Evaluation of $GaAs/Al_{0.3}Ga_{0.7}As$ multiple-quantum-well waveguides for pulsed squeezed light generation

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We have measured the nonlinear refractive index n_2 and two-photon absorption coefficient β in $GaAs/Al_{0.3}Ga_{0.7}As$ multiple-quantum-well waveguides in the band tail region about 45 meV below the $n = 1$ heavy hole exciton absorption line. At 883 nm we find that $\beta = 1.9 \times 10^{-8}$ cm W^{-1} and that $n_2 \approx -1 \times 10^{-12}$ cm^2 W^{-1}. The linear loss coefficient is measured to be 6.3 cm^{-1} at the same wavelength. Based on these values, we estimate that up to 4.5 dB pulsed squeezing is possible.

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I. INTRODUCTION

Squeezed light is a form of the quantized electromagnetic field in which the quantum noise in one of the phase quadratures is reduced below the shot-noise limit. It is a purely quantum form of light with no classical analog, and finds applications in optical measurements which are otherwise shot-noise limited. Generation schemes use either second- or third-order optical nonlinearities [1]. Despite the good number of successful experiments reported to date, squeezing has only been achieved at relatively few wavelengths. Since squeezing is destroyed by losses, research to extend the availability of squeezing to new wavelengths focuses on nonlinear materials with small losses matched to convenient laser sources.

Semiconductors have large third-order nonlinear optical coefficients at wavelengths close to the fundamental absorption edge at the band gap E_g [2]. At the same time the absorption coefficient decreases exponentially as a function of detuning below E_g [3]. There is thus a reasonable prospect to have a large nonlinearity with low absorption losses in the band tail region just below E_g [4]. This is a similar situation to the original sodium squeezed state experiment, where a wavelength in the wings of the D lines was used in order to retain some of the resonant enhancement of the nonlinearity, while keeping the absorption losses at an acceptable level [5].

In this paper we investigate the feasibility of generating squeezed light in the technologically important wavelength range 800–900 nm using a semiconductor nonlinear material. This wavelength range matches well to the one-photon band gap of GaAs-based materials. $GaAs/Al_{0.3}Ga_{0.7}As$ multiple quantum wells were selected because of their enhanced excitonic nonlinearities at room temperature compared to the bulk material [6]. In our experiments we worked in the band tail more than one longitudinal optic phonon energy below the $n = 1$ heavy hole exciton where the linear absorption decreases exponentially with the detuning from the exciton and the coherent optical nonlinearity arises mainly from the ac Stark effect [6]. Since the maximum thickness of depleted multiple quantum wells is limited by residual impurities to ~ 1 μm, we used waveguide structures to increase the nonlinear interaction length. We limit our investigation to the case of generating pulsed squeezed light [7] because the higher intensities available from pulsed lasers increase the likelihood of obtaining squeezing.

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II. EXPERIMENTAL DETAILS

The quantum well waveguide samples were grown by atmospheric pressure metal organic vapor phase epitaxy on a GaAs substrate. A schematic diagram of the structures is given in the inset of Fig. 1. The core region is a 70-period $GaAs/Al_{0.3}Ga_{0.7}As$ nominally undoped superlattice with 80-Å quantum wells and 60-Å barriers (average background doping $p \sim 1 \times 10^{15}$ cm^{-3}). This region has an average refractive index n_0 of 3.51 at 880 nm, while the cladding $Al_{0.3}Ga_{0.7}As$ layers have $n_0 = 3.39$. A 1.0-μm-thick $Al_{0.6}Ga_{0.4}As$ leakage stop layer was grown between the substrate and the guiding layers.

The light is confined in the growth direction by the mismatch in the refractive indices. Lateral confinement is achieved by etching ribs into the top $Al_{0.3}Ga_{0.7}As$ layer by reactive ion etching. Most of our results were obtained from waveguides with a rib width of 4.8 μm. The effective area of the fundamental mode is estimated to be 5.2 μm^2. Anti-reflection coated samples were used, with reflection losses of $\sim 1\%$ per facet.

The laser source was a cw mode-locked Ti:sapphire

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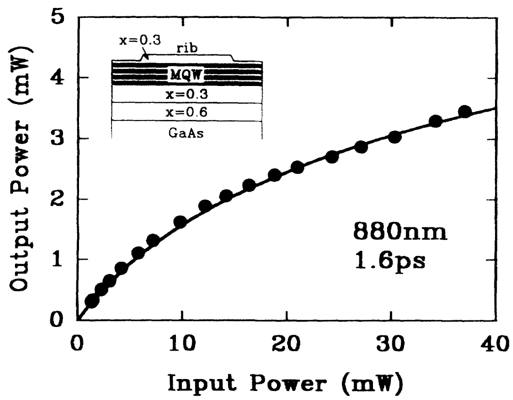

FIG. 1. Power out vs power in for 1.6-ps 880-nm pulses through a 0.98-mm-long waveguide. The solid line is a fit assuming the following parameters: $\alpha_0 = 6.3$ cm^{-1}, $\beta = 1.9 \times 10^{-8}$ cm W^{-1}, and coupling of 43%. The inset shows a schematic diagram of the GaAs/Al$_x$Ga$_{1-x}$As multiple quantum well waveguide used.

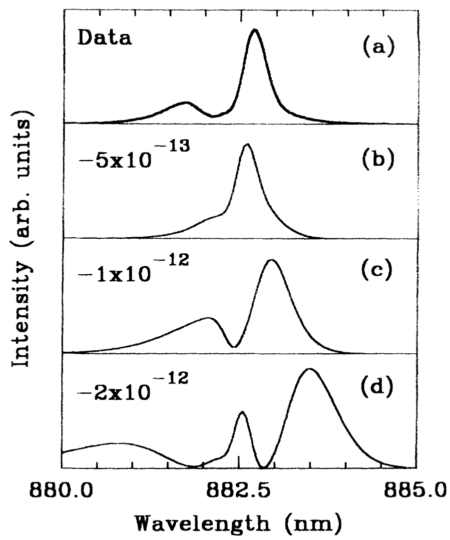

FIG. 2. (a) Output spectrum of the transmitted light through the 0.98-mm waveguide with 1.95-ps transform-limited pulses at the input facet. The input power was 30 mW. (b)–(d) Simulated spectra for three different values of n_2 in cm^2 W^{-1}.

laser producing pulses of duration 100 fs–5 ps at a repetition rate of 82 MHz. Average power levels up to 600 mW were available in the wavelength range 800–900 nm. A $\times$20 microscope objective was used to couple the beam into TE modes of the waveguides, with typical coupling losses into antireflection coated samples of $\sim$ 3 dB.

III. RESULTS

The $n = 1$ heavy hole exciton absorption line was measured to be at 854 nm at room temperature. Our measurements were made between 880 nm and 885 nm, i.e., with detunings of 43–51 meV. By working at these detuning values, we avoid problems of pulse broadening due to band edge dispersion and we keep the linear loss at an acceptable value. The linear loss coefficient α_0 was measured to be 6.3 ± 0.7 cm^{-1} by the fringe contrast method [8]. About 80% of this loss is caused by waveguide scattering, while the remainder is residual bandtail absorption.

Severe problems with nonlinear absorption were encountered when using subpicosecond pulses. Using 100-fs pulses, it was not possible to transmit more than 0.5 mW through a 0.98-mm-long sample. The dominant mechanism for the nonlinear absorption is two-photon absorption; the free carrier absorption due to the carriers generated by the linear and two-photon absorption is at least an order of magnitude smaller. By using broader pulses, we were able to transmit more power. Figure 1 shows the power transmitted as a function of input power with 1.6-ps pulses through the same waveguide. The equation of propagation for the optical intensity I in a medium with two-photon absorption coefficient β is

$$\frac{dI(z)}{dz} = -\alpha_0 I(z) - \beta I(z)^2 , \qquad (1)$$

where z is taken as the propagation direction. The power-dependent transmission can be calculated by integrating Eq. (1) over z and over the pulse width. The solid curve in Fig. 1 is a fit obtained using the following parameters: coupling efficiency of 0.43, $\alpha_0 = 6.3$ cm^{-1}, and $\beta = 1.9 \times 10^{-8}$ cm W^{-1}. Our value of β is the same as that measured in bulk GaAs at 950 nm [9].

The nonlinear refractive index n_2 is given by $n(I) = n_0 + n_2 I$ and can be estimated from the power dependence of the pulse spectrum emitted at the output facet [10,11]. Figure 2(a) shows the transmitted power spectrum for 1.95-ps full width half maximum pulses centered at 882.5 nm after having propagated through the 0.98-mm-long sample. The input power to the waveguide was 30 mW. The pulse spectrum may be modeled using the theory developed by Stolen and Lin for optical fibers [12]. We modified this theory to include two-photon absorption by incorporating an intensity dependence into both the transmission and the effective nonlinear length. The measured spectrum is highly asymmetric which indicates that either the pulses are asymmetric or that the nonlinear coefficients are dispersive [13]. In our calculations we used sech^2 pulses with a rise time twice as long as the fall time and the same values of α_0 and β as for Fig. 1. We were not able to get an acceptable fit to the data within the limits of our simplified model, which did not include dispersion. The best result was obtained with a value of $n_2 \approx -1 \times 10^{-12}$ cm^2 W^{-1}. We estimate that the accuracy of this value is a factor of 2 on either side. Figures 2(b)–2(d) show the effect of changing n_2 between -5×10^{-13} cm^2 W^{-1} and -2×10^{-12} cm^2 W^{-1}.

The value we obtain for n_2 at a detuning of 47 meV is larger than the values reported at longer wavelengths [14,15]. This is to be expected, due to the inverse power law dependence of virtual carrier nonlinearities on the detuning [2]. We can compare our value to published results for the ac-Stark effect in GaAs/$Al_{1-x}Ga_xAs$ multiple quantum wells with near-resonant excitation [16,17]. These papers do not quote values of n_2, but an analysis of their results suggests that our value is of the correct order of magnitude. On the other hand, the effects of the real carriers generated by linear and two-photon absorption are expected to be much smaller. The carrier densities generated by the two absorption mechanisms are estimated to be 1×10^{16} cm^{-3} and 1×10^{17} cm^{-3}, respectively. The nonlinear refractive index cross section for 300 K two-dimensional carriers at a detuning of 47 meV can be estimated to be $\sim -2 \times 10^{-20}$ cm^3 by extrapolating the published values [6]. The carrier density generated by linear absorption is insufficient to produce the required refractive index change, whereas the carriers generated by two-photon absorption are not expected to be very effective in contributing to the nonlinear refractive index with 1.95-ps pulses. This is because the carriers are excited high up in the bands and are three dimensional in character, causing only a broadening of the exciton lines [18]. The carriers are eventually captured by the wells and cool to the lattice temperature, but this process takes a time comparable to or longer than the pulse width used in this experiment [19].

IV. DISCUSSION AND CONCLUSIONS

Slusher *et al.* [4] have given the following criterion for the evaluation of nonlinear materials for squeezed state generation:

$$\xi = \frac{2\pi \Delta n_{max}}{\alpha \lambda} \gg 1, \tag{2}$$

where Δn_{max} is the maximum nonlinear refractive index change, α is the absorption coefficient, and λ is the wavelength. In our case, both Δn and α increase linearly with intensity: $\Delta n = n_2 I$ and $\alpha = \alpha_0 + \beta I$. Thus the maximum value of ξ is $2\pi n_2/\beta\lambda$ at high intensities, which is ~ 4 for our samples at 883 nm. Since our material barely satisfies the criterion, we only expect to obtain a moderate level of squeezing, as discussed below.

The amount of squeezing in a lossy waveguide with a $\chi^{(3)}$ nonlinearity has been calculated for the case of optical fibers [20]. In applying this model to the case of pulsed squeezing in semiconductor waveguides, we are faced with several complications: (i) the model was developed for cw squeezing; (ii) the decay of the pump as a function of z due to absorption is not properly included; (iii) the absorption is assumed to be independent of intensity and z, whereas in our case it will depend on both by way of β; and (iv) we must consider the effects of extraneous noise sources, such as guided acoustic-wave Brillouin scattering (GAWBS) [21], spontaneous emission [5], and free carrier scattering [4].

We can obtain a conservative estimate for the maximum squeezing in the absence of unavoidable noise sources using the worst value of the loss in the waveguide and the lowest value of the nonlinear coupling. We assume that the pulsed squeezing will be detected in the frequency spectrum between the harmonics of the pulse train (82 MHz). The measured noise level V is then given by [20]

$$4V = 1 + \eta \left[\frac{4r^2}{L^2}(1 - e^{-L} - Le^{-L})(1 - \cos 2\theta) + \frac{2r}{L}(1 - e^{-L}) \sin 2\theta \right], \tag{3}$$

where η is the detection efficiency, r is the squeeze parameter, L is the single pass loss, and θ is the phase angle with the local oscillator. The standard shot-noise limit corresponds to $V = \frac{1}{4}$. The squeeze parameter r is equal to the pump-induced nonlinear phase shift $\frac{2\pi}{\lambda} n_2 I l$, where l is the length of the nonlinear material [22].

Figure 3 shows the minimum value of $4V$ calculated from Eq. (3) as a function of coupled input intensity $I(0)$ for three different waveguide lengths. The following parameters were used: $|n_2| = 1 \times 10^{-12}$ cm^2 W^{-1}, $\alpha_0 = 6.3$ cm^{-1}, and $\beta = 0.019$ cm MW^{-1}. The calculation does not take account of the z-dependence of the loss and squeeze parameter. Instead we use the worst case values for both. Thus we use $(1 - e^{-\alpha(0) l})$ for L and $\frac{2\pi}{\lambda} n_2 I_{min} l$ for r. $\alpha(0)$ is the highest absorption in the waveguide, namely, $\alpha_0 + \beta I(0)$, and I_{min} is an underestimate of the lowest value of the intensity in the waveguide, namely, $I(0)e^{-\alpha(0) l}$. The calculation shows that the best squeezing is obtained for short waveguides. With longer waveguides, the effects of two-photon absorption at high intensity eventually limit the squeezing obtainable. For a 0.5-mm waveguide, 65% (4.5 dB) squeezing is possible at 800 MW cm^{-2}. This intensity is readily available from a cw mode-locked Ti:sapphire laser: with an 82-MHz train of 10-ps pulses, it corresponds to 14 mW at the output facet of the waveguide. We tested a typical homodyne detection system and found that we were able to detect the shot noise in the light easily when the average power was above 10 mW. Thus, in principle, the squeezing should be detectable.

The measured squeezing will be less than that predicted from Eq. (3) because of unavoidable noise gen-

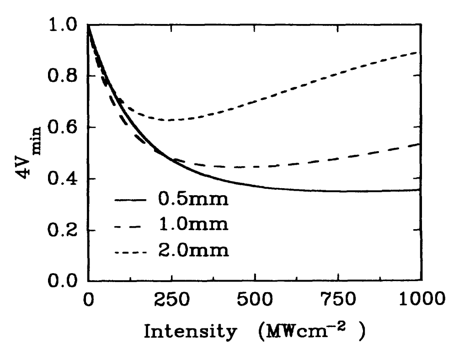

FIG. 3. Estimated values of the minimum noise level as a function of coupled input intensity $I(0)$ for three different waveguide lengths.

eration and inefficient detection. We do not expect that spontaneous emission and GAWBS, which were encountered in previous experiments [5,21], to be too serious a problem because the luminescence line shape is not Lorentzian and the waveguides are located near the acoustic node at the surface. The random scattering by the carriers generated by linear and two-photon absorption (density $\sim 10^{17}$ cm^{-3} at 800 MW cm^{-2}) is a potential problem [4]. However, since our scheme does not rely on real carrier nonlinearities to generate the squeezing, in principle we should only be limited by the Thomson scattering, which contributes much less than the quantum noise. The detection efficiency is affected by a number of factors including the quantum efficiency of the photodiodes, unavoidable optical losses, and the mode matching between the squeezed light and the local oscillator. Typical silicon photodiodes have peak detectivity around 900 nm, which is a clear advantage compared to other experiments. Optical losses can be kept small by using high numerical aperture microscope objectives and antireflection coated optics throughout. One way to achieve good mode-matching is to use a counterpropagating Sagnac interferometer [23,24]. In this configuration the local oscillator is derived from the coherent part of the laser pulse propagating through the waveguide, which is separated from the squeezed light at the 50:50 beam splitter. In preliminary measurements on such an experimental configuration, we were able to obtain a 9:1 power ratio at the two output ports of the 50:50 beam splitter after having propagated both beams through the waveguide.

Some of the problems relating to the sample losses can be overcome by working below $E_g/2$, where both the linear loss and the two-photon loss are much smaller [25,15]. However, the nonlinearity is also significantly smaller. Zhang *et al.* have recently considered the possibility of squeezing in a $Ga_xAl_{1-x}As$ waveguide below $E_g/2$ and have predicted squeezing as large as 80% [26]. A potential drawback of working around $E_g/2$ is that neither the lasers nor the detectors are as convenient as at E_g.

In conlcusion, we have measured the optical losses and nonlinearity in $GaAs/Ga_{0.3}Al_{0.7}As$ multiple quantum well waveguides in the band tail region about 30 nm below the heavy hole exciton. Our measurements predict that up to 4.5 dB squeezing might be obtained with perfect detection efficiency and with no spurious noise sources. This could well prove to be difficult to achieve in practice, and further investigations will be needed to confirm our predictions.

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[1] J. Opt. Soc. Am. B **4** (10) (1987), special issue on squeezed states of the electromagnetic field, edited by H.J. Kimble and D.F. Walls; J. Mod. Opt. **34** (6/7) (1987), special issue on squeezed light, edited by R. Loudon and P.L. Knight, Appl. Phys. B **55** (3) (1992), special issue on quantum noise reduction in optical systems-experiment, edited by E. Giacobino and C. Fabre.
[2] See, for example, M.G. Burt, Semicond. Sci. Technol. **5**, 1215 (1990).
[3] F. Urbach, Phys. Rev. **92**, 1324 (1953).
[4] R.E. Slusher, S.L. McCall, A. Mysyrowicz, S. Schmitt-Rink, and K. Tai, in *Nonlinear Optics of Organics and Semiconductors*, edited by T. Kobayashi, Springer Proceedings in Physics Vol. 36 (Springer-Verlag, Berlin, 1989), p. 24.
[5] R.E. Slusher, L. W. Hollberg, B. Yurke, J.C. Mertz, and J.F. Valley, Phys. Rev. Lett. **55**, 2409 (1985).
[6] S. Schmitt-Rink, D.S. Chemla, and D.A.B. Miller, Adv. Phys. **38**, 89 (1989).
[7] R.E. Slusher, P. Grangier, A. LaPorta, B. Yurke, and M. J. Patasek, Phys. Rev. Lett. **59**, 2566 (1987).
[8] P. Li Kam Wa and P.N. Robson, IEEE J. Quantum Electron. **QE-23**, 1962 (1987).
[9] M. D. Dvorak, W. A. Schroeder, D. R. Andersen, A. L. Smirl, and B. S. Wherrett, IEEE J. Quantum Electron. **30**, 256 (1994).
[10] S.T. Ho, C.E. Soccolich, M.N. Islam, W.S. Hobson, A.F.J. Levi, and R.E. Slusher, Appl. Phys. Lett. **59**, 2558 (1991).
[11] A. Villeneuve, C.C. Yang, G.I. Stegeman, C.-H. Lin, and H.-H. Lin, Appl. Phys. Lett. **62**, 2465 (1993).
[12] R.H. Stolen and C. Lin, Phys. Rev. A **17**, 1448 (1978).
[13] C.C. Yang, A. Villeneuve, G.I. Stegeman, C.-H. Lin, and H.-H. Lin, Appl. Phys. Lett. **63**, 1304 (1993).
[14] F.R. Laughton, J.H. Marsh, and C. Button, Appl. Phys. Lett. **61**, 1493 (1992).
[15] C.C. Yang, A. Villeneuve, G.I. Stegeman, C.-H. Lin, and H.-H. Lin, Electron. Lett. **29**, 37 (1993).
[16] D. Hulin, A. Mysyrowicz, A. Antonetti, A. Migus, W.T. Masselink, H. Morkoç, H.M. Gibbs, and N. Peyghambarian, Appl. Phys. Lett. **49**, 749 (1986).
[17] M. Joffre, D. Hulin, and A. Antonetti, J. Phys. (Paris) Colloq. **48**, C5-537 (1987).
[18] W.H. Knox, D.S. Chemla, D.A.B. Miller, J.B. Stark, and S. Schmitt-Rink, Phys. Rev. Lett. **62**, 1189 (1989).
[19] M.R.X. Barros, P.C. Becker, D. Morris, B. Deveaud, A. Regreny, and F. Beisser, Phys. Rev. B **47**, 10 951 (1993).
[20] G.J. Millburn, M.D. Levenson, R.M. Shelby, S.H. Perlmutter, R.G. DeVoe, and D.F. Walls, J. Opt. Soc. Am. B **4**, 1476 (1987).
[21] R.M. Shelby, M.D. Levenson, S.H. Perlmutter, R.G. DeVoe, and D.F. Walls, Phys. Rev. Lett. **57**, 691 (1986).
[22] M.D. Levenson, R.M. Shelby, and S.H. Perlmutter, Opt. Lett. **10**, 514 (1985).
[23] M. Rosenbluh and R.M. Shelby, Phys. Rev. Lett. **66**, 153 (1991).
[24] K. Bergman and H.A. Haus, Opt. Lett. **16**, 663 (1991).
[25] R.J. Deri, E. Kapon, and L.M. Schiavone, Appl. Phys. Lett. **51**, 789 (1987).
[26] X. Zhang, M.K. Udo, and S.-T. Ho (unpublished).