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It is demonstrated that the frequency spectrum of femtosecond pulses becomes highly asymmetric when propagating as transverse magnetic modes in semiconductor multiple quantum well channel waveguides at photon energies near half the band gap. Calculations based on the frequency dispersion in two-photon transitions provide results consistent with the experiment.

Optical nonlinearities near half the band gap ($E_g/2$) in semiconductors such as bulk AlGaAs and multiple quantum well (MQW) GaAs/AlGaAs have proven useful for efficient, femtosecond all-optical switching.[1,2] Near $E_g/2$, the two-photon absorption coefficient β_2 decreases towards zero and there is a maximum in the nonlinear refractive-index coefficient n_2 of the order of 10^{-13} cm^2/W.[3–8] The multi-π nonlinear phase shifts needed for switching require GW/cm^2 waveguide intensities.[1,2,4] Thus, self-phase modulation (via n_2) and to a lesser degree two-photon absorption (via β_2) are important nonlinear effects which also occur in the waveguides. Near two-photon transitions both n_2 and β_2 are strongly frequency dispersive, especially when coupling to the excitons which occur in MQW structures.[8,9] When femtosecond pulses centered near the two-photon transitions are used, different frequency components within the pulse can experience different nonlinear effects, potentially leading to pulse distortion, etc. A similar pulse breakup effect has just been reported in GaAs just below the band gap.[10]

In this letter we report experimental and theoretical results on femtosecond pulse transmission through MBE-grown bulk AlGaAs and MQW GaAs/AlGaAs channel waveguides near half the band gaps. Previous measurements of n_2 and β_2 around 1550 nm showed much larger frequency dispersion in the MQW than the bulk sample.[7,8] By comparing the transmitted frequency spectra from the two samples, the effects of dispersion in the nonlinearity on the frequency spectrum can be studied.

The MQW sample consisted of 85 periods of 70 Å GaAs wells and 100 Å $Al_{0.32}Ga_{0.68}As$ barriers, sandwiched by $Al_{0.27}Ga_{0.73}As$ cladding layers. The upper cladding layer was chemically etched to form 5.5 μm wide strip-loaded channels, 1.5 cm long. The bulk AlGaAs channel waveguides were 2.0 cm long, 6 μm wide and consisted of a $Al_{0.18}Ga_{0.82}As$ guiding film sandwiched by $Al_{0.25}Ga_{0.75}As$ cladding layers. From other measurements, we estimated the linear loss coefficient of the MQW and bulk AlGaAs waveguides to be 0.64 and 0.3 cm^{-1}, respectively.[7,8] Therefore, although the bulk AlGaAs waveguide is longer, its linear loss is smaller. 400 fs pulses from an additively pulse-mode-locked (APM) color center laser were end-fire coupled into the waveguides with typically 50% coupling efficiencies. The output spectra were monitored with a spectrum analyzer.

Figures 1 and 2 show the output frequency spectra near 1550 nm propagated in the transverse magnetic (TM) mode of the MQW and bulk AlGaAs waveguides, respectively, with input peak intensities of about 13 GW/cm^2. In both spectra there is a sharp spurious component centered near 1545 nm which corresponds to the residual mode-locked color center pulse energy ($\simeq$ps wide) which was not narrowed by the APM process. Note the APM-induced shift of the central wavelength from 1545 nm to about 1550 nm.

A comparison between Figs. 1 and 2 indicates that the output spectral asymmetry of the MQW TM mode is larger than that of the bulk AlGaAs sample. When the nonlinearities at the central pulse wavelength are assumed, the bulk AlGaAs TM mode is expected to have the larger

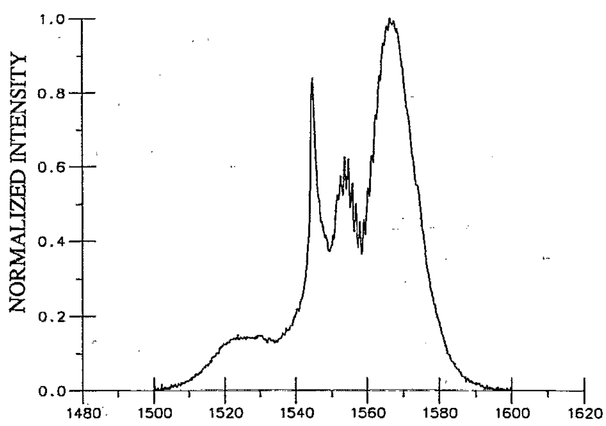

FIG. 1. Experimental output frequency spectrum of a 400 fs pulse in the TM mode of a MQW GaAs/AlGaAs channel waveguide.

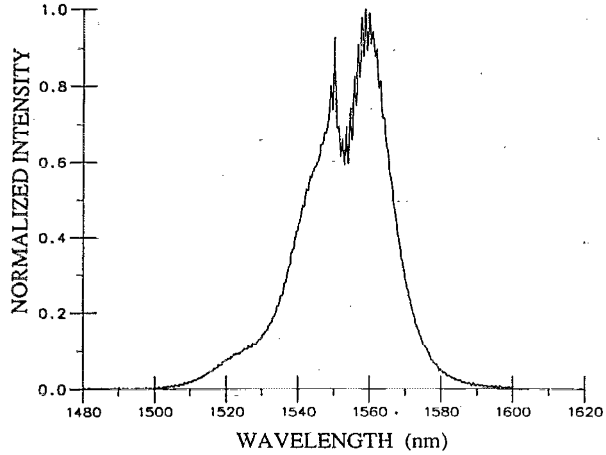

FIG. 2. Same as Fig. 1 but for a bulk AlGaAs waveguide.

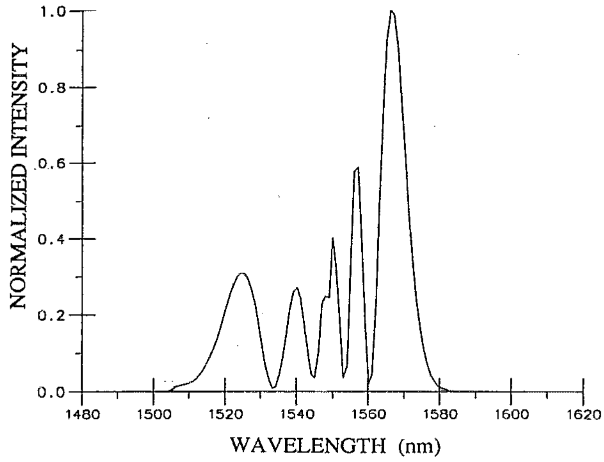

FIG. 3. Theoretical simulation of the TM mode output spectrum of the MQW waveguide.

spectral broadening because (1) n_2 (β_2) is larger (smaller, $n_2=1.9\times10^{-13}$ cm^2/W and $\beta_2=0.4$ cm/GW) than for the MQW case ($n_2=1.6\times10^{-13}$ cm^2/W and $\beta_2=1$ cm/GW); (2) the bulk AlGaAs waveguide is longer and hence the interaction length is longer; (3) the linear loss of the bulk AlGaAs waveguide is smaller than that of the MQW waveguide. However, this is not the case in the comparison between Figs. 1 and 2. The asymmetric nature and larger breadth of the MQW pulse spectrum clearly indicates that the effects of spectral dispersion in n_2 and β_2 are important.

Previous measurements with TM polarization have reported strong dispersion in n_2 and β_2 between 1500 and 1600 nm in MQW waveguides.[8] Calculations have shown that there are two conduction subbands ($C1$ and $C2$), three heavy-hole subbands ($H1$, $H2$, and $H3$), and two light-hole subbands ($L1$ and $L2$) in the GaAs quantum wells.[11] Note that there are no distinct exciton features in the transverse electrical (TE) mode because the two-stage transition includes interband and an intraband transitions whose final states are $2P$ excitons. Since both the binding energies and oscillator strengths of a $2P$ exciton are small, no distinct exciton features are expected.[8,12] On the other hand, in the TM mode distinct exciton features were observed.[8,12] Because in the TM mode the intraband transitions are forbidden and intersubband transitions are allowed, $1S$ excitons can be the final states of two-photon transitions. Since transitions between the conduction and heavy-hole bands are forbidden for the TM mode, only two interband transitions $C1\rightarrow L2$ and $C2\rightarrow L1$ ($C1L2$ and $C2L1$) with strong exciton features are expected to couple to the TM mode for wavelengths shorter than 1524 and 1490 nm, respectively. Regarding the excitons, for example, if the binding energy of the $1S$ exciton associated with $C1L2$ transition is assumed to be about 9 meV, the corresponding transition should occur near 1532 nm. The process just discussed is expected to be the principal contribution to the dispersion in n_2 and β_2.

To calculate the frequency dispersion, we used the following equation for the evolution of the complex field amplitude $A(z,\omega)$:

$$\frac{\partial}{\partial z}A(z,\omega)=-\frac{\alpha}{2}A(z,\omega)+\frac{a_2}{2\pi}\int_{-\infty}^{\infty}d\omega_1 p(z,\omega_1)A(z,\omega-\omega_1)\times\left(\frac{i(\omega+\omega_0)}{c}n_2(\omega+\omega_0,\omega_1+\omega_0)-\frac{1}{2}\beta_2(\omega+\omega_0,\omega_1+\omega_0)\right). \quad (1)$$

Here z is the propagation distance, α is the linear absorption coefficient (assumed to be frequency independent), a_2 is a waveguide modal overlap factor assumed to be 0.5, c is the vacuum speed of light, and $p(z,\omega_1)$ is the Fourier transform of the optical intensity $|A(z,t)|^2$ (time-domain complex amplitude). Equation (1) is based on the assumption that the appropriate third-order susceptibility $\chi^{(3)}$ is only dependent on $\omega_0+\omega$ and $\omega_0+\omega_1$, the two frequencies of the two photons involved in the two-state transition, where ω_0 is the pulse center frequency, and ω_1 and ω are frequency deviations from ω_0. Note that the mixing terms which require phase matching are not important and ignored in this assumption.

Expressions for the nondegenerate n_2 and β_2 were obtained from theories of two-photon transitions, with their magnitudes normalized by previous measurements on degenerate n_2 and β_2.[8,9] These theories provide the frequency dependence of β_2 and the Kramer–Kronig relation provides the frequency dependence of n_2. Shown in Fig. 3 is a simulation of the experiment data in Fig. 1, based on a peak pulse wavelength (λ_0) of 1550 nm and $\alpha=0.64$ cm^{-1}. Strong spectral asymmetry is predicted, similar to that observed, due to the large spectral dispersion in n_2 and β_2, for example, $n_2(\beta_2)=3\times10^{-13}$ cm^2/W (4 cm/GW) at 1525 nm, 1.6×10^{-13} cm^2/W (1 cm/GW) at 1550 nm, and 1.3×10^{-13} cm^2/W (0.3 cm/GW) at 1575 nm. The different contributions to the spectrum from the spectral dispersion of n_2 and β_2 are shown in Fig. 4. When n_2 is fixed at 1.6×10^{-13} cm^2/W (solid line), the strong nonlinear absorption for wavelengths shorter than λ_0 reduces the spectral broadening there relative to the long wavelength side. For β_2 fixed (1 cm/GW, dashed line), the spectral broad-

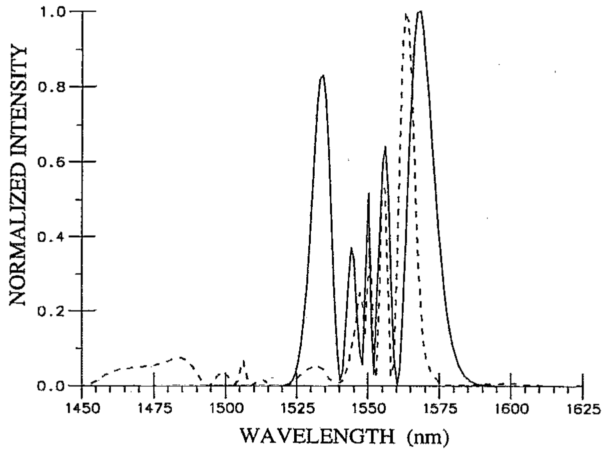

FIG. 4. Theoretical output spectra assuming a frequency independent n_2(1.6×10^{-13} cm^2/W, solid curve) or β_2 (1 cm/GW, dashed curve).

ening is larger on the shorter wavelength side because n_2 is larger on this side. Hence, although the spectrum is asymmetric, the spectral broadening is about the same on either side of λ_0, as shown in Fig. 3.

Other effects can lead to asymmetries. Although group velocity dispersion (GVD) is negligible for 1.5 cm GaAs waveguides for pulse widths larger than 200 fs, its effect in our MQW sample is unknown and was neglected. An initial asymmetry of the input pulse can also contribute to the observed asymmetry. However, this asymmetry was measured to be small. Raman scattering, which can also lead to asymmetries, is usually much weaker than the two-photon transitions. Finally, we note that the asymmetry manifests itself as a distorted pulse in the time domain, namely the peak is shifted slightly towards the trailing edge where the pulse is also steeper.

In conclusion, we have investigated the asymmetric spectra of femtosecond pulses after TM mode propagation through bulk AlGaAs and MQW GaAs/AlGaAs channel waveguides. The larger MQW asymmetries were attributed to the large frequency dispersion in n_2 and β_2 associated with two-photon transitions. This spectrum asymmetry would seriously affect the efficiency in nonlinear switching applications. When such an application is considered, the wavelength ranges of strong dispersion, i.e., near strong exciton features, must be avoided.

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