Photon-Number Squeezed Solitons from an Asymmetric Fiber-Optic Sagnac Interferometer

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Direct photon-number squeezing is demonstrated, for the first time to our knowledge, in a nonlinear fiber-optic interferometer. Launching 126-fs solitons into a highly asymmetric Sagnac loop, the maximum photocurrent noise reduction was 3.9 ± 0.2 dB below shot noise, corresponding to 6.0 ± 0.9 dB, when corrected for linear losses. The loop is a model system for squeezing generated by the interference of two pulses after nonlinear propagation through a fiber. [S0031-9007(98)07158-0]

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Optical solitons in fibers are an experimentally accessible model for studying nonlinear dynamics in a quantum field theory based on the quantum nonlinear Schrödinger equation (QNLSE) [1]. Furthermore, the unique properties of optical solitons in fibers make them attractive for high-bit rate long-distance repeaterless communication systems [2] and all-optical cascadable switching [3].

The quantum nature of optical solitons imposes a fundamental limit, e.g., to high precision measurements or Terabaud communication systems [4]. It has been shown that the quantum uncertainty of solitons can be reduced [5–7]. The strongest squeezing in fibers so far has been achieved for nonsoliton pulses in the zero dispersion regime at about 1.3 μm [8]. However, substantially more squeezing has been predicted for solitons, but has not yet been verified experimentally [9].

The first fiber soliton squeezing experiments [5] used a balanced Sagnac loop and a local oscillator for projecting out the below-vacuum uncertainty of the squeezed state. If corrected for the detection efficiency, up to 3.2 dB of squeezing was inferred [10]. Theoretically, more than 10 dB squeezing is predicted in this system [10–13], but the experiments and a numerical simulation [14] showed that already a slight imbalance of the splitting ratio limits the observable squeezing [10]. Therefore, this theoretically promising system seems impractical as a stable source for highly squeezed quantum solitons.

Experimental generation of amplitude-squeezed solitons by spectral filtering was recently pioneered [6] and optimized [7]. The technique is almost immune to phase noise and the squeezing can be directly detected. So far it has yielded the strongest observed noise reduction for solitons in fibers of 3.8 ± 0.2 dB [7], but a comparison of the inferred squeezing (6.4 dB) with theory (8 dB) [15] suggests that this method has been optimized as far as possible.

In this Letter we present the first experimental results of strong noise reduction of 3.9 ± 0.2 dB below the standard quantum limit, using a highly asymmetric Sagnac interferometer. The fiber loop interferometer is a model system for a new broad class of squeezing systems based on the interference of two pulses that acquire intraspectral quantum correlations according to the QNLSE [16]. The observed photon-number squeezing reflects the quantum characteristics of distinct frequency components in the multimode field rather than the noise variances averaged over the spectral and temporal modes. The observed photocurrent noise reduction is already comparable to the, so far, best results for fiber solitons [7] and a recent first theoretical analysis already predicted more than 11 dB of squeezing for this system using a 90:10 splitting ratio [14]. Based on a linearized model for the propagation of quantum fluctuations [17], we calculated the same noise reduction for our experimental fiber length and a splitting ratio of 92.5:7.5, if the Raman effect can be neglected, thus demonstrating the high potential of this squeezing mechanism. In contrast to the balanced Sagnac loop, the highly asymmetric Sagnac interferometer produces directly detectable squeezing and does not require a local oscillator for extraction of the squeezed signal. Additionally, it is insensitive to small changes in the splitting ratio. These two significant experimental advantages make it more likely to reach the envisioned theoretical limit. Therefore this novel squeezing system combines the high theoretical potential of the balanced Sagnac loop with the advantage of direct photon-number squeezing and the robustness of the spectral filtering method. It could pave the way towards a reliable and stable source for the efficient generation of highly squeezed quantum solitons.

The experimental setup is shown in Fig. 1. A chromium-YAG laser is passively mode locked by a saturable absorber and produces stable, bandwidth-limited solitons with a duration of 126 fs (FWHM), centered at 1.51 μm. The soliton pulses are launched into a Sagnac ring interferometer consisting of a beam splitter (BS1) with a highly asymmetric splitting ratio and 6.40 m of polarization-maintaining single-mode fiber (3M-FSPM 7811, MFD = 5.5 μm). The soliton energy was experimentally determined to be 56 ± 4 pJ by studying the nonlinear pulse evolution. The polarization of the two pulses is adjusted to one of the main axes of the birefringent fiber by half-wave plates (HP). While counterpropagating through the fiber loop, both pulses acquire a nonlinear phase shift relative to each other due to their different intensities and

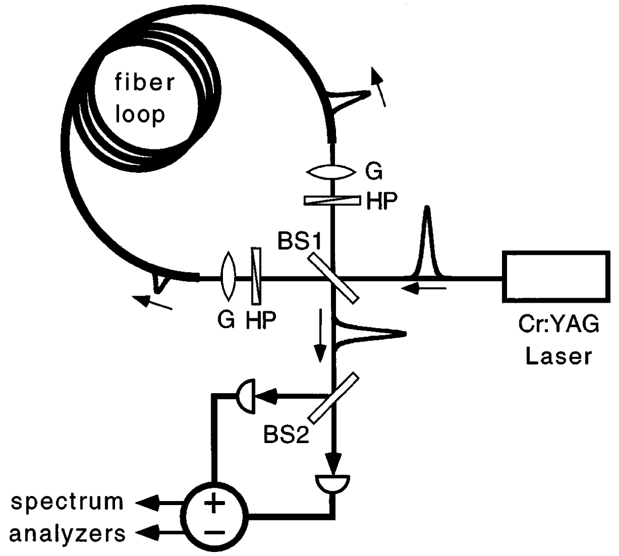

FIG. 1. Experimental setup for directly detectable squeezing from an asymmetric fiber-optic Sagnac interferometer. (BS) beam splitter, (HP) half-wave plate, (G) grin lens.

the Kerr-nonlinear refractive index. This intensity dependent phase shift controls the interference at the beam splitter. Hence the transmission at the output port of the fiber varies periodically as a function of the light intensity at the input port [18,19].

The transmitted light is analyzed with a balanced two-port detector consisting of a 50:50 beam splitter (BS2) that directs the light onto two photodetectors. In order to avoid a saturation of the transimpedance amplifiers for the ac-current, the repetition frequency of the laser was suppressed by more than 40 dB. The ac photocurrents were measured at a frequency of 20 MHz. The sum of the ac photocurrents represents the photon-number fluctuations of the detected light and the difference current calibrates the shot-noise reference level. The two noise levels were simultaneously recorded by two spectrum analyzers with zero span and a resolution bandwidth of 30 kHz. One hundred sweeps of 15 ms each were averaged to yield one data point in the noise measurements. Using an amplitude-modulated diode laser, the two-port detector was balanced to an extinction ratio better than 31 dB.

In order to minimize the linear losses in the detection system, gradient index lenses (G) were antireflection (AR) coated on one side and index matched to the fiber on the other side. The detectors were equipped with AR-coated InGaAs photodiodes (Epitaxx ETX-500T) that were especially preselected for high quantum efficiency. The window caps of the photodiodes were removed to avoid Fresnel losses at the glass surfaces and the measured quantum efficiency was (92 ± 5)%. The overall detection efficiency was measured to be (79 ± 5)%.

The experimental results of this setup are shown in Fig. 2. In the upper picture (a) the transmitted pulse energy is plotted versus the launched input-pulse energy. This transfer function is highly nonlinear and shows oscillations as expected from theory. The modulation depth of the oscillations is not very pronounced, due to the highly asymmetric splitting ratio of 90:10, where the interference contrast can only be partial. With increasing input-pulse energy the modulation depth is decreased even further. This can be attributed to the intensity dependent stimulated Raman scattering which separates the counterpropagating pulses temporally and spectrally. Thus the interference at the beam splitter is degraded, which ultimately leads to an incoherent summation of the pulse intensities at the detector.

In Fig. 2(b) the relative signal-noise power is plotted normalized to the shot-noise reference level, which is set to zero on a logarithmic scale. The quantum noise is reduced to a minimum at each input energy, where the nonlinear input-output transfer function approaches zero slope, thus showing an optical limiting effect. The best squeezing occurs at a pulse energy of 60 pJ, corresponding to a fundamental soliton in one propagation direction and an essentially dispersive pulse in the other direction.

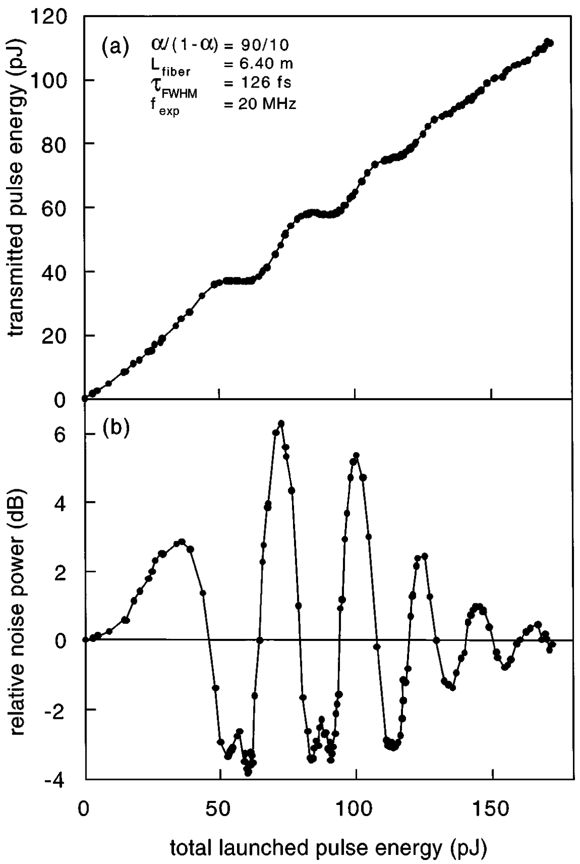

FIG. 2. Nonlinear energy-transfer function and squeezing from a 90:10 asymmetric Sagnac loop, plotted versus the launched pulse energy. (a) The transmitted output pulse energy shows an optical limiting effect at input energies of 53 pJ and 83 pJ. (b) Photocurrent noise power relative to shot noise (0 dB). The quantum fluctuations are reduced below shot noise at input energies where optical limiting occurs.

At those energies where the transfer function is especially steep the output quantum fluctuations are increased up to 6 dB above shot noise. For higher input-pulse energies, squeezing and antisqueezing of the quantum fluctuations disappear, as the Raman effect degrades the interference at the beam splitter. The phenomenon of quantum noise reduction corresponding to optical limiting, as well as the coincidence of noise enhancement and a steep slope of the energy-transfer function, is repeated regularly. This squeezing behavior can be made qualitatively plausible in a heuristic classical picture, where the absolute steepness of the slope is mainly responsible for the noise transfer [20]. For a correct and quantitative understanding of the quantum noise transfer, a quantum mechanical analysis is of course necessary and will be briefly discussed below.

In Fig. 3 the squeezing behavior was investigated for different splitting ratios of 79.5:20.5, 87.5:12.5 and 90.0:10.0 and the detection efficiency was 71%, 72%, and 79%, respectively. The strongest squeezing of 3.9 ± 0.2 dB corresponds to (59 ± 2)% photocurrent noise reduction. It was observed for a splitting ratio of 90.0:10.0. If corrected for linear losses, more than 6.0 ± 0.9 dB of squeezing can be inferred. For more symmetric splitting ratios the squeezing deteriorates, which suggests that a splitting ratio more asymmetric than 90:10 might yield even better squeezing. Moreover, the squeezing regions and the corresponding zero-slope parts of the transfer function are shifted to higher input-pulse energies for a more symmetric Sagnac loop. This is evident, since the location of a zero slope is determined by a certain intensity difference of the counterpropagating light beams, which is achieved at higher input-pulse energies for a more symmetric splitting ratio. A variation of the fiber length is not expected to change the situation drastically, since within a wide range an increase of the fiber length is almost equivalent to an increased input energy and therefore mainly rescales the input energy axis. A deviation from this behavior is mainly due to pulse distortion and higher order effects. Therefore, the fiber length was chosen such that a clean, unchirped $N = 1$ soliton travels on the 90% path of the 90:10 loop interferometer at that input energy, where optimum squeezing is expected at the first optical limiting plateau.

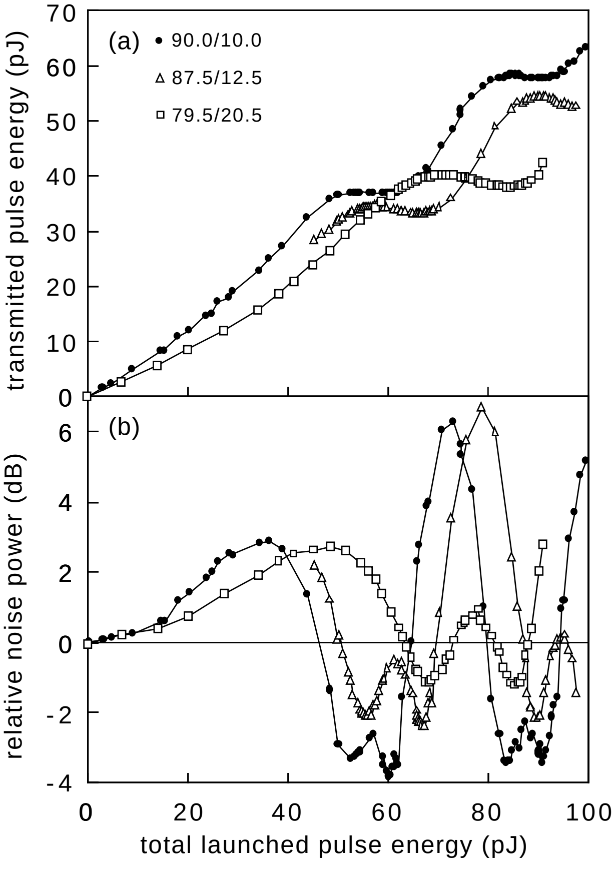

FIG. 3. (a) Nonlinear input-output behavior and (b) squeezing for different splitting ratios of the asymmetric Sagnac interferometer.

The squeezing regions in Fig. 3 show a double minimum structure already observable in Fig. 2. The input-output functions are not only flattening where squeezing occurs but exhibit a local maximum and minimum with zero slope where the quantum fluctuations are maximally reduced. Inbetween, the slope is negative and the steepness increases. Consequently, the squeezing is degraded, confirming the heuristic picture.

The shot-noise reference level was verified by two additional, mutually independent calibrations. First, the squeezed signal was attenuated by various neutral density filters and proved to scale as expected for quantum noise. Second, the polarization of one of the counterpropagating pulses was rotated by 90° and then launched onto the orthogonal birefringent axis of the polarization-maintaining fiber. Because of the different group velocities, the pulses no longer coincide at BS1 and the noise powers of the sum and the difference current become equal. Since our laser source was thoroughly checked to be shot-noise limited, this confirms our shot-noise reference level. In addition, this procedure excludes the possibility that the squeezing is caused, e.g., by spectral filtering at the photodiodes, since in that case the squeezing should not disappear. Both procedures reproduced the original shot-noise calibration within an experimental error bar of 0.2 dB.

In order to compare the experimental results with theory, the pulse propagation through the Sagnac loop was numerically simulated in a quantum mechanical approach. For this purpose only the lowest order effects of group-velocity dispersion and self-phase modulation of the QNLSE were considered:

$$\frac{\partial \hat{A}}{\partial z} = i\gamma \hat{A}^{\dagger}\hat{A}\hat{A} - \frac{i}{2}\,\beta_2\,\frac{\partial^2}{\partial T^2}\,\hat{A}\,. \qquad (1)$$

The operator $\hat{A}$ is linearized by separating the classical mean value and the quantum mechanical part: $\hat{A} = \langle A \rangle + \hat{b}$, and the operator $\hat{b}$ is then discretized and expanded in a basis of creation and anihilation operators that fulfill the boson commutation relations [17]:

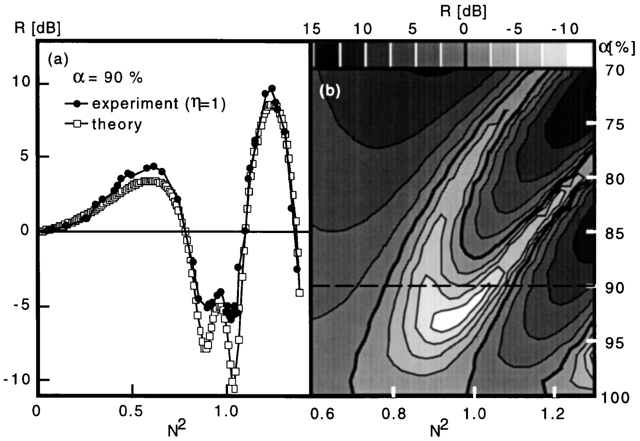

FIG. 4. Theoretical simulation of squeezing of 126-fs pulses in a 6.4-m-long fiber (approximately 8 times the soliton period) based on a linearization of quantum fluctuations. (a) Comparison with experimental data. (b) Contour plot of the relative noise power R [dB] in dependence of the splitting coefficient α (vertical axis) and the input-pulse energy scaled in soliton units (horizontal axis). The shot-noise level is marked by bold lines.

$$\hat{b}_i = \sum_k \mu_{ik} \hat{a}_k + \nu_{ik} \hat{a}_k^\dagger . \tag{2}$$

The coefficient matrices are propagated through the Sagnac interferometer using the symmetrized split-step Fourier method. In Fig. 4(a) the results of this theoretical simulation are compared to the experimental results, which are corrected for the detection efficiency, and the axis for the soliton energy (N^2) has been adjusted by 5% within its experimental error bar. The theoretical calculations did not involve any fitting routines. Theory and experiment agree qualitatively well, but quantitatively the inferred squeezing does not reach the predicted value. There are two likely explanations. First, there is a residual mode mismatch of the interfering light fields at beam splitter BS1. Second, the squeezing is increasingly degraded for higher input energies by the Raman effect, which is not yet included in the numerical calculations. In a future experiment the influence of the Raman effect may be reduced by working with longer pulses.

Figure 4(b) shows a theoretical contour plot of the quantum fluctuations for varying splitting ratios. Regions with squeezing (antisqueezing) are filled with bright (dark) gray shades. The dashed line corresponds to the simulation in Fig. 4(a). The best squeezing is achieved for a splitting ratio of 92.5:7.5, where maximum and minimum transmission of the nonlinear transfer curve merge together to a saddle point, resulting in a broad plateau, where the quantum noise is maximally reduced by more than 11.0 ± 0.5 dB below shot noise. For decreasingly asymmetric splitting ratios the transfer curve exhibits two zero-slope extrema, which are responsible for two distinct squeezing minima that are incresingly sharp, but less deep. For more asymmetric splitting ratios the oscillations of the input-output curve disappear and so does the squeezing. Those calculations show that the optimum squeezing critically depends on the splitting ratio. Further numerical calculations show that the fiber length, in contrast, can be varied within a wide range without significant degradation of squeezing, provided that a shorter fiber is compensated for by an increased input energy.

In conclusion, we have shown experimentally, for the first time to our knowledge, that a highly asymmetric Sagnac interferometer can be used to deamplify quantum fluctuations below the shot-noise level. In contrast to earlier squeezing experiments with balanced Sagnac loop interferometers, directly detectable photon-number squeezing was produced. The best observed squeezing was 3.9 ± 0.2 dB (6.0 ± 0.9 dB inferred). The experiments were found to be in good agreement with a quantum mechanical model that predicts more than 11 dB for this novel squeezing system.

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