Observation of Optical Soliton Photon-Number Squeezing

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We report the photon-number squeezing of optical solitons. 2.7 ps pulses were launched as solitons down a 1.5 km optical fiber. For energies slightly above that of fundamental solitons, they broadened spectrally due to self-phase modulation caused by $\chi^{(3)}$ nonlinearities. Filtering away outlying components of the broadened spectra squeezed the soliton's photon-number fluctuations to 2.3 dB (41%) below the shot-noise limit. Accounting for losses, this corresponds to 3.7 dB (57%) photon-number squeezing. A quantum field-theoretic model shows that the outlying spectral components have large energy fluctuations, so that their removal causes squeezing. [S0031-9007(96)01512-8]

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An optical soliton in an optical fiber acts as a "particle" of light, according to classical electrodynamics, and can propagate long distances without changing shape or losing energy. Its particlelike nature is robust—a soliton is insensitive to perturbations and undistorted by collisions with other solitons. This, understandably, has practical implications and soliton-based telecommunication technologies are actively being pursued [1].

A classical electrodynamical description of soliton propagation is inadequate if a soliton's quantum mechanical properties are of interest. Quantum mechanical descriptions not only better describe a soliton's noise properties, but also predict the existence of unique quantum mechanical soliton effects [2–9]. Most of the desirable properties of classical optical solitons, including their particlelike nature, are retained by such quantum mechanical descriptions [2–4].

The first quantum mechanical soliton effect to be observed experimentally was quadrature-amplitude squeezing, predicted by Carter *et al.* [5,6]. For such squeezing, soliton amplitudes can fluctuate with magnitudes either smaller or greater than the standard quantum limit (SQL) of coherent light pulses, depending on the measured phase [5]. The "entanglement" of two solitons makes quantum nondemolition measurements possible, and was the second quantum mechanical soliton effect to be observed [7]. As described by Haus *et al.,* two solitons with different velocities become quantum mechanically entangled when they collide [8]. A measurement of the phase of one soliton then allows the photon number of the other soliton to be determined without introducing losses or photon-number noise.

Recently, we have observed an unanticipated new quantum mechanical soliton effect—soliton photon-number squeezing [9]. By removing a soliton's outlying spectral components with a spectral bandpass filter, we were able to reduce its photon-number fluctuations to as much as 2.3 dB (41%) below the SQL. (For photon-number squeezing, the SQL is the usual shot-noise limit for coherent pulses of light.) Accounting for measurement losses and imperfect detector efficiencies, this implies a total photon-number squeezing of 3.7 dB (57%). Only squeezed light generation using a cw semiconductor laser at 66 K has produced photon-number squeezing with greater magnitudes [10]. At room temperatures, a maximum of 3.7 dB (57%) has been observed using second-harmonic generation in a monolithic $MgO:LiNbO_3$ resonator cavity [11]. The observed maximum for semiconductor lasers at room temperature was 2.3 dB (41%) [12]. For optical pulses, the maximum observed photon-number squeezing was 0.5 dB (11%) using a nondegenerate optical parametric amplifier [13] and 1.0 dB (20%) in a photon-antibunching experiment [14].

The experimental method used to squeeze solitons is outlined in Fig. 1. Short optical pulses were launched as $N > 1$ solitons in an optical fiber with anomalous group velocity dispersion, and broadened spectrally. (For hyperbolic secant launch pulses, the peak amplitude N is normalized so that $N \equiv 1$ for fundamental solitons.) After leaving the fiber, the solitons were sent through a spectral bandpass filter that narrowed their bandwidth, removing 5% to 10% of their energy.

In our experiment, optical pulses from a mode-locked NaCl color center laser (CCL) pumped by a Nd:YAG laser were shortened by a modified fiber-grating pulse compressor [7]. Pulses from the compressor were slightly chirped, with a 1.25 nm bandwidth and an estimated 2.7 ps

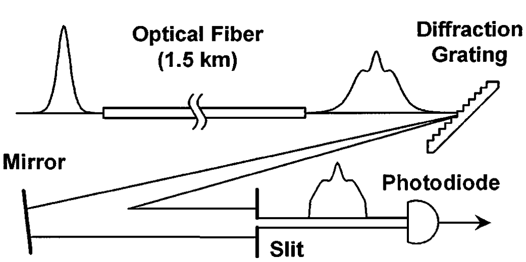

FIG. 1. The soliton squeezing apparatus. Optical pulses acquired spectral sidebands by propagating as $N > 1$ solitons down a 1.5 km length of single-mode, anomalous group velocity dispersion optical fiber. Filtering the soliton with a spectral filter (shown as a diffraction grating and a slit) produced photon-number squeezed light.

duration, centered at 1.455 μm, and at a 100 MHz repetition rate. (Pulse durations and bandwidths are given using their full width at half maximum [FWHM] values.) The optical fiber was a 1.5 km length of single-mode, polarization-preserving, Ge-doped silica-core PANDA fiber (Fujikura SM.13-P) with a $1/e^2$ mode field diameter of 9 μm at 1.3 μm, n_2 taken as 2.6×10^{-16} cm^2/W, and a dispersion D of 10 ps/km nm at 1.455 μm. The soliton period was estimated to be 330 m. Spectral bandpass filtering was done using either a diffraction grating and a slit or a 0.25 m grating monochromator with a 0.2 nm resolution. The best squeezing was obtained for solitons that left the fiber with a 1.5 ps duration, a spectral bandwidth of 1.65 nm, and energies of 12 pJ. Measured fundamental soliton energies were 8 pJ.

The magnitude of the photon-number squeezing was determined by comparing the intensity fluctuations of the squeezed soliton with the intensity fluctuations of a SQL reference pulse having the same energy [15]. Two different comparison methods were used, both yielding the same results. In the simpler method, squeezed solitons were compared with CCL pulses attenuated by 20 dB to remove excess noise [15]. Unattenuated CCL pulses were nearly at the shot-noise level. The delay-line method divided the energy of the soliton equally between two photodiodes using a 50/50 beam splitter. Current from one of the photodiodes was sent through a 30 m electrical delay line, imposing an rf frequency-dependent phase shift with respect to the other photocurrent. Combining the photocurrents gave the squeezed noise level or the SQL level, depending on the relative phase of the photocurrents. This allowed more trustworthy measurements as light levels on the photodiodes did not vary, eliminating intensity or position-dependent photodiode effects.

Squeezing data from a delay line measurement is graphed in Fig. 2. The upper half of the figure shows two rf spectrum-analyzer traces. The upper trace, taken without the delay line, characterizes the rf response of the measuring system. The lower trace, showing both the minima corresponding to the soliton noise level and the maxima (at 6.6 MHz and multiples) corresponding to the SQL, is the squeezing data. (For both traces, the thermal electronics noise was subtracted off.) The noise and corresponding SQL levels are shown more clearly in the lower half of the figure, obtained by subtracting the upper trace from the lower trace and introducing an offset to compensate for the delay line losses. The lower figure shows the difference between the squeezed soliton noise and the SQL to be ~2.1 dB (38%).

Measurements were also made using the attenuated CCL pulse as the SQL reference. The maximum squeezing then observed was 2.3 dB (41%). In both cases, the overall quantum efficiency of the measurement was 72%, including 4% Fresnel coupling losses at the fiber end, 83% grating reflectivities, and 90% detector quantum efficiencies. This implies a total squeezing of 3.7 dB (57%).

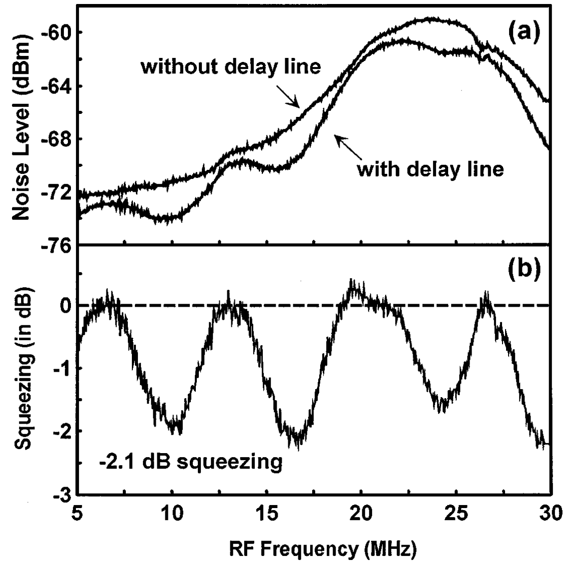

FIG. 2. Experimental squeezing data. The lower curve of (a), obtained using the delay line, gives the soliton noise level and the soliton SQL level. Subtracting off the system frequency response [upper curve in (a)] gives the curve in (b) and shows the squeezing more clearly. The difference between the minima (soliton noise) and the maxima (SQL level) shows the squeezing to be about 2.1 dB.

Measured soliton spectra for several monochromator bandwidths are shown in Fig. 3. Noise levels (adjusted for losses) as a function of the filter bandwidth are shown in the inset. With the monochromator output slit at maximum width, the resulting bandwidth of 2.6 nm was sufficient to obtain 1.0 dB squeezing (A). The best squeezing, 2.7 dB, was obtained for a bandwidth of 1.4 nm (B). For a bandwidth of 0.9 nm, excess noise of 2.3 dB was observed (C). Narrowing the bandwidth to 0.4 nm increased the excess noise to 10.9 dB (D).

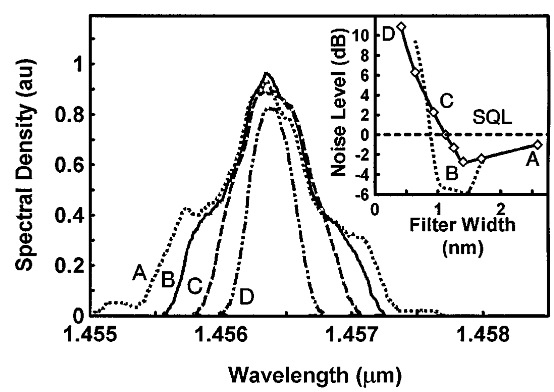

FIG. 3. Measured soliton spectra, and noise levels for varying filter bandwidths (inset). Curves A–D correspond to FWHM monochromator bandwidths of 2.6, 1.4, 0.9, and 0.4 nm. The inset shows the noise levels for curves A–D and other filter bandwidths as a solid line. Theoretical calculations for parameters given in the text are shown as a dotted line in the inset.

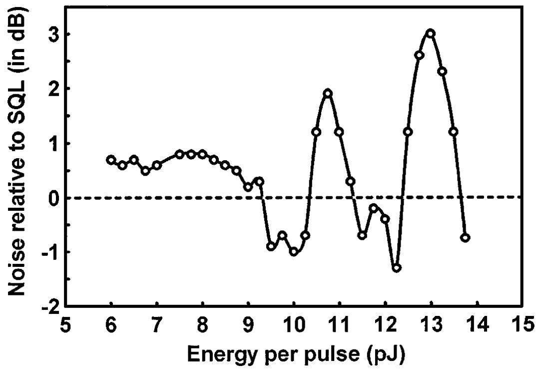

FIG. 4. Squeezing versus launch energy at a fixed filter bandwidth. At low launch energies, excess noise of about 0.6 dB was observed. As launch energies increased, regions of squeezing and excess noise alternated.

Figure 4 shows the variation of the filtered soliton's noise level as the soliton energy was increased. In this case, the grating-slit filter bandwidth was fixed at ~2 nm to give maximum squeezing. At low energies, soliton noise levels were 0.6 dB above the SQL, decreasing to 1.0 dB below as energies were increased. Further increases caused the noise to rise to 2 dB above, to plummet to 1.3–1.4 dB below, to rise again to 3 dB above, and then to fall again to below the SQL. Similar modulations were observed whenever filter bandwidths were large. Other measurements showed that the modulations paralleled changes in the energy transfer input/output curve (see Fig. 5).

To explain how soliton propagation and filtering leads to photon-number squeezing, we first consider the physics

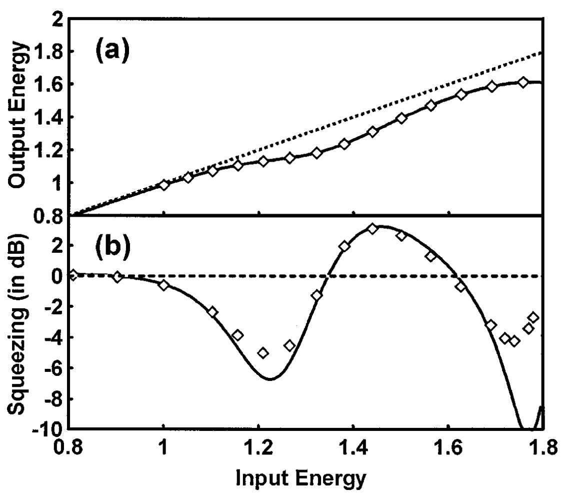

FIG. 5. Squeezing calculations. In (a), the output energy of the filtered soliton is shown plotted against the soliton input energy for parameters given in the text. In (b), the noise levels for filtered solitons are shown, along with the calculated squeezing from the simple heuristic model (solid lines) and the quantum field-theoretic model (rectangular markers). The dotted line corresponds to the SQL and the fundamental soliton energy is taken as unity.

of soliton propagation. Suppose that an $N > 1$ soliton is introduced into an optical fiber. As it propagates, self-phase modulation due to the fiber $\chi^{(3)}$ nonlinearity and the fiber group velocity dispersion interact to cause the soliton's spectrum to periodically broaden and shrink [16]. The soliton energy determines the periodicity of the broadening and shrinking, and the maximum spectral width. Accordingly, when the soliton leaves the fiber and goes through a fixed-width spectral filter, the filtering losses depend on the soliton's energy. A combination of soliton propagation and spectral filtering therefore leads to a nonlinear input/output energy relationship. This is shown numerically in Fig. 5(a) for a spectrally filtered soliton launched as a 2.7 ps, 1.25 nm chirped hyperbolic secant pulse in a fiber 4.5 soliton periods long. Solitons leaving the fiber are assumed to go through a spectral filter with a 2.52 nm step-function passband centered on the pulse's spectrum.

Suppose that the photon-number noise of the launched solitons is due to small amplitude fluctuations of fixed-width hyperbolic secant pulses. Soliton propagation converts these amplitude fluctuations to fluctuations in the spectral width and shape of the soliton as it leaves the fiber. This, in turn, leads to nonlinear loss modulations after spectral filtering. Squeezing occurs when increasing amplitudes lead to increasing losses (and decreasing amplitudes lead to decreasing losses) so that the loss modulations cancel out the photon-number fluctuations. We estimate the magnitude of the squeezing by numerically propagating and filtering a set of three solitons: one at the mean photon number and the others at the mean photon number $\pm$ one SQL standard deviation. (We take an $N = 1$ soliton to have a mean photon number of 10^8 with an SQL standard deviation of 10^4.) After propagation and filtering, we calculate the differences in photon number between the solitons and compare this with the expected shot-noise level. We assume that the filters randomly delete photons as in a beam splitter, acting to push the noise towards the shot-noise level [15]. This gives a correction factor, and we obtain the squeezing curve shown as a solid line in Fig. 5(b).

A description of soliton photon-number squeezing that is better than the simple heuristic model described above can be given by a quantum field-theoretic model that uses a coherent state positive-P representation to derive a stochastic nonlinear Schrödinger equation [6,17]. An Ito stochastic partial differential equation for the scaled photon flux amplitude field is

$$\frac{\partial \phi}{\partial \zeta} = \left[-\frac{i}{2}\left(1 \pm \frac{\partial^2}{\partial \tau^2}\right) + i\phi^\dagger\phi + \sqrt{i}\,\Gamma(\zeta,\tau)\right]\phi\,, \tag{1}$$

where Γ is a real Gaussian noise with zero mean and a correlation $\langle \Gamma(\zeta,\tau)\Gamma(\zeta',\tau')\rangle = \delta(\zeta-\zeta')\delta(\tau-\tau')/\bar{n}$. Here $\bar{n}$ is a dimensionless photon number scale, and the length and time variables (ζ, τ) are the scaled coordinates in a reference frame that moves with the propagating field at the group velocity of the center frequency of the soliton. For this equation and the corresponding Hermitian conjugate equation for $\phi^\dagger$, the length scales as $t_o^2/|k''|$, with t_o the pulse width and k'' the fiber's group velocity dispersion. Quantum field propagation is performed numerically [17,18]. The output field photon number in the positive-P representation, after spectral filtering, is

$$\langle n \rangle = \int d\omega |f(\omega)|^2 \langle \phi^\dagger(-\omega)\phi(\omega)\rangle, \qquad (2)$$

where $f(\omega)$ is the spectral filter function. Assuming the same initial conditions as for the heuristic model, the calculated squeezing is that given by the rectangular markers in Fig. 5(b). The error bars due to sampling and discretization errors are typically 0.2 dB or less. The result clearly shows that removing the outlying spectral components with a spectral filter reduces the soliton noise fluctuations. From this, we can infer that the photon-number fluctuations of the outlying spectral components are nearly the same as the photon-number fluctuations of the unfiltered soliton.

Calculations from both models gave results in qualitative agreement with the experimental data. The heuristic model, however, overestimates the squeezing. For fixed launch energies, both models show that narrowing the filter bandwidth causes the noise to first dip below the SQL and then to rise as high as 10 dB above the SQL. Numerical results from the quantum field-theoretic model showing this effect are shown as a dotted line in the inset of Fig. 3. Both models also show that as launch energies increase, noise levels at a fixed filter bandwidth first fall below and then rise above the SQL, consistent with the experimental data shown in Fig. 4. The models do not agree in detail with the experimental data, however, although we expect calculations based on the quantum field-theoretic model to be accurate. Lack of agreement is mainly because the initial pulse and the filter characterizations, to which the models are sensitive, are inexact. But some of the discrepancy is due to Raman noise, which has been shown to reduce the squeezing [19].

Reviewing our results, several points stand out. By launching $N > 1$ solitons into optical fibers and spectral filtering away the outlying parts of the resulting broadened spectra, we were able to photon-number squeeze solitons by up to 3.7 dB (57%). Only photon-number squeezing from low temperature semiconductor lasers is larger. Fixing the spectral filter bandwidth and increasing the soliton launch energies, we see alternating regions of squeezing and excess noise generation. Fixing the soliton launch energy slightly above the fundamental soliton energy, we observe squeezing and then excess noise as the spectral filter bandwidth is narrowed. These phenomena are predicted by our models.

We should note that it is quite easy to generate photon-number squeezed light using solitons. All that is needed is a pulse source of the appropriate wavelength, a spectral filter, and a single-mode optical fiber several soliton periods long. We expect soliton photon-number squeezing, like its quadrature-amplitude counterpart [4–6], to be broadband with bandwidths approaching 100 THz. Like soliton quadrature-amplitude squeezing, soliton photon-number squeezing can be generated *in situ* in ultra low-loss fiber waveguides (by using in-line spectral filters) and therefore can be protected from even the small losses that otherwise would destroy its useful properties.

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