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The wavelength dependence of the nonlinear refractive index and two-photon absorption coefficient near half the band gap was measured in an AlGaAs waveguide. The two photon figure of merit for efficient nonlinear optics in AlGaAs is shown to be quite favorable for photon energies less than one half the band gap.

Since its inception in the 1960's, a major activity of nonlinear optics has been the search for third-order nonlinear materials which can be used for applications. Experience has shown that absorption, both linear and nonlinear, is usually a limiting factor to obtaining ultrafast, efficient, nonlinear interactions. Although the nonlinearity in glass is very small, fibers have been a wonderful testbed for nonlinear interactions solely because the linear and nonlinear losses are negligible beyond 1 μm, as quantified by the figures of merit (FOM) W and T.[1] Put simply, these FOMs quantify the nonlinear phase shift achievable over one linear (W) or one nonlinear (T) absorption length.[2] Recently, it has been shown that the ultrafast optical nonlinearities in AlGaAs waveguides for photon energies below one half the band gap ($E_{gap}/2$) are ultrafast, orders of magnitude larger than in glass, and have attractive FOM. In fact, applications to efficient, ultrafast all-optical switching have already been demonstrated.[3–5] Therefore AlGaAs used at photon energies below $E_{gap}/2$ is very promising for a wide variety of nonlinear optical interactions in a wavelength range which overlaps the important communications band at 1.55 μm.

The key to optimizing the operating conditions for nonlinear optics in AlGaAs involves the tradeoff between the two photon absorption coefficient β_2 and the nonlinear index coefficient n_2. This is quantified by $T=2\beta_2\lambda/n_2$ which should be as small as possible, certainly less than one for all-optical switching.[2] Although a number of measurements have been reported in MQW samples (for which T is not as promising as for bulk AlGaAs),[6–8] only a few measurements of n_2 and β_2 available in bulk AlGaAs at the wavelengths 1.55 and 1.68 μm, both on different samples.[5,6] The 1.55 μm values were deduced from the operating characteristics of a nonlinear directional coupler, assumed to have an ideal response.[5] On the theoretical side, using the two parabolic band approximation essentially at 0 K, the variation of β_2 with photon energy has been calculated, and from it n_2 via the Kramers–Kronig relations.[9] These calculations predict that β_2 vanishes at $E_{gap}/2$ and do not include a two photon tail for smaller photon energies, similar to the Urbach tail observed in linear absorption just below the band gap.[10] Therefore the only way to evaluate T below $E_{gap}/2$ in bulk AlGaAs is to measure the β_2 and n_2 coefficients.

In this letter, we report the first measurements of β_2 and n_2 over the wavelength range from 1490 to 1660 nm in a MBE-grown, AlGaAs channel waveguide. The strip-loaded channel waveguides used were 2 cm long and consisted of a 1.5 μm $Al_{0.18}Ga_{0.82}As$ guiding layer sandwiched by a 5 μm $Al_{0.25}Ga_{0.75}As$ bottom cladding layer and a 1.5 μm top cladding layer of the same composition. The top cladding layer was chemically etched to form loading ridges, 6 μm wide. Almost transform-limited pulses with widths ranging from 4 to 6 ps from a color center laser were end-coupled into the waveguide. The inverse transmission and the output spectrum were recorded as functions of intensity. By measuring the pulse spectrum broadened by self-phase modulation, the n_2 values could be obtained. Since the observed self-phase modulation has a response time shorter than the pulse width, the origin of the nonlinearity should be the ultrafast electronic nonlinearity, excluding any slow thermal effects.

The β_2 values were deduced by simulating the inverse transmission and fitting it to the data. The equation for the optical intensity $I(z,t)$

$$\frac{\partial I(z,t)}{\partial z}=-\alpha I(z,t)-a_2\beta_2 I^2(z,t) \tag{1}$$

was solved numerically. Here, t is the time, z is the distance from the input facet, α is the linear loss coefficient, and a_2 is the modal structure factor of the waveguide. It was assumed that the modal profile was approximately Gaussian in both transverse waveguide dimensions and hence a_2 was approximated by 0.5. The n_2 values were determined by fitting the data to simulations obtained from solutions to the equation

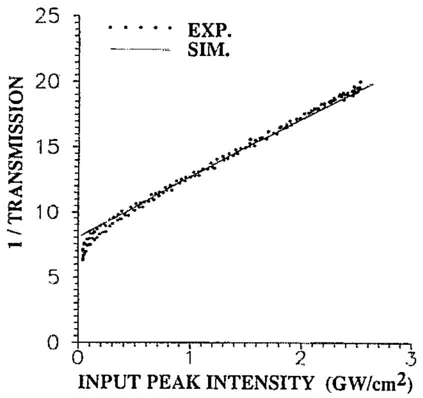

FIG. 1. A typical fit to the measured inverse transmission used to determine β_2.

$$\frac{\partial A(z,t)}{\partial z}=\frac{i2\pi a_2 n_2}{\lambda}|A|^2A-\frac{\alpha}{2}A-\frac{a_2\beta_2}{2}|A|^2A. \qquad (2)$$

Here, $A(z,t)$ is the slowly varying complex amplitude of the optical pulse in the waveguide and λ is the wavelength in vacuum.

Two typical fits for β_2 and n_2, respectively, are shown in Figs. 1 and 2. In Fig. 1, the theoretical result (continuous curve) fits the experimental data very well. In Fig. 2, a typical fit between the simulated (dashed curve) and experimental spectra (continuous curve) is shown. The asymmetric nature of the spectrum is attributed to the slight asymmetry of the input pulse and appropriately asymmetric sech^2-like pulses were used for the simulation inputs. The observed three-peak spectrum, obtained with an input peak power of 430 W at 1550 nm, means that the nonlinear phase shift at the pulse's peak is $\simeq 2.5\pi$.[1]

The wavelength dependencies of the measured β_2 and n_2 are shown by the vertical bars in Figs. 3 and 4, respectively. The large error bars are attributed to the uncertainty in the linear loss in the waveguide. The error bars were basically determined by assuming that the input coupling efficiency was between 30% and 60%, typical for the strip-loaded waveguide used.[5] Based upon this assumption, the linear loss was estimated to lie between 0.2 and 0.5 cm^{-1} over the whole wavelength range of the measurements. In Figs. 3 and 4, the theoretical β_2 and n_2 values, respectively, are based on a simple two-parabolic-band structure and are plotted as continuous curves.[9] Figure 3 shows that the measured β_2 values are larger than the theoretical predictions. The difference can be attributed to: (i) exciton effects were not taken into account in the theoretical model. They will enhance the continuous transitions and extend the absorption edge.[11] (ii) The hole band degeneracy was not considered in the cited theory. The inclusion of the hole band degeneracy will also enhance the two-photon absorption predictions.[11] (iii) Other absorption mechanisms such as three-photon absorption[5,12] and free-carrier absorption[13] may mix with two-photon absorption and make the calibrated β_2 values larger. This is particularly relevant for the wavelengths beyond half the band gap.

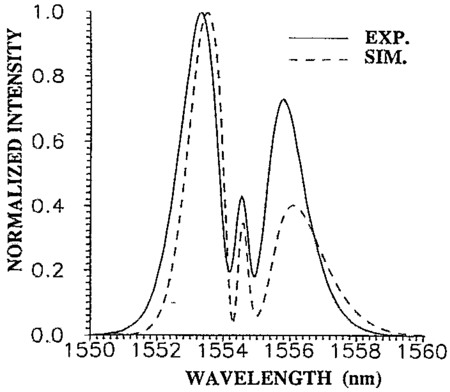

FIG. 2. A typical fit to the normalized frequency spectrum used to determine n_2.

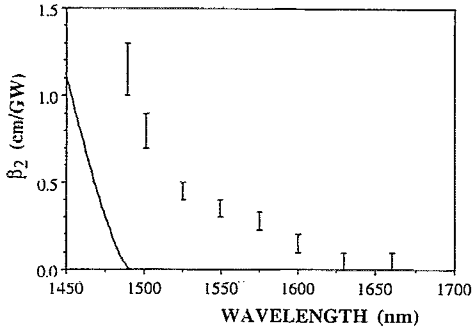

FIG. 3. Wavelength dependence of β_2. The vertical bars represent the experimental data and the continuous curve stands for the theoretical prediction based upon a simple two-parabolic-band structure.

As shown in Fig. 4, the measured n_2 values are of the order of 10^{-13} cm^2/W in the wavelength range investigated. There is a maximum near 1500 nm. The theoretical predictions are in good agreement with the measured values at long wavelengths but are underestimated at short wavelengths. This difference is probably due to the neglect of exciton effects and hole band degeneracy, as explained in the last paragraph. Our measured n_2 values are consistent with other single-frequency measurements and estimates in literature.[5,6]

The wavelength dependence of the estimated figure of merit T is plotted in Fig. 5. The T values were obtained by using the β_2 and n_2 values at the centers of error bars. T decreases with increasing wavelength, implying that the

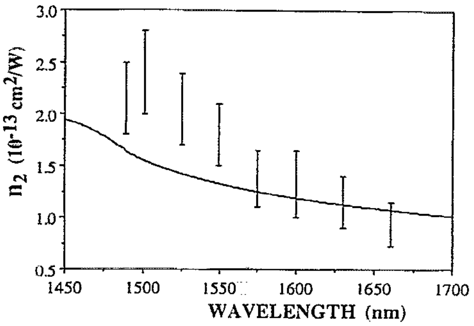

FIG. 4. Same as Fig. 3 except for the nonlinear effective-index n_2.

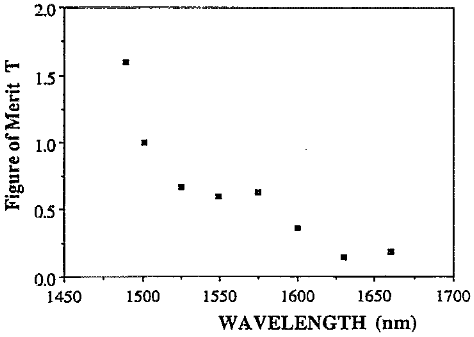

FIG. 5. Wavelength dependence of the estimated figure of merit, *T*, based on the data in Figs. 3 and 4.

efficiency of nonlinear optical interactions also increases for wavelengths below half the band gap. However, for photon energies sufficiently far below half the band gap, the dominating absorption mechanism becomes the three-photon absorption and another figure of merit related to the three-photon absorption also needs to be considered.[12] At 1630 nm, *T* is about 0.14. Note that at a similar wavelength this value is lower than the *T* in both TE and TM modes of a multiple quantum well channel waveguide (of different compositions).[8]

In conclusion, we have reported the measurements of the nonlinear refractive-index and two-photon absorption coefficient from 1490 to 1660 nm in an AlGaAs channel waveguide. The two photon figure of merit deduced shows exceptional promise for efficient nonlinear optical interactions. The measured values are consistent with previous reported data.

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