Experimental evidence for Raman-induced limits to efficient squeezing in optical fibers

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We report new experiments on polarization squeezing using ultrashort photonic pulses in a single pass of a birefringent fiber. We measure what is to our knowledge a record squeezing of -6.8 ± 0.3 dB in optical fibers, which when corrected for linear losses is -10.4 ± 0.8 dB. The measured polarization squeezing as a function of optical pulse energy, which spans a wide range from 3.5–178.8 pJ, shows a very good agreement with the quantum simulations, and for the first time we see the proof experimentally that Raman effects limit and reduce squeezing at high pulse energy. © 2008 Optical Society of America

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Quantum communication and information science are undeniably important areas in modern physics, highlighted by their rapid expansion in recent years. Within the framework of quantum continuous variable information protocols [1], nonclassical polarization states of light have recently attracted particular interest [2–7] due to their compatibility with the spin variables of atomic systems [8] and their simple detection without additional local oscillators [9]. Early experimental generation of polarization squeezing used continuous wave light and parametric processes [3,4,8], cold atomic samples [5], and silica fibers [6].

It is well known [10] that a single pass of an ultrashort pulse through an optical fiber can generate quadrature squeezing due to the optical Kerr effect. However, this is not measurable in direct detection since the Kerr nonlinearity conserves the photon number. An external local oscillator is also unsuitable, because of phase noise from intrafiber Brillouin scattering.

A significant improvement in the fiber-based production of polarization squeezing came with the implementation of the single-pass method [7]. This scheme was greatly simplified compared with previous experiments and achieved polarization squeezing up to -5.1 ± 0.3 dB. Furthermore, it enabled a way to directly characterize the noise statistics of a fiber-squeezed quantum state. Subsequent first-principles simulations, which showed excellent agreement with the experimental measurements [11], provided a comprehensive theory to quantitatively explain the quantum-noise properties of the ultrashort pulses in the fiber. Theoretical limits on fiber squeezing due to Raman effects were predicted at energies higher than those previously investigated.

In this Letter we present new results of polarization squeezing based on an optimized version of the single-pass scheme. Furthermore, a substantially wide range of pulse energies is investigated to fully characterize the quantum-noise properties of the ultrashort pulses in the fiber. In comparisons of the experimental measurements with the simulations, the very good agreement provides evidence that the deteriorated squeezing at high energy is due to Raman effects.

The experimental setup is shown in Fig. 1. A homemade Cr^{4+}:YAG laser is used as a source of 140 fs (full width at half-maximum) sech-shaped optical pulses at a repetition rate of 163 MHz. The spectra are centered at $\lambda_0=1.5\ \mu$m with a bandwidth of 19 nm. The fiber we use is a 13.2 m long polarization-maintaining (PM) fiber, 3M FS-PM-7811 with a 5.7 μm core diameter and an average nonlinear refractive index of $n_2=2.9\times10^{-20}\ \mathrm{m^2/W}$. The second-order and third-order dispersion of the fiber at the optical wavelength λ_0 are experimentally determined to be $\beta_2=-11.1\ \mathrm{fs^2/mm}$ and $\beta_3=83.8\ \mathrm{fs^3/mm}$, respectively, using white-light interferometry.

In this experiment, we prepare ultrashort pulses of the same optical power and couple them into the two orthogonal polarization axes, x and y, of the fiber. After the fiber, we obtain two independent Kerr squeezed beams with approximately the same

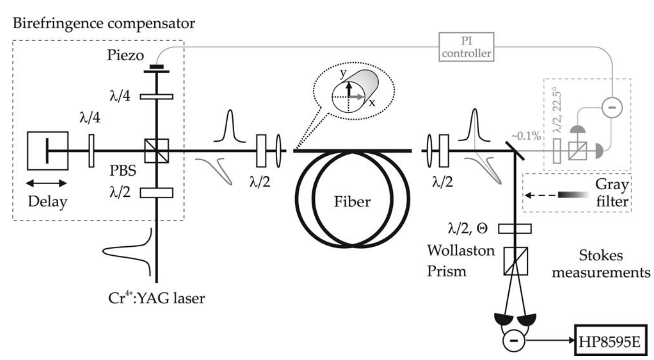

Fig. 1. Experimental setup for efficient polarization squeezing generation. PBS, polarizing beam splitter; (λ/2), half-wave plates; (λ/4), quarter-wave plates.

quadrature noise property $\Delta^2\hat{X}_{x,\theta}=\Delta^2\hat{X}_{y,\theta}=\Delta^2\hat{X}_{\theta}$ (the squeezed quadratures rotated by an angle $\theta_{\rm sq}$ relative to the amplitude quadrature). Overlapping them with a $\pi/2$ relative phase shift by use of a birefringence compensator [6,7,12], as well as a locking loop based on 0.1% of the fiber output, we produce a circularly polarized beam ($\langle\hat{S}_1\rangle=\langle\hat{S}_2\rangle=0$, $\langle\hat{S}_3\rangle=\langle\hat{S}_0\rangle=\alpha^2$). The corresponding Stokes operator uncertainty relations are reduced to a single nontrivial one in the so-called $\hat{S}_1-\hat{S}_2$ dark plane: $\Delta^2\hat{S}_{\theta}\Delta^2\hat{S}_{\theta+\pi/2}\geq|\langle\hat{S}_3\rangle|^2$ ($\hat{S}_{\theta}$ denotes a general Stokes parameter rotated by θ in the dark $\hat{S}_1-\hat{S}_2$ plane with $\langle\hat{S}_{\theta}\rangle=0$). Therefore, polarization squeezing occurs if $\Delta^2\hat{S}_{\theta}<|\langle\hat{S}_3\rangle|=\alpha^2$, in which $\Delta^2\hat{S}_{\theta}$ can be directly measured in a Stokes measurement [7]. As the noise of Stokes parameters $\hat{S}_{\theta}$ is linked to the quadrature noise of the Kerr squeezed modes in the same angle: $\Delta^2\hat{S}_{\theta}=\alpha^2\Delta^2\hat{X}_{\theta}$ [7], we can simply characterize the noise statistics of a fiber-squeezed quantum state by measuring the polarization-squeezed state.

The Stokes measurement is made with a half-wave plate ($\lambda/2$) and a polarizing beam splitter. We use a Wollaston prism for higher extinction ratio ($>10^5$ for both polarizations), and the outputs are detected directly by the use of a pair of balanced photodetectors based on custom-made pin photodiodes (Laser Components GmbH, 98% quantum efficiency at dc). The difference of the detected ac photocurrents provides measurement of the optical noise. The uncertainty limit is determined by measuring the intensity fluctuation of a beam from the laser that was verified to be shot-noise limited by balanced detection ($\Delta^2\hat{S}_0=\alpha^2$). The measurement is recorded by a HP8595E spectrum analyzer operated at 17.5 MHz with 300 kHz resolution bandwidth and 30 Hz video bandwidth; the measured noise traces are corrected for an electronic noise of −85.1 dBm.

To ensure that the balanced detectors are not saturated by the strong optical powers in the experiments, we establish a set of measurements to check both the dc and the ac outputs as a function of the optical pulse energy from 3.5–178.8 pJ. In Figs. 2(a) and 2(b) we show the dc response of one single detector, as well as the difference of the ac photocurrents from the pair of detectors versus the optical energy of a coherent state. It can be seen that the detector response is linear and, therefore, that the squeezing measurements carried out in this region are unsaturated.

However, saturation is still possible for the antisqueezing measurement as the rf noise for a given optical power is much greater. We check this by using a variable gray filter with which the optical power of the squeezed beam is varied, as shown in Fig. 1. The optical pulse energy was fixed to the maximum (178.8 pJ), and the Stokes measurement was set to measure the antisqueezed quadrature. The measurement of the noise variance as a function of the transmittance of the optical field through the gray filter is shown in Fig. 2(c). The linear dependence confirms

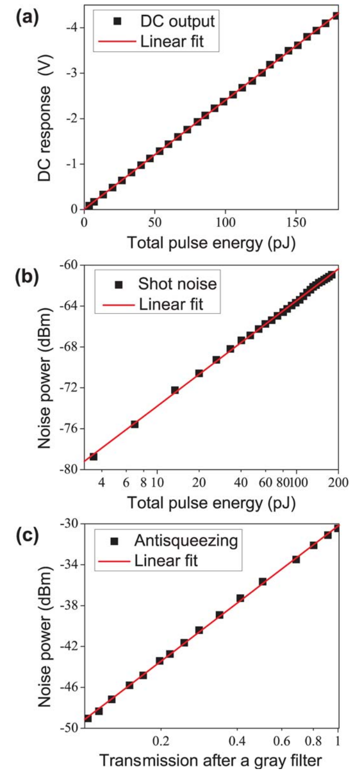

Fig. 2. (Color online) Plots of (a) dc response of one of the detectors pair, and (b) noise power measured at 17.5 MHz by the minus output of the detectors pair versus the optical pulse energy from the fiber. (c) Measured antisqueezed noise as a function of the transmittance after a gray filter.

that the detectors are unsaturated even up to the maximum optical power achievable.

The squeezed and antisqueezed quadratures and the squeezing angle, $\theta_{\rm sq}$, were experimentally investigated as a function of the pulse energy from 3.5 to 178.8 pJ, and the results are plotted in Fig. 3. The maximum observed squeezing is -6.8 ± 0.3 dB at an energy of 98.6 pJ. The corresponding antisqueezing of this state is 29.6 ± 0.3 dB, and the squeezing angle is 1.71°. The loss of the setup was found to be 13%: 5% from the fiber end, 4.6% from optical elements, attenuation of the fiber (2.03 dB/km at 1550 nm), 2% from incomplete interference between two polarization modes (99% visibility was measured), and 2% from the photodiodes. Thus we infer a maximum polarization squeezing of -10.4 ± 0.8 dB. As the optical energy goes beyond 98.6 pJ, the squeezing is reduced, eventually reaching the shot-noise limit, and the increment of antisqueezing slows down to a plateau area. By applying the first-principles quantum dynamics of radiation propagating in a single-mode optical fiber and phase-space methods [11,13], the squeezing, antisqueezing, and squeezing angle at different input energies are simulated. The fraction of the nonlinearity that is due to the Raman gain is estimated as 15%, and the photon number ($2\bar{n}$) in a fundamental soliton pulse as 4.5×10^8. The excess phase noise, such as depolarizing guided acoustic wave Brillouin scattering (GAWBS) [11], is estimated by fitting the simulated squeezing angles to the experimentally measured squeezing

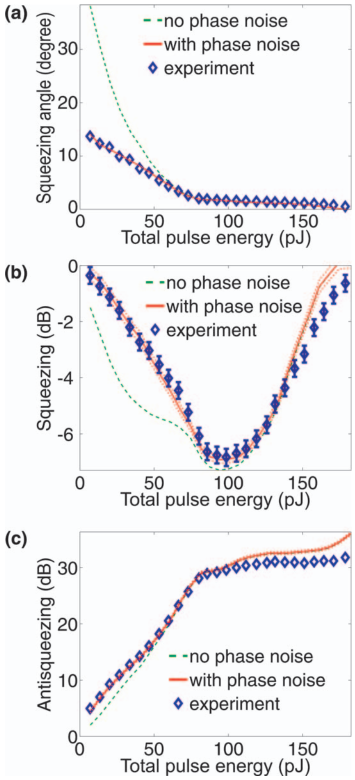

Fig. 3. Diamonds show the experimental results of the (a) squeezing angle, (b) squeezing, and (c) antisqueezing for the 13.2 m fiber. Error bars on the squeezing data indicate the uncertainty in the noise measurement; for the antisqueezing, the error bars were too small to be plotted. Solid and dashed curves show the simulation results with and without additional phase noise, respectively. Dotted curves indicate the sampling error in the simulation results.

angles as shown by the red solid curve in Fig. 3(a). After taking the 13% linear loss into account, the theoretical results for squeezing and antisqueezing, which are given in Figs. 3(b) and 3(c) by red solid curves, achieve a very good match with the experimental results. From the simulations, the effect of the GAWBS is seen to be a reduction in squeezing for lower pulse energies. Above the soliton energy (≈120 pJ), the deterioration of squeezing is attributed to the Raman effects, since it cannot be reasoned by the simulations with only electronic nonlinearity and dispersive effects; in addition, the third-order dispersion has a noticeable effect on the squeezing.

In conclusion, we have demonstrated what is to our knowledge a new record of squeezing -6.8 ± 0.3 dB (-10.4 ± 0.8 dB after correction for linear losses) in optical fibers. We also provided the experimental evidence of the Raman-induced limit to the squeezing in the fiber, which fits very well with the simulations. Although there is still residual discrepancy between simulations and experiments in the squeezed and antisqueezed quadratures at higher energy, which could be due to effects such as imperfect Raman spectrum modeling or initial pulse-shape distortion, the theoretical model has been proved to be comprehensive and highly efficient. Through the work, the further improvement of squeezing generated in fibers is expected by tailoring the optimal fiber length. This highly squeezed polarization state is also a good source for applications in quantum information and communication, particularly due to the ease of detection without the need for an external phase reference, for example, distillation of quantum states afflicted by non-Gaussian noise [14] and entangled states [15].

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