-power Nd:YAG or Nd:glass laser. Since the spatial (and most likely the temporal) profile of the output pulse is significantly distorted, one might replace the pinhole with a beam homogenizer [15] of similar aperture. This would produce a uniform and well regulated output fluence and could find applications in materials processing [16]. We recognize, of course, that in the present configuration the 1 μJ output would limit the application to fine-scale rather than large area processing. Nevertheless, as we have mentioned, the output energy can be increased by adjusting the geometry of the device. We emphasize that optical limiting by TPA and nonlinear refraction due to TPA-generated free-carriers is not restricted to 1 μm radiation in GaAs. The technique we have used here represents proof of principle and can be extended to cover a broad range of wavelengths simply by choosing alternative semiconductors. In fact, semiconductors such as CdS and ZnS, which are three- and four-photon absorbers respectively at 1 μm (i.e., transparent in the visible) might be ideal candidates for optical-limiters in the visible region of the spectrum. These semiconductors, used with an $f/1$ focusing geometry could be used to protect against retinal damage in visually-oriented optical systems. Alternatively, narrow-band-gap semiconductors such as InSb and HgCdTe are excellent candidates for optical limiting of infrared radiation.

Two-Photon Absorption

Although TPA in GaAs has been extensively studied [1], [2], [8]-[12], [17]-[19], it is well known that large discrepancies exist in the experimentally determined values of β reported in the literature. These values range from a low [9] of 20 to a high [18] of 5600 cm/GW (for a table of reported values see [9]). There are several possible explanations for this disparity. Sample preparation can have an effect on the measured value of β through deep-impurity-level resonant enhancement of the two-photon transitions. We reemphasize that the GaAs used for the present study was high-purity undoped material. Also, since an accurate knowledge of the pulse irradiance is required, one must use an extremely well calibrated laser to obtain an accurate value for β. The irradiance for both temporally and spatially Gaussian pulses is given by

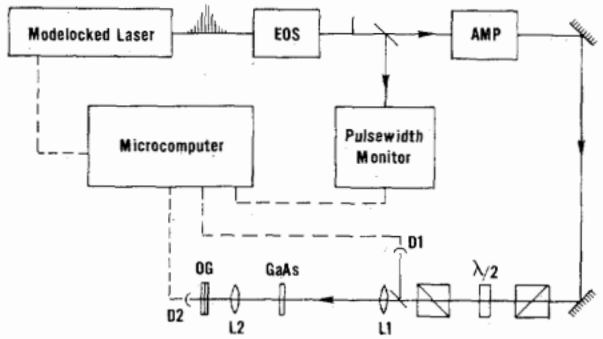

Fig. 3. General experimental configuration used for the TPA measurements. EOS is an electrooptic shutter, AMP is a single stage amplifier, $D1$ and $D2$ are Si p-i-n photodiodes, and OG is a double stack of flashed opal glass.

$$I = E/\pi^{3/2}\,\tau w^2 \tag{1}$$

where E is the total pulse energy, τ is the temporal width, and w is the spatial width (both half width at $1/e$ of maximum intensity). It is clear that this quantity depends upon three experimentally determined parameters that in general vary for each laser pulse. Additionally, even when nonlinear refraction is unimportant *within* the material [9], one must ensure that "external" self-action [13] does not result in overfilling the transmission detector—an occurrence that would result in an overestimate of β. An overestimate can also arise from free-carrier absorption (FCA) [20]. It is not surprising that most of the larger values of β reported in the literature were measured with nanosecond pulses, where the effects of FCA and nonlinear refraction are much more evident than for picosecond pulses of equal irradiance. For this reason, mode-locked lasers are preferred over Q-switched lasers for these studies [9]. Even for picosecond pulses, however, one must determine that FCA does not effect the measurement of β. This can be accomplished by measuring the nonlinear absorption with pulses of various temporal duration as we describe below.

The measurements reported here were conducted with three separate, well-characterized, picosecond laser systems: 1) an actively/passively mode-locked Nd:YAG laser that provided pulses of 45, 90, and 108 ps (FWHM) at 1.064 μm, 2) a passively mode-locked Nd:YAG laser that produced pulses of duration 40 and 150 ps at 1.064 μm, and 3) a passively mode-locked Nd:glass laser that provided 7 ps pulses at 1.054 μm. The Nd:YAG laser pulses were varied in width by selecting etalon output couplers of differing thicknesses. All three lasers operated in the TEM_{00} transverse mode. The general experimental configuration is shown in Fig. 3. A single pulse was selected from the mode-locked train by a photodiode-triggered electrooptic shutter. A portion of this pulse was delivered to a calibrated pulsewidth monitor similar to that used in [9]. This allowed us to determine the temporal pulsewidth on a shot-to-shot basis. The pulsewidth monitor, along with all other detectors and the laser, was interfaced with a microcomputer for data acquisition and manipulation. The microcomputer was programmed to accept only shots that fell within 20 percent

of a preselected pulsewidth, thereby preventing spurious shots from affecting the average irradiance and transmission within a given group. The main pulse then passed through a single stage amplifier operating in the linear gain regime. The lack of both saturation and self-focusing effects in the amplifier was verified by spatial beam profile scans taken before and after the amplifier. The pulse then passed through a half-wave plate placed between a pair of crossed polarizers, which acted as a continuously variable attenuator. Both reflecting and absorbing neutral density filters were found to spatially distort the beam and were not used as attenuators in the incident beam. After passing thorugh the attenuator, a portion of the pulse was directed to a silicon p-i-n photodiode that was calibrated absolutely against a pyroelectric joulemeter. This gave an accurate measure of the pulse energy for each shot. The main pulse was then focused onto the sample by a "best form" lens, designed for minimum spherical aberrations. The focused spot was scanned in both the vertical and horizontal dimensions with a small diameter pinhole placed in the plane of the sample. This method was used to determine the focused spot size and to ensure that the beam profile was Gaussian. The uniformity of the focused spot was checked by melting the surface of a highly polished wafer of single crystal silicon and then examining the recrystallized spot with a Normarski microscope. In addition, numerous vidicon scans of the unfocused beam showed that there was no significant shot-to-shot variation in the spatial profile. Considerable effort was made to avoid overfilling the transmission detector (also a silicon p-i-n photodiode) when the transmitted beam spread from nonlinear refraction. This was accomplished by focusing the transmitted beam, after suitable filtration, with a large-aperture, short-focal-length lens onto a double stack of flashed opal glass placed directly in front of the detector. This geometry provided a detector response that was independently verified to be linear and insensitive to spot size fluctuations. All detectors were both optically and electrically shielded, and suitable narrow band pass filters were used to avoid the detection of undesirable signals (luminescence, flashlamp, etc.). The transmission was measured by comparing the incident and transmitted energies, taking into account the relative responses of the two detectors. For each group of shots, the irradiance was calculated by using the average incident energy, the average pulsewidth, and the known spot size.

The data for one TPA measurement are shown in Fig. 4, where we show the inverse transmission as a function of incident irradiance for the 45 ps pulses from the actively/passively modelocked Nd:YAG laser. Each data point represents the average of five shots. Similar data were obtained for the other five pulsewidths.

The data were analyzed by obtaining a best fit for the numerical solution of the coupled differential equations

$$\frac{dI(r,z,t)}{dz} = -\left[\alpha + \beta I(r,z,t) + \sigma N(r,z,t)\right] I(r,z,t) \qquad (2)$$

and

$$\frac{dN(r,z,t)}{dt} = \frac{\alpha I(r,z,t)}{\hbar\omega} + \frac{\beta I^2(r,z,t)}{2\hbar\omega} \qquad (3)$$

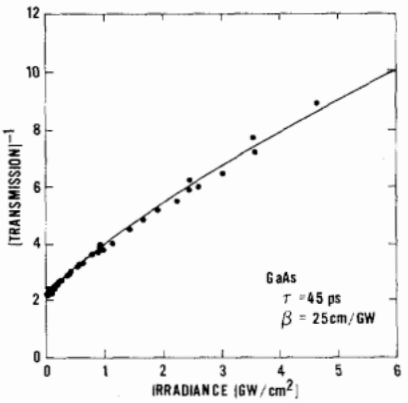

Fig. 4. TPA data (circles) for the 45 ps (FWHM) pulses and theoretical fit (solid line) obtained with the parameters mentioned in the text.

where α is the linear absorption coefficient, σ is the free-carrier-cross section, N is the carrier density, ω the optical circular frequency, and I is the irradiance inside the material at longitudinal position z and radial position r.

In order to solve (2) and (3) we must choose a value for α, σ, and of course, β. Knowing the thickness of the sample and the reflectivity, the value of $\alpha = 0.55$ cm^{-1} was easily obtained from the low irradiance data. The choice of σ is somewhat more complicated since the reported values at 1.06 μm vary [17], [21] from 2×10^{-18} cm^2 to 3×10^{-17} cm^2. This uncertainty hinders the accurate determination of β from a measurement with a single pulsewidth. To circumvent this problem, we used the following iterative procedure [20]. Since FCA is least important for the shortest pulsewidth and low irradiance, we fit the low irradiance 7 ps data with σ set to zero to obtain an initial guess for β. Using this β, we then chose a value for σ that provided the best fit to the data sets. With σ fixed at this value of 3×10^{-18} cm^2, we then varied β to refine the fit to the data. We emphasize that the effects of FCA were weak for the pulsewidths and irradiance levels used in these studies, and consequently, we do not claim to have extracted an accurate value for σ. Still, the value obatined is reasonable and is easily within the range of cross sections reported in the literature.

The solid curve in Fig. 4 is a numerical fit to the data with $\alpha = 0.55$ cm^{-1}, $\sigma = 3 \times 10^{-18}$ cm^2, and $\beta = 25$ cm/GW. Similar curves were generated for the other sets of data using β as the only free parameter. The extracted values of β range from a high of 36 cm/GW to a low of 19 cm/GW with an average value for the six different pulsewidths of 26 cm/GW. There was no apparent systematic trend in the discrepancies in the data that might indicate that the deviations arose from an incorrect free-carrier cross section. The deviations appear to reflect day-to-day variations in calibrating the pulse energy, temporal width, and spatial extent. We conservatively estimate our knowledge of these three parameters and the absolute transmission all to within 10 percent. This gives a root mean square of the absolute error of 22 percent which together with the relative error associated with the six measurements gives a total root mean square error of 32 percent or a TPA coefficient of $\beta = 26 \pm 8$ cm/GW. This value is in excellent agreement with the smallest experimentally determined values of β reported in the literature

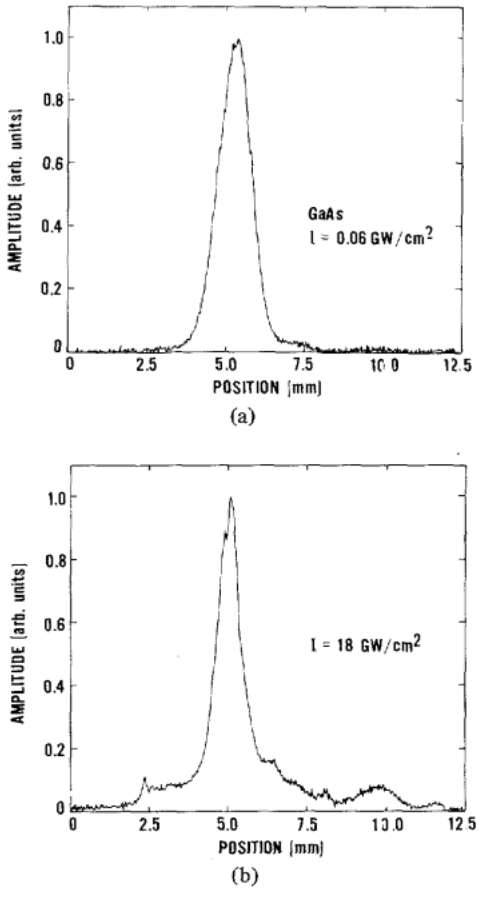

Fig. 5. Spatial beam profiles taken in the plane of the aperture for (a) low and (b) high irradiance.

[1], [8]-[11], and is in reasonable agreement with several existing theoretical models [22]-[24]. Again, the choice of σ used in our analysis did not *strongly* influence the extracted value of β. Any σ within the range mentioned above would still give a β much smaller than those in the literature [2], [12], [17]-[19].

Nonlinear Refraction

In a semiconductor, a number of nonlinearities can lead to nonlinear refraction [25]. For photon energies much less than the band gap, one expects the nonlinear refraction to arise from nonresonant nonlinearities, i.e., those involving virtual transitions. Such nonlinearities result from the anharmonic response of bound electrons and, for heavily doped semiconductors, the nonlinear motion of free carriers caused by energy band nonparabolicity. For above bandgap excitation, the optically generated electron-hole plasma can result in strong nonlinear refraction. This Drude plasma provides a negative contribution to the refractive index and leads to self-defocusing. Self-defocusing has been observed in a variety of semiconductors and has been used to demonstrate optical limiting [7] and weak-wave retardation [26] in Si and to measure n_2 in HgCdTe [14] and InSb [27]. The significant TPA observed in GaAs indicates that a large number of carriers is photogenerated which should result in substantial self-defocusing. We have verified that the sign of this self-refraction is negative by the characteristic *near-field* beam deformation [27] observed in vidicon scans taken directly behind the sample.

The contribution to the limiting action is apparent from vidicon scans taken in the plane of the aperture. The limiter geometry ensured that the measured spatial profiles in this plane were *far-field* diffraction patterns. Both two- and one-dimensional scans were made of the beam at this position. Typical 1-D scans are shown in Fig. 5 for (a) low input ($I = 0.06$ GW/cm^2) and (b) high input ($I = 18$ GW/cm^2) irradiances. The high-frequency modulation in Fig. 5(a) is due to interference fringes caused by neutral density filters that were used as attenuators in front of the vidicon; this modulation was not present on the incident beam. Fig. 5(a) is essentially identical to the input beam. At the higher irradiance, however, the transmitted beam is highly distorted with a large amount of energy redistributed into the wings. This "beam breakup" is a result of both whole beam self-defocusing resulting from the Gaussian spatial beam profile and small scale self-defocusing that arises from small imperfections in both the sample and the incident beam [6]. The results are important in that they demonstrate the sensitivity of these defocusing measurements to the number of carriers present. Clearly, even though the number of free carriers is not sufficient to significantly alter the transmission of the GaAs, the two-photon-generated free-carriers are easily detected by the beam distortion measurements. We point out that the irradiance level of the pulse used for Fig. 5(b) is near the melting threshold of the GaAs. Severe broadening of the beam was noticed, however, for input irradiance levels far below this value.

It is clear from these measurements that caution must be exercised in designing the collection optics for nonlinear transmission measurements. Materials with significant nonlinear absorption frequently exhibit substantial nonlinear refraction. Fig. 5 illustrates how this nonlinear refraction, coupled with, e.g., a small area transmission detector, could lead to a drastic overestimation of the nonlinear absorption.

Optically-Induced Phase Transitions

As we have mentioned, the GaAs OPL continues to clamp the output energy at approximately 1 μJ even for input energies a factor of 12 above the GaAs melting threshold. This is clearly an attractive characteristic of this device, since it allows the protection of down-line components from extremely intense optical pulses. In addition, we have found that multiple exposure at this high input level does not reduce the limiting capability of the device, although the linear response is somewhat degraded by the irreversible surface damage. The latter result is an unfortunate disadvantage of the present device if used in an imaging system. Nevertheless, this problem could be overcome by simply repositioning the sample after each exposure at fluences above threshold. This might be done in real-time by monitoring the surface reflectivity with a CW HeNe beam. When melting occurs, the surface reflectivity increases dramatically. A stepping motor could be programmed to move the GaAs when this increased reflectivity is detected, so that virgin material is once again exposed. Moreover, depending on the field of view of the optical system, a small damage spot on

the GaAs could appear as nothing more than an annoying blemish without affecting the overall system performance. Even though the device can be operated at fluences above the GaAs melting threshold, it is important to notice that the limiting action begins well below threshold. In the present configuration, the device can be operated in the clamped mode and below threshold for a range of input energies that varies by more than an order of magnitude.

We have previously briefly reported the details of the GaAs melting threshold and surface morphology [28]. We observe features similar to those observed in Si such as surface ripples, rings of material of alternating composition, and evaporation of material. Clearly, the crystalline-to-molten phase transition has a dramatic effect on the optical properties of the GaAs. The molten region assumes metallic properties resulting in a greatly enhanced absorption coefficient and reflectivity. It may seem surprising then that we observe no discontinuity in either the transmission or the limiter response as the input fluence is increased beyond the melting threshold. One must remember, however, that, at threshold, melting occurs only at the temporally trailing edge and only near the center of the spatial profile of the Gaussian pulse. As the fluence increases, the portion of the pulse (both temporally and spatially) that is blocked by the molten layer is increased. This process occurs in a smooth and continuous manner—the GaAs does not suddenly become completely opaque at E_{TH}.

Conclusions

We have described and demonstrated an effective GaAs nonlinear optical limiter for 1 μm radiation. The below bandgap excitation provides a high transmission for low input energies, but TPA, nonlinear refraction, and (above threshold) laser-induced melting of the GaAs surface clamp the device output for high input energies. The limiting action of this passive device has a subpicosecond initiation time, since it results from electronic transitions, and the recovery time is predominantly determined by the carrier lifetime. These measurements represent proof of principle, i.e., the technique can be extended to other semiconductors for operation of a host of devices at a broad range of wavelengths. We also determined the TPA coefficient using six separate measurements with pulsewidths ranging from 7-150 ps. This pulsewidth study of the TPA coefficient clearly demonstrates that for the pulsewidths used and the irradiance levels obtained ($I < 6$ GW/cm^2), free-carrier absorption is negligible. Nevertheless, we find that a sufficient number of free-carriers is generated to cause severe defocusing of the incident beam. Considering the wide disparity in the reported values of β for GaAs, our value of 26 ± 8 cm/Gw is an important corroboration of the smallest reported values [1], [8]-[11].

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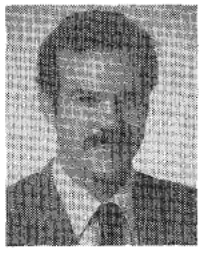


Thomas F. Boggess, Jr. (S'81–M'82) was born in Corpus Christi, TX, on March 10, 1955. He received the B.S. degree in physics from Lamar University, Beaumont, TX, in 1978, and the M.S. and Ph.D. degrees in physics from North Texas State University, Denton, in 1980 and 1982, respectively.

In 1982 he joined the Center for Applied Quantum Electronics, North Texas State University, where he was a Robert A. Welch Foundation Postdoctoral Fellow. He is currently a Research Scientist at the same institution. His current research interests include nonlinear optical properties of semiconductors, picosecond spectroscopy, and high density and ultrafast carrier dynamics.

Dr. Boggess is a member of the American Physical Society and the Optical Society of America.

Arthur L. Smirl (S'65–S'73–M'75–SM'84) was born in Borger, TX, in 1944. He received the B.S. degree in mathematics and electrical engineering from Lamar University, Beaumont, TX, in 1968, the M.S.E. degree in electrical engineering from the University of Michigan, Ann Arbor, in 1969, and the M.S. and Ph.D. degrees in optical sciences from the Optical Sciences Center, the University of Arizona, Tucson, in 1975.

He was a Staff Scientist for Sandia Corporation, Albuquerque, NM, from 1968 to 1971. He is currently Associate Professor of Physics and a member of the Center for Applied Quantum Electronics, North Texas State University, Denton.

Dr. Smirl is a member of the Optical Society of America and the American Physical Society.

Steven C. Moss (M'84) was born in Ann Arbor, MI, on March 19, 1948. He received the B.S. degree in physics from Arkansas A & M College, Monticello, AR, in 1970, the M.S. degree in physics from Purdue University, West Lafayette, IN, in 1972, and the Ph.D. degree in physics from North Texas State University, Denton, TX, in 1981.

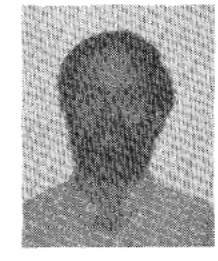
During the period 1981–1982 he held a National Research Council Postdoctoral Research Associateship at the U.S. Naval Research Laboratory in Washington, D.C. From 1982 to 1984 he was a Research Associate at the Center for Applied Quantum Electronics and Department of Physics, North Texas State University, Denton. In 1984 he joined the Aerospace Corporation in Los Angeles, CA, where he is a member of the technical staff. His research interests include ultrafast phenomena, nonlinear optics, and ultrashort pulse generation.

Dr. Moss is a member of the IEEE Lasers and Electro-Optics Society, the Optical Society of America, the American Physical Society, and the Materials Research Society.

Ian W. Boyd was born in Peebles, Scotland, on October 24, 1958. He received the B.Sc. degree in applied physics with solid-state electronics in 1979, and the Ph.D. degree in physics in 1982, from Heriot-Watt University, Edinburgh, Scotland. His thesis work was on CW laser oxidation of silicon, and the growth and structural properties of thin silicon oxides.

From 1982 to 1984, as a research scientist at North Texas State University, Denton, he carried out research into the fundamentals and applications of the interaction of picosecond radiation with semiconductors. He is presently a faculty member of the Electrical Engineering Department of University College London, where he is continuing research into laser processing, laser-induced damage, and fast nonlinear optical processes in materials.

Dr. Boyd is a member of the American Physical Society, the Materials Research Society, and the British Institute of Physics.



Eric W. Van Stryland was born June 3, 1947. He received the Ph.D. degree in physics in 1976, from the University of Arizona, Tucson, AZ, where he worked at the Optical Sciences Center on optical coherent transients.

He worked in the areas of femtosecond pulse production, multiphoton absorption in solids, and laser-induced damage at the Center for Laser Studies at the University of Southern California, Los Angeles, CA. He joined the physics department at North Texas State University in 1978 pursuing similar studies and is currently an Associate Professor with the Department of Physics at the newly formed Center for Applied Quantum Electronics.