Squeezed Light Generation in Semiconductors

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We have generated pulsed squeezed light using the third-order nonlinear susceptibility of the semiconductor ZnS at room temperature. The photon energy was chosen to be below midgap in order to minimize nonlinear absorption. Efficient quadrature squeezing of 2.2 dB (40%) was obtained using 125 fs pulses at a center wavelength of 780 nm. The measured noise is suppressed below the quantum limit over the entire range of our detection bandwidth (30–50 MHz). The scheme employed can generally be applied to semiconductors, and opens the way for squeezed light generation over a wide range of wavelengths.

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The pioneering work on squeezing in Na vapor by Slusher *et al.* [1] provided the first demonstration of suppression of fluctuations in an optical field below the quantum noise limit. Important subsequent developments have resulted from increasing the optical interaction length. Squeezing has been obtained using the third-order nonlinear susceptibility of optical fibers [2], and the strongest effects to date have been obtained using materials with a large second-order nonlinearity in an optical cavity [3]. Pulsed squeezed light has also been generated by picosecond [4] and nanosecond [5] parametric amplification, and in optical fibers [6,7]. In this Letter we describe an important new breakthrough—the generation of femtosecond-pulsed quadrature squeezed light by the optical Kerr effect in a semiconductor. The technique is straightforward, does not require cryogenic cooling or cavity enhancement, and produces strong squeezing in a small interaction length. Our results indicate that squeezing can be obtained quite generally in semiconductors, and open the way for the generation of squeezed light over a broad wavelength range.

In order to generate squeezed light it is necessary to have a large ratio of the nonlinear phase shift $\Delta\phi_{\mathrm{NL}}$ to the optical losses [8]. This criterion is conveniently expressed as

$$\xi = \frac{\Delta\phi_{\mathrm{NL}}}{\alpha L} \simeq \frac{n_2 I \omega}{(\alpha_0 + \alpha_2 I)c} \gg 1\,, \qquad (1)$$

where $\alpha = \alpha_0 + \alpha_2 I + \cdots$ is the optical absorption coefficient at angular frequency ω, c is the speed of light *in vacuo*, and L is the sample length. n_2 is the nonlinear refractive index defined by $n = n_0 + n_2 I + \cdots$, and I is the intensity. In a semiconductor, ξ is expected to be a strong function of ω relative to the band gap Ω_g. There are three frequency regions which are important in the present context: $\omega > \Omega_g$, $\omega \lesssim \Omega_g$, and $\omega < \Omega_g/2$. For frequencies above Ω_g there is a large enhancement in n_2, but this is more than offset by the large increase in α_0. For $\omega \lesssim \Omega_g$, ξ should increase because the nonlinearity decreases only as a power law of the detuning from Ω_g, whereas α_0 decreases exponentially. However, since higher intensities are required to produce a significant phase shift, nonlinear absorption becomes a severe problem. For example, experiments on GaAs/GaAlAs waveguides found that two-photon absorption ultimately limited ξ to ~ 4 [9]. It has recently been shown that large ratios of nonlinearity to loss can be obtained when $\omega < \Omega_g/2$ [10], due to n_2 having a broad midgap resonance [11] and α_2 being small because two-photon absorption is forbidden. For this reason we have investigated squeezing in the spectral region close to $\Omega_g/2$.

The samples used in our experiments were the II-VI semiconductors ZnS and ZnSe, in the form of 2 mm thick optical windows. The experiments were performed at room temperature using a Ti:sapphire laser with a tuning range 750–890 nm. In order to produce the required intensity, the laser was mode locked: the pulse train consisted of transform limited $\tau_p = 125$ fs pulses at 82 MHz repetition frequency, and the average power could be varied up to 1 W.

We first measured the nonlinear absorption and self-phase modulation as a function of incident power. Figure 1 shows the transmitted power and peak nonlinear phase shift as a function of input power at $\omega = 0.43\Omega_g^{\mathrm{ZnS}}$ for the ZnS sample without antireflection coatings. The output is a linear function of input up to 400 mW, when nonlinear absorption begins to cause saturation. Up to this point the transmissivity is measured to be 0.71, which is consistent with Fresnel losses at the surfaces. The nonlinear phase shift was determined by fitting the spectral broadening caused by self-phase modulation using the theory first developed for optical fibers [12]. The inset to Fig. 1 shows a typical fit to the data. The peak nonlinear phase shift is also seen to vary linearly with input power, and yields a value of $|n_2| \sim 1 \times 10^{-14}$ cm^2 W^{-1}, which is in good agreement with theoretical predictions [11]. We estimate an upper value of the internal loss of the sample to be 1%, and thus obtain a value of $\xi > 100$. While the value of n_2 we obtain for ZnSe at $\omega = 0.52\Omega_g^{\mathrm{ZnSe}}$ is slightly larger, the nonlinear loss is significantly higher, and the value obtained for ξ is ~ 10.

Figure 2 shows a schematic diagram of our squeezing apparatus. The squeezed light is generated in the sidebands of the longitudinal laser modes by four-wave mixing after a single pass through the semiconductor. In

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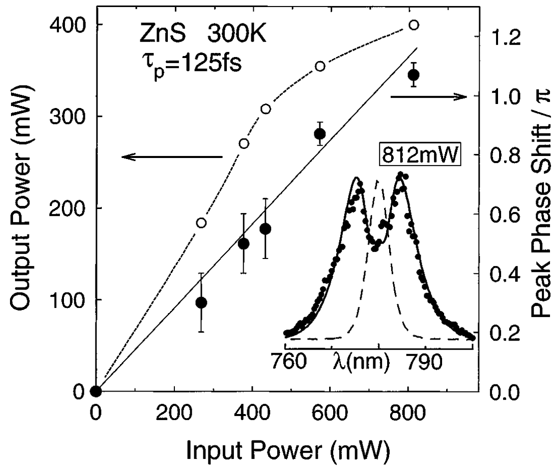

FIG. 1. Output power (○) and peak nonlinear phase shift (●) versus average input power at 780 nm. The solid straight line corresponds to $|n_2| = 1 \times 10^{-14}$ cm^2 W^{-1}. The inset shows the output spectrum and fitted self-phase modulation curve (solid curve) at a power of 812 mW compared to the input spectrum (broken curve).

order to separate the squeezed light from the laser modes a nonlinear interferometer is used [13]. We used the Sagnac configuration, similar to that of recent successful fiber squeezing experiments [6,7]. In this configuration, the pump beam is incident on the input port of a 50% beam splitter BS2, while vacuum noise enters through the other unused port. The two counterpropagating pump pulses are focused into the semiconductor sample to a spot diameter of 16 μm and confocal parameter ~600 μm. The collimated transmitted beams recombine at BS2 where they interfere. The vacuum noise cotemporal with the pump pulses is squeezed in the semiconductor, and also recombines at BS2. Typically the measured contrast ratio of the interferometer is in excess of 50; this is limited by phase front distortion in the optics and sample, and also by departures of the beam splitting ratio from 50%

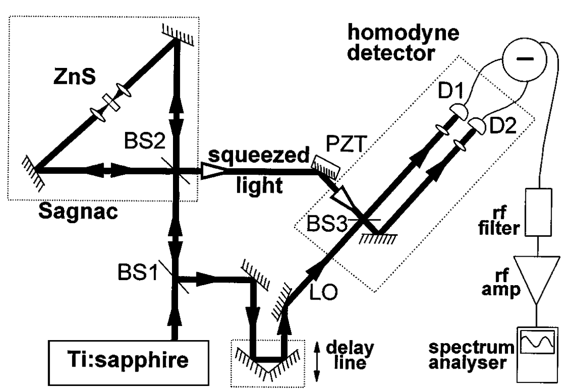

FIG. 2. Schematic diagram of the apparatus used to generate the squeezed light. BS1 is a 15% beam splitter; BS2, BS3 are 50% beam splitters. The piezoelectric transducer (PZT) is swept at 10 Hz and shifts the phase of the local oscillator (LO) relative to the squeezed light by several wavelengths. D1 and D2 are a matched pair of silicon photodiodes.

over the beam width and laser bandwidth. In order to minimize optical losses within the Sagnac, antireflection coatings were applied to the sample and focusing lenses, and p polarization was used to minimize Fresnel losses at the uncoated surface of the beam splitter. In ideal circumstances "bright" squeezed light is returned along the input path while a squeezed vacuum emerges from the unused port. In practice, the interference at BS2 is never perfect, and a small fraction of the laser pulse copropagates with the squeezed vacuum.

The squeezed light was measured with a balanced homodyne detector and a spectrum analyzer [4,14]. The local oscillator (LO) was obtained by splitting off 15% of the transmitted pump beam with the beam splitter BS1. This ensures that the squeezed light and the LO have matched spatial and temporal profiles which is essential for good detection efficiency. The phase of the squeezed light relative to the LO could be varied up to 4π by translating the mirror mounted on a piezoelectric transducer (PZT). The LO pulses were delayed and overlapped with the squeezed light at a second 50% beam splitter BS3, and the combined beams were detected with matched silicon photodiodes. The difference current was amplified and then spectrum analyzed. The photodiodes were linear in both power and noise response up to 40 mW incident power. The detected signals could be balanced to better than 30 dB. The bandwidth investigated was constrained to the range 30–50 MHz by rf filters in order to prevent saturation by low frequency noise and spikes at the 82 MHz mode-locking frequency. The shot-noise level of the local oscillator was calibrated in two ways. Firstly, the measured noise power was confirmed to be consistent with an $I^{1/2}$ dependence, and secondly, the noise power measured from a known shot-noise limited source was found to be the same as that from our local oscillator. In this way we found that the Ti:sapphire laser was shot-noise limited in our detection bandwidth, except from 41 MHz modulation arising from the mode-locking electronics.

Figure 3(a) shows noise traces at 35 MHz obtained for ZnS at 780 nm as a function of the phase shift between the squeezed light and the LO. The average power in the Sagnac was 490 mW (i.e., 245 mW in each direction), and the overall transmission of the focusing lenses and sample was measured to be 87%. The LO power was 28 mW per diode, while the power transmitted at the output port of BS2 was 3 mW. When the LO and squeezed pulses were adjusted to arrive simultaneously at BS3 ($\Delta t = 0$), a phase dependent noise of period π is observed. Under identical conditions without the sample no such modulation is found, precluding contributions from pump laser instability or diode nonlinearity. The shot-noise level (SNL) is recorded by presenting the same optical power to each photodiode (29.5 mW) from solely the LO input. The minimum noise ($S_{\min}$) drops 0.9 dB (20%) below this SNL, while the maximum noise ($S_{\max}$) is enhanced by 2 dB (60%). No phase dependent noise was observed when the

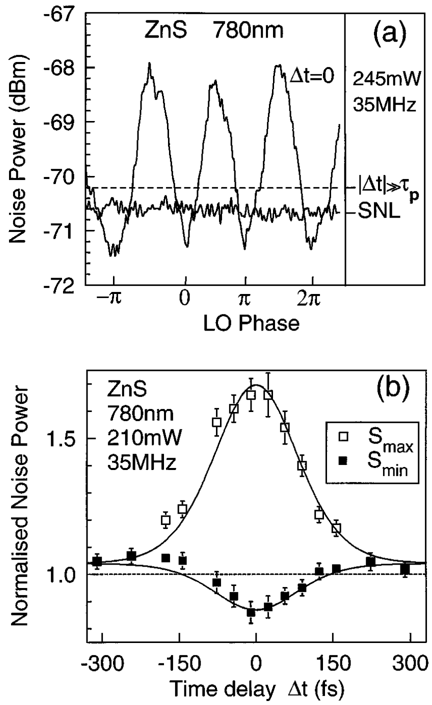

FIG. 3. (a) Phase dependent noise and shot-noise level (SNL) measured with 245 mW in each beam of the Sagnac. (b) Dependence of the maxima (□) and minima (■) of the phase dependent noise on the time delay Δt at 210 mW. The dashed line in (a) shows the average noise power measured when $|\Delta t| \gg \tau_p$. The solid lines in (b) are autocorrelations of a 125 fs pulse. For both (a) and (b) the frequency was 35 MHz with a 3 MHz resolution bandwidth, and 300 Hz video bandwidth.

ZnS sample was replaced by ZnSe and the laser retuned to its low frequency limit $\omega = 0.52\Omega_g^{\mathrm{ZnSe}}$. This may be due to the strong nonlinear absorption which substantially reduces ξ for $\omega > \Omega_g/2$.

The phase dependent noise observed in ZnS is only seen when the LO pulses arrive together with the squeezed pulses. If they are temporally separated ($|\Delta t| \gg \tau_p$), a larger noise level [shown by the broken line in Fig. 3(a)] is obtained. The additional 0.4 dB may originate from the extra noise of directly detected squeezed light which has super-Poissonian statistics. In distinct contrast, the noise in just one quadrature is substantially squeezed below the SNL. The squeezing was found to have no significant dependence on frequency within the bandwidth of the detection electronics (30–50 MHz).

The maximum and minimum values of the phase dependent noise are displayed in Fig. 3(b) as a function of LO delay and normalized to the SNL. Both approximately follow the laser pulse autocorrelation given by the solid curves (suitably normalized in each case). This result shows that the LO effectively "projects out" the noise in each quadrature at time delay Δt.

Figure 4 shows the dependence of the extrema of the noise levels for ZnS as a function of power in each beam of

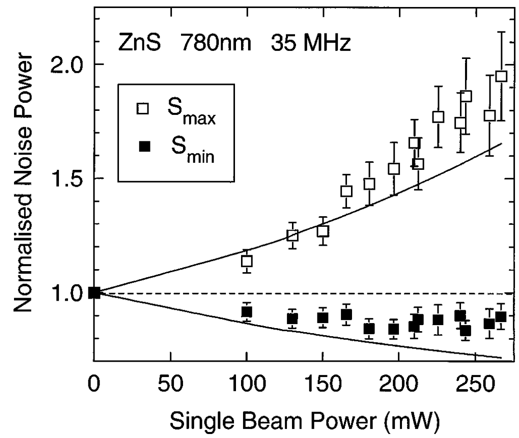

FIG. 4. Power dependence of the maxima (□) and minima (■) of the normalized phase dependent noise at 35 MHz. The solid lines show the results of Eq. (2) discussed in the text.

the Sagnac, again normalized to the SNL. The data points are compared to the results of a simplified model of the noise levels produced by four-wave mixing [15]:

$$S_{\substack{\min \\ \max}} = 1 - \eta \frac{\Delta\phi_{\mathrm{NL}}}{\Delta\phi_{\mathrm{NL}} \pm \alpha L}[1 - \exp\{\mp\Delta\phi_{\mathrm{NL}} - \alpha L\}], \tag{2}$$

where η is the total detection efficiency, estimated to be ~0.5. This factor allows for imperfect antireflection coatings, other beam propagation losses, the quantum efficiency of the photodiodes, and the beam overlap. The model includes the nonlinear phase shift and the absorption losses, but neglects dispersion and the pulsed nature of the squeezing. For the case $\alpha = 0$ it gives similar results to other simplified models which do not include losses (e.g., Ref. [13]), and is a useful starting point for comparison with the experimental data. The values of $\Delta\phi_{\mathrm{NL}}$ and αL are derived from the data in Fig. 1. The agreement between the calculated and measured noise levels is remarkably good considering the simplicity of the model, although at higher powers the measured values are larger than those calculated. The reason for this is not clear, but points to the need for a more complete theoretical model. It is noteworthy that there is no large excess noise in $S_{\max}$ as was observed in optical fibers [6]. The squeezed state generated in the semiconductor therefore appears to be close to a minimum uncertainty state.

The experimental results also show that $S_{\min}$ appears to saturate at a value of 0.8 SNL. This does not seem to be caused by the onset of nonlinear absorption, which becomes important above 400 mW incident power. It may be due to unavoidable phase mismatch between the LO and the squeezed light at BS3, which mixes the quadratures. On the basis of Eq. (2), we see that the main factor reducing the measured squeezing is the low detection efficiency. When allowance is made for this and we set $\eta = 1$, we obtain a value of 2.2 dB (40%) squeezing.

In conclusion, we have reported the first experimental demonstration of quadrature squeezed light generation in a semiconductor. We used femtosecond laser pulses with high peak power to produce a strong nonlinear phase shift, and chose the photon energy to lie below midgap in order to reduce nonlinear absorption. Both factors give the added advantage of suppressing contamination of the squeezed light by spontaneous emission. This technique complements recent efforts in the generation of photon-number squeezed states from optoelectronic semiconductor devices [16]. The results indicate that our method is quite generally applicable to semiconductors, and opens the way for squeezed light generation at a wide range of wavelengths for possible applications in high-resolution spectroscopy, quantum nondemolition experiments, quantum communications, and low-light-level microscopy [17,18]. Of particular interest will be GaAs-based materials, including quantum-confined structures and materials with narrow gaps, where the prospects for squeezing are strongly favored by the Ω_g^{-4} dependence of n_2.

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