Quantum-Nondemolition Measurement of the Photon Number of an Optical Soliton

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(Received 23 March 1992)

We report the quantum-nondemolition measurement of the photon number of an optical soliton. Taking advantage of the conservation properties of quantum solitons, we were able to read out the photon number of a "signal" soliton via the phase of a "probe" soliton after a soliton collision in a single-mode low-loss optical fiber. Subsequent noise measurements showed the photon number fluctuations of the signal soliton at the shot-noise limit to be correlated to the phase fluctuations of the probe soliton, signifying a backaction-evading measurement of the photon number.

PACS numbers: 42.50.Dv, 03.65.Bz, 42.50.Rh

An act of quantum measurement usually disturbs the system being observed, while an act of classical measurement leaves a macroscopic system unaffected. However, every quantum measurement does not necessarily disturb the variable being measured. Variables that can be measured without being perturbed are quantum-nondemolition (QND) observables, and the associated interaction Hamiltonian between the system and a probe is labeled "backaction evading" [1]. Consider the photon number of an optical soliton confined to a low-loss optical fiber. As the photon number is a QND observable, repeated backaction-evading measurements of the soliton's photon number are feasible—noise is introduced only into the soliton's phase. This implies that a soliton can be prepared in a near photon number eigenstate and that repeated measurements can be performed on such a quantum-mechanical eigenstate [2,3]. This would allow tests of proposed QND measurement schemes [1], make possible increased measurement accuracies, and ultimately lead to an improved understanding of quantum-mechanical states.

In this Letter, we report the QND measurement of the photon number of an optical soliton. Previous QND measurements determined the cw quadrature amplitude of light in an optical fiber [4] or a parametric downconvertor [5], or the cw intensity of light passing through a cavity [6]. For such experiments, the photon number for a finite measurement time or frequency interval was not an exactly conserved quantity, due to the dispersion and nonlinearity of the fiber or the nonlinear medium, the birefringence in the parametric down-conversion medium, or the finite photon lifetime in the cavity.

Optical solitons have particularly advantageous propagation and collision properties [7]. They propagate and collide without changing shape or losing energy by maintaining a balance of self-phase-modulation from the fiber's Kerr nonlinearity and the fiber's negative group-velocity dispersion (GVD). The consequence is that the photon number of a soliton changes neither with propagation nor by interaction with other solitons, thus allowing the QND measurement of a pulse with a well-defined photon number. As optical fiber losses are ~ 0.2 dB/km at 1.52 μm, solitons can travel and interact over many meters, giving rise to large effective nonlinear interactions. By using solitons of short duration, Brillouin scattering can be eliminated and phase noise from guided-acoustic-wave Brillouin scattering (GAWBS) can be greatly reduced [4]. This makes possible broad-bandwidth optical fiber QND measurements at room temperatures.

We used soliton collisions, recently observed experimentally [8,9], to perform the QND measurement. When two solitons with different wavelengths and velocities collide (Fig. 1), their respective phases and center positions are shifted according to their photon number and momentum. Inverse scattering theory describes such a soliton collision as an $N=2$ soliton solution of the classical nonlinear Schrödinger equation, and shows it to be well approximated by two $N=1$ solitons far from the collision center [10]. Solutions of a quantum nonlinear Schrödinger equation behave in a similar way, with quantum soliton states as superpositions of soliton eigenstates of both photon number and momentum operators [7,11]. Photon number and momentum are QND observables, phase and center position are the corresponding readout observables, and the QND and corresponding readout observables obey uncertainty relationships.

As a result of a soliton-collision QND measurement, a probe soliton acquires a phase shift ϕ_p and a timing shift t_p given by

$$\phi_p = 2\arctan\left[\frac{\eta_p+\eta_s}{\xi_p-\xi_s}\right] - \arctan\left[\frac{\eta_p-\eta_s}{\xi_p-\xi_s}\right] \qquad (1)$$

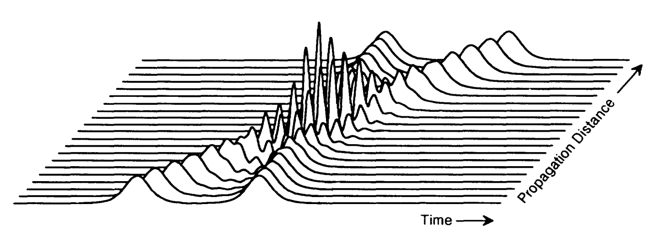

FIG. 1. The collision of two optical solitons.

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and

$$t_p = \frac{1}{2\eta_p} \ln \left[\frac{(\xi_p - \xi_s)^2 + (\eta_p - \eta_s)^2}{(\xi_p - \xi_s)^2 + (\eta_p + \eta_s)^2} \right], \tag{2}$$

where $2\xi_{s,p}$ and $2\eta_{s,p}$ correspond to the velocities and peak amplitudes of the signal and probe solitons, with the soliton photon number $N_{s,p}$ proportional to $4\eta_{s,p}+1 \approx 4\eta_{s,p}$ [10,11]. When $\eta_p > 0.5$ and $\xi_p - \xi_s > \pi/2$, a soliton collision causes a phase shift ϕ_p roughly proportional to the photon number N_s of the signal soliton. A similar phase shift ϕ_s is imposed on the signal soliton, introducing a measurement backaction noise $\Delta\phi_s$ into the phase of the signal soliton as a result of the photon number noise of the probe soliton.

To perform the QND measurement, we allowed a signal and probe soliton to collide in a 400-m single-mode polarization-preserving optical fiber. To eliminate timing and phase jitter, all solitons were prepared from single pulses (9 ps duration) from a mode-locked NaCl color-center laser operating at 100-MHz rates at 1457 nm. This was accomplished by broadening the color-center pulse bandwidth to 10 nm by self-phase-modulation in 1 km of single-mode polarization-preserving positive-GVD fiber (Fig. 2), and then using a diffraction-grating pair in a pulse-compression configuration to image the pulse spectrum onto a mask. Slits in the mask at appropriate positions selected out the desired wavelengths from the spectrum, which were reflected back past the diffraction-grating pair to a soliton-collision fiber having a GVD of −10 ps/km nm (Fig. 3) [8,12]. Timing of the pulses with respect to each other was set by mirror offsets. The resulting solitons consisted of a signal at 1460.7 nm with a full width at half maximum (FWHM) spectral width of 0.83 nm, a FWHM pulse width of 2.6 ps, an energy of 15 pJ (1.1×10^8 photons), and a time-bandwidth product of 0.30 (versus 0.314 for an ideal soliton), and an identical probe and reference (separated by 30 ps) with corresponding values of 1455.0 nm, 0.86 nm, 3.6 ps, 6 pJ (4.4×10^7 photons), and 0.44. The signal soliton led the probe by 12 ps going into the fiber and trailed by 12 ps leaving the fiber, avoiding the reference soliton. After the fiber, the signal soliton was separated away by a diffraction grating (with 87% reflection efficiency). The proximity of the probe and reference solitons severely reduced the detrimental effects of GAWBS noise on the determination of phase shifts [4].

The phase shift of the probe soliton was determined by a Mach-Zehnder interferometer configured as a phase-to-amplitude convertor (Fig. 3). The probe and reference pulses were split between the two arms of the interferometer, one slightly longer than the other, and superimposed at the output beam splitter as shown in the inset of Fig. 3. The difference of the photocurrents of the two photodiodes (individually, 200 to 300 μA) gave a readout of the phase shift of the probe soliton relative to the phase of the reference soliton, plus an offset determined by the path length difference between the two interferometer arms. Note that path length differences $\Delta l = m\lambda + \lambda/4$ and $\Delta l = m\lambda + 3\lambda/4$, where m is an integer, correspond to maximum phase sensitivity of the interferometer (with opposite signs) whereas $\Delta l = m\lambda + \lambda/2$ eliminates the interferometer sensitivity. The interferometer drift was very small, and was eliminated during experiments by negative feedback techniques. The interferometer visibility was 33%. Probe phase shifts of ~1.22 rad (70°) and an average 0.7-dB increase in interferometer output spectral densities (measured at 10 MHz using an rf spectrum analyzer) were observed when the signal soliton was chopped on and off.

To show the QND nature of the measurement, we must demonstrate (1) a correlation between the signal and the probe, (2) that the measurement introduces no noise into the signal QND observable, and (3) that the correlation between the signal and the probe is not due to

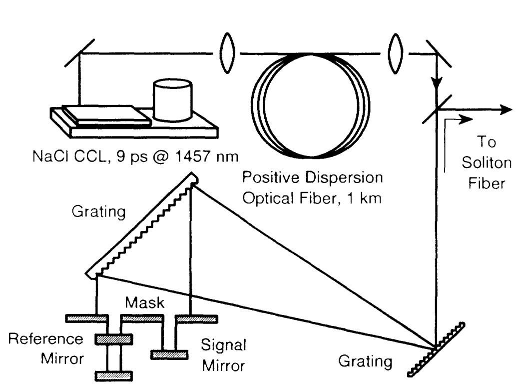

FIG. 2. Two-color soliton source. Color-center laser pulses acquire additional bandwidth through self-phase-modulation in an optical fiber. A mask with two slits, mirrors, and a grating pair are used to form three solitons.

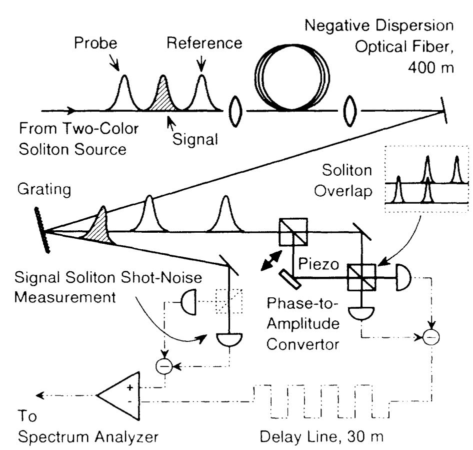

FIG. 3. QND measurement apparatus. A signal and probe soliton collide in an optical fiber. The resulting probe soliton phase shift is a readout of the signal soliton photon number, and can be determined with the help of a reference soliton.

extraneous factors unrelated to the measurement [13]. This was accomplished experimentally by demonstrating a correlation between the probe soliton phase and the signal soliton photon number fluctuations, and showing the signal soliton to be shot-noise limited. The correlation was obtained by adding the delayed output of the phase-to-amplitude convertor to the signal soliton photocurrent (950 μA) obtained with an InGaAs photodiode (RCA C30617E). The 30-m delay line made correlations visible as a ~6.4-MHz sinusoidal modulation of the noise spectrum. The noise level of the signal soliton was determined by comparison with the corresponding quantum-limited shot-noise level, obtained by directing the signal soliton through a 50/50 beam splitter onto two identical photodiodes and subtracting the resulting identical photocurrents. All measurements were recorded by an HP Series 70000 spectrum analyzer with resolution and video bandwidths of 300 and 10 kHz, and averaged over 100 traces. The thermal noise levels of the unloaded photodiodes and associated electronics, down > 5 dB from the signal soliton shot-noise level and > 10 dB from the phase-to-amplitude convertor output, were subtracted away. No photodiode or amplifier saturation effects were noted in either the correlation or calibration measurement systems. Losses affecting the measurements include intrinsic loss in the fiber (0.1 dB), coupling from the fiber (~0.2 dB), the diffraction grating (~0.6 dB), the photodiodes (~1.7 dB), and other losses in the interferometer.

Two correlation measurements, obtained with the interferometer at maximum sensitivity but with a $\lambda/2$ difference in the interferometer path length, are shown in Fig. 4(a). The periodic variations indicate a correlation between the signal soliton photon number and the probe soliton phase. The correlations are more clearly seen in Fig. 4(b), which shows the difference of the two measurements. Other correlations, obtained with the phase-to-amplitude convertor insensitive to probe fluctuations and corresponding to the combined noise level of both the phase-to-amplitude and signal soliton measurements, fall halfway between the two curves in Fig. 4(a), and correspond to the 0.0-dB line in Fig. 4(b). Noting that Fig. 4(b) shows correlations that are twice the actual value, we see that the correlations dip 0.25 dB below the combined noise level, which we estimate to be about 5 dB above the signal soliton shot-noise level [the 0.0-dB line in Fig. 4(c)] because of background phase noise.

The results of measurements to determine the excess noise of the signal soliton, performed immediately following the measurements of Figs. 4(a) and 4(b), are shown in Fig. 4(c). At frequencies exceeding 12 MHz, the excess noise level is less than the measurement accuracy of ~0.1 dB. Other measurements at later times gave similar results from 5 to 30 MHz. Therefore, we can conclude that the QND measurement introduces no observable excess noise into the signal soliton photon number. The lack of excess noise also rules out the possibility that

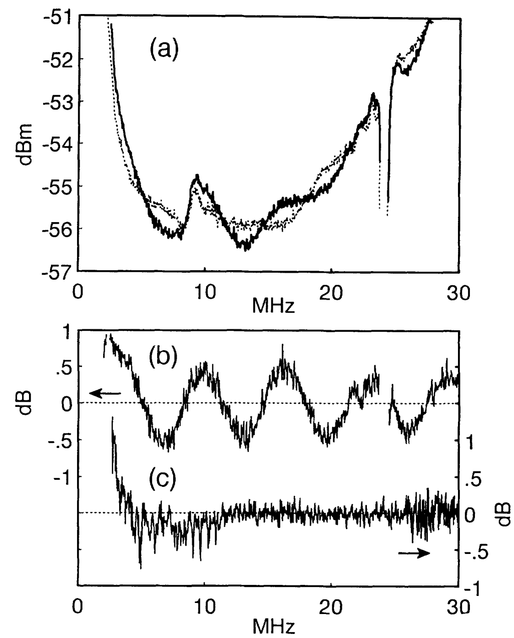

FIG. 4. (a) Two experimental measurements showing the correlation between the signal soliton photon number fluctuations and the probe soliton phase fluctuations. They differ due to a path length difference of $\lambda/2$ in the interferometer. (b) The difference of the two correlations in (a). The 0.0-dB level corresponds to the absence of a correlation. (c) The excess noise of the signal soliton relative to the quantum noise limit.

the observed correlations are due to excess noise coupled to the soliton photon number and the probe phase simultaneously (or transferred to the probe from the signal). Indeed, we would not expect such excess noise, as our measurement is a traveling-wave measurement in an optical fiber with a far-off-resonant nonlinearity and extremely low losses [4,13].

As the correlations plotted in Figs. 4(a) and 4(b) show the phase noise of the probe to be correlated with the shot noise of the probe and there is little or no excess noise in the signal soliton photon number fluctuations of Fig. 4(c), we conclude that we have performed a QND measurement of the photon number of the signal soliton. We note that an evaluation of Eq. (1) using parameters for our solitons suggests a probe phase shift of 1.2×10^{-8} rad/photon—our measured results were 1.1×10^{-8} rad/photon. This implies that after the collision, roughly 60% (rms) of the phase noise of the probe soliton is a "QND" readout due to the shot noise of the signal soliton. Taking into account the measurement process, losses, and photodiode quantum efficiencies, it can be shown that the correlations should dip 1.5 dB below the combined noise level of the measurement, provided that the signal soliton noise is amplified to the same level as the QND phase noise. Our experimental results are smaller than this mainly due to the effect of suboptimum gain of the signal noise gain level.

Finally, we note that as our solitons were initially in a coherent state, as shown by shot-noise measurements similar to that of Fig. 4(c), their quantum state is (partially) collapsed by the QND measurement. If the measurement were ideal, the QND measurement would produce a photon number eigenstate—our unsharp QND measurement produces a photon-number-squeezed state [3]. Thus, to test the QND measurement schemes of Ref. [1], one could perform in sequence two soliton-collision measurements as described here. The first would serve to produce a photon-number-squeezed state, and the second would serve to measure that state. Such a measurement is made possible by the conservation of photon number unique to solitons.

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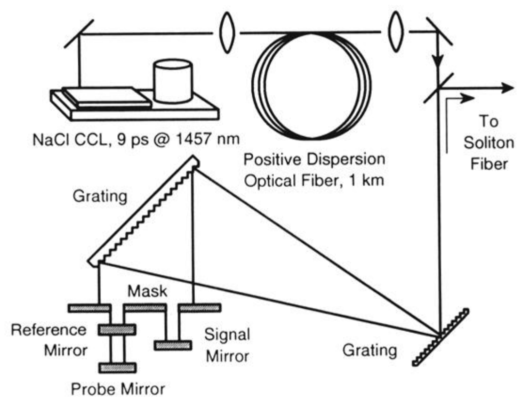

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