Amplitude-squeezed solitons from an asymmetric fiber interferometer

Dmitriy Krylov and Keren Bergman

Department of Electrical Engineering, Princeton University, B312, E-Quad, Olden Street, Princeton, New Jersey 08544

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We experimentally demonstrate a new scheme for generating amplitude-squeezed solitons in an asymmetric fiber Sagnac loop. We measure by direct detection what is to our knowledge a record reduction of 5.7 ± 0.1 dB (73%) and, with corrections for linear losses, 6.2 ± 0.1 dB (76%) in the photon-number fluctuations below the shot-noise level. The same scheme is also shown to generate significant classical noise reduction and is limited by Raman effects in fiber.

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Generation of amplitude-squeezed states by use of Kerr nonlinearity in optical fibers was recently demonstrated in a novel scheme pioneered by Friberg *et al.*, who used soliton propagation followed by spectral filtering.[1] By launching a solitonlike pulse with energy slightly greater than the fundamental soliton energy ($N > 1$) into a fiber of length equivalent to several soliton periods followed by a spectral filter, it is possible to observe a reduction in photon-number fluctuations by direct detection. In subsequent experiments a reduction of as much as 3.8 dB was directly detected with femtosecond pulses.[2,3] The filtering action also introduces additional zero-point fluctuations into the system, limiting the highest achievable squeezing to approximately 8 dB below the shot-noise level for ideal fibers and bandpass filters.[4]

Recently it was proposed that amplitude-squeezed pulses can be produced by interference between counterpropagating fields in an asymmetric fiber Sagnac loop.[5] For the case of soliton squeezing the idea that interfering a high-energy ($N > 1$) soliton pulse with a weaker pulse or a dispersive wave can produce squeezing is also consistent with soliton perturbation treatment[6] as well as the general quantum theory of soliton propagation.[7,8] The geometry proposed in Ref. 5 is well suited for testing this idea in practice and was recently explored experimentally by Schmitt *et al.*[9] Different geometries for achieving amplitude squeezing, such as polarization interferometry, were also demonstrated recently.[10] In this Letter we experimentally demonstrate the asymmetric fiber Sagnac approach and report what is to our knowledge a record 5.7 ± 0.1 dB (73%) directly detected photon-number squeezing below the shot-noise level. With correction for linear system losses, the actual amplitude squeezing is 6.2 ± 0.1 dB (76%). We have also measured a significant reduction in the classical noise inherent in the optical signal.

The experimental setup is shown in Fig. 1. A Spectra-Physics Opal optical parametric oscillator is used as a source of 182-fs (FWHM) sech-shaped optical pulses at a repetition rate of 82 MHz and centered at 1550 nm. The corresponding dispersion length ($\beta'' = -19\ \mathrm{ps}^2/\mathrm{km}$) in the standard polarization-maintaining (PM) fiber, Fujikura SM15-P-8 with an 8-μm core diameter, that was used in the experiments is ~54 cm, and the soliton period is 86 cm. The average power required for production of a fundamental ($N = 1$) soliton, as determined by measurement of the pulse temporal autocorrelation and the optical spectrum following propagation in 10 m of the PM fiber, is 20 ± 1 mW. We use an asymmetric Sagnac loop configuration in which the light is split by a free-space antireflection-coated beam splitter and then coupled from both ends into a 3.5-m section of the PM optical fiber. The free-space configuration is necessary to preserve the spectrum of the signal in both arms of the interferometer, which is not always possible with fiber splitters for femtosecond pulses. The experiment is not critically sensitive to the splitting ratio, as the same qualitative results are obtained with a range of splitting ratios. In the experiments reported here the fiber coupling was varied until optimal squeezing was observed for input splitting of 88/12. Subsequently, all the optical powers specified below incorporate the losses that were due to the fiber coupling and correspond to the optical powers that were propagating in the fiber.

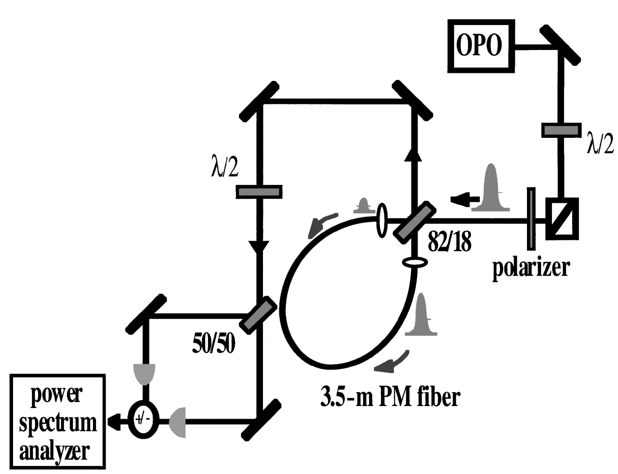

Fig. 1. Experimental setup: OPO, optical parametric oscillator; $\lambda/2$, half-wave plates.

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With such highly asymmetric splitting, most of the energy propagates in the 88%-reflection arm. The noise properties of this pulse are modified in accordance with the quantum nonlinear Schrödinger equation.[5,6,11] For lower input optical powers, the field in the 12%-transmission arm is a dispersive wave that propagates linearly in the fiber loop but begins to exhibit solitonlike behavior for higher input powers. We carefully control the polarization of the pulses entering and exiting the fiber loop to ensure optimal interference. The photocurrent fluctuations associated with the pulse, which result from the interference of the two counterpropagating fields in the loop, are measured by a balanced receiver followed by a HP3588A power spectrum analyzer (PSA) operated in the zero-span regime in a narrow-band interval centered around 5 MHz with a resolution bandwidth of 17 kHz. The PSA measures the noise power as the rms fluctuations in the resolvable flat window around 5 MHz, which then are normalized to a 1-Hz bandwidth. We use the subtraction mode of the receiver for shot-noise calibrations, and the summing mode is used for direct detection of the amplitude fluctuations.

Using the balanced receiver configuration is a convenient way of keeping the maximum power falling on the two reverse-biased photodiodes (Epitaxx ETX-1000T; quantum efficiency 95% at 1550 nm) below saturation values. The signal beams are carefully focused to just fit within the 1-mm-diameter active area of the two photodetectors, since both underfocusing and overfocusing the beam introduce additional noise. To avoid saturation of the electronics by the strong 82-MHz frequency component owing to the repetition rate of the laser system, the overall bandwidth of the receiver is limited to 35 MHz.

We performed several calibrations within the experimental setup as well as in free space to establish accurately the relevant noise levels. Subtracting the photocurrents eliminates the classical fluctuations present in the laser signal with an extinction ratio of $\sim$25 dB, and the measured noise levels following this subtraction accurately represent the shot noise. The noise floor of the PSA is at -138 dBm/Hz, which is also the noise magnitude of the dark current. By comparison, the thermal noise that is due to the shunt resistance of the receiver is approximately -128 dBm/Hz. The dominating noise source is the 45-dB power amplifier used between the receiver and the PSA in conjunction with a 35-MHz low-pass filter with a 50-dB roll-off at 82 MHz. The measured noise floor of the whole detection setup, with the photodiodes covered by dark cloth, is -116 dBm/Hz. With the optical powers used in the experiment, the shot noise is at least 7 dB above this noise floor, so squeezing can be observed. All the values for the shot-noise levels were confirmed to within 0.1 dB by measurement of the noise power versus the incident optical power for the above experimental setup as well as in free space. These noise values were shown to scale correctly in all cases as the optical power was reduced to the noise floor of the receiver. We performed free-space calibration to eliminate any potential noise sources associated with fiber nonlinearities. Comparing the free-space calibration values with those obtained for a straight piece of fiber as well as with those obtained within the experimental setup allowed us to determine accurately the shot-noise level for the entire range of experimental results. The sum of the photocurrent fluctuations as a function of incident power measured in free space represents the classical noise inherent in the laser signal, which can be more than 3 dB above the shot-noise level.

The results of the squeezing experiments are shown in Fig. 2. Figure 2(a) is the plot of the shot-noise level, the classical noise, and the noise variations that are due to amplitude squeezing and antisqueezing in units of dBm per Hertz all as a function of the incident optical power. In Fig. 2(b) the classical noise and the noise variations that are due to amplitude squeezing and antisqueezing are normalized to the shot-noise level and plotted as a function of the incident optical power. We observe three squeezing resonances (at 30, 52, and 68 mW). The largest resonance occurs at the input power into the loop of 68 mW, which corresponds to $N = 1.85 \pm 0.05$ in soliton units. The reduction below shot noise is measured to be 5.7 ± 0.1 dB (73%). Taking into account 90% overall detection efficiency, which includes detector quantum efficiencies and 5% losses that include losses at the fiber outputs and the imperfect mode overlap at the output beam splitter, this squeezing level corresponds to 6.2 ± 0.1 dB (76%) reduction. This result is in very

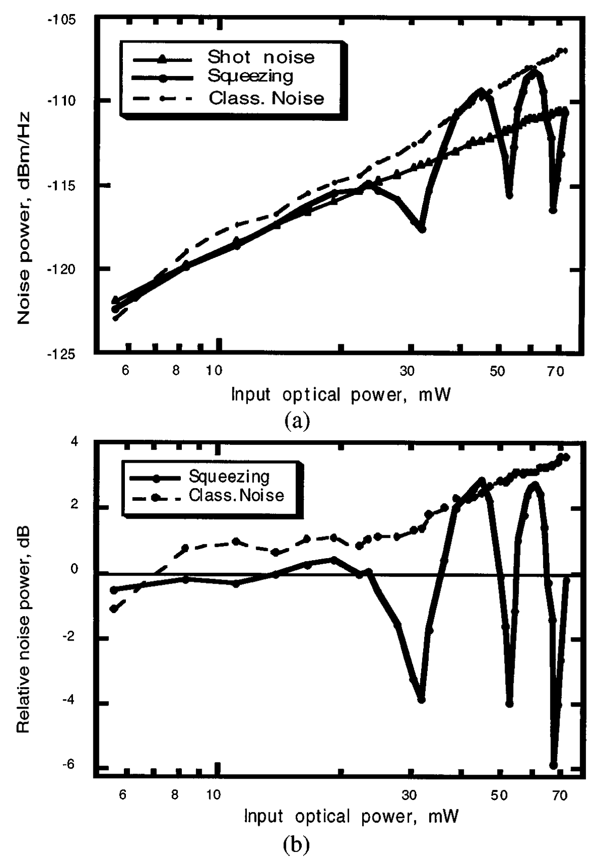

Fig. 2. Absolute (a) and relative (b) noise power fluctuations versus optical power incident into the 88%-reflection port.

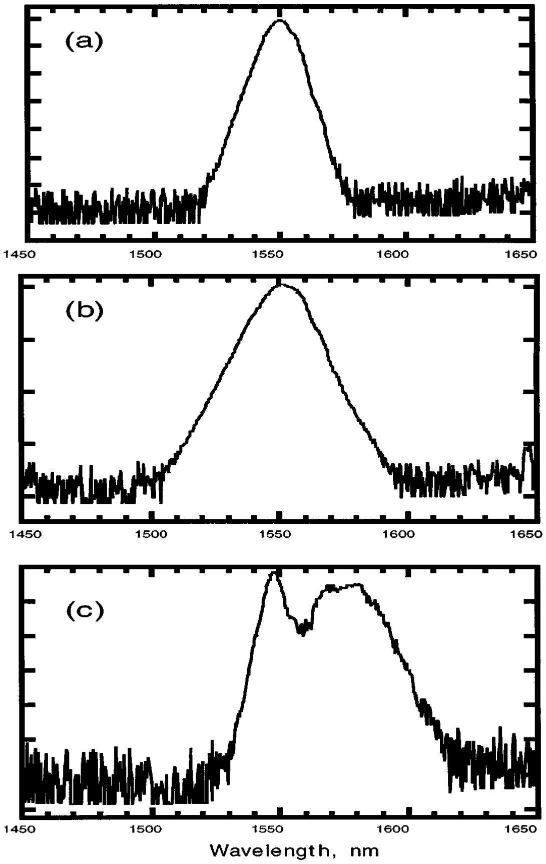

Fig. 3. Input (a) and output pulse spectra of a 182-fs $N = 1.8$ soliton after propagating through 3.5 m (b) and 9 m (c) of standard PM fiber.

good agreement (within 0.5 dB, or 10%) with numerical simulations done for an $N = 1.7$ sech pulse propagating through 6.4 dispersion lengths in a loop with a 90/10 splitting ratio.[12] We also note that an important practical advantage of this squeezing scheme is the removal of the classical noise inherent in the laser signal in addition to reduction in quantum photon-number fluctuations. For the largest squeezing resonance at 68 mW incident power we observe more than 3 dB of classical noise reduction. The total noise reduction including classical and quantum amplitude fluctuations is in excess of 9 dB.

Raman effects in fibers have been predicted to limit the amount of squeezing observed for longer propagation distances.[8,12] To test this we also performed additional experiments with different fiber lengths (up to 9 m). Figure 3(a) shows the spectra of the input soliton pulse ($N = 1.85$) and of the same pulse after it propagates through 3.5 m (b) and 9 m (c) of fiber. We note that, while after the pulse propagates through 3.5 m of fiber, the spectrum is slightly broadened but virtually unchanged, after the pulse propagates through 9 m of fiber, most of the pulse energy has been shifted by approximately 30 nm toward the longer wavelengths. Since the pulse traveling in the 12%-transmission arm does not have enough energy to experience a significant Raman shift, one might expect that the interference is no longer optimal and the squeezing is reduced. In fact, the maximum amplitude squeezing observed for the long fiber lengths was approximately 2.5 dB. In addition to shifting the spectrum, noise from Raman effects as shown to limit the maximum observable squeezing with femtosecond pulses to approximately 8 dB from a possible 11 dB for ideal fibers.[12] The Raman noise–imposed limit on squeezing is still a subject of continuing theoretical and experimental investigation.

In conclusion, we have experimentally demonstrated a new scheme to produce nonclassical states of light in a highly asymmetric Sagnac loop and measured what is to our knowledge a record 5.7 ± 0.1 dB (6.2 ± 0.1 dB with correction for losses) reduction in photon-number fluctuations of soliton optical pulses. This experiment conclusively shows that interference between the two counterpropagating fields is the main mechanism that produces the noise reduction. The scheme is also useful in removing classical noise from the signal and appears to be limited by the Raman effect for longer propagation distances.

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