Squeezing in fibers with optical pulses

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A novel method of squeezing with optical pulses in a fiber ring reflector is demonstrated experimentally. Squeezing of greater than 5 ± 0.3 dB has been observed. The pump is separated from the squeezed radiation with a fiber ring reflector and can be reused, in principle fully, as the local oscillator. The detection is at low frequencies (35–85 kHz) and is unaffected by guided-acoustic-wave Brillouin scattering.

Extremely sensitive phase-measurement devices such as gravitational wave detectors[1] and laser gyroscopes[2] have been recently realized. Many of these interferometric sensors are currently limited by shot noise originating from the fluctuations of the vacuum field. Squeezed vacuum can, however, improve on the signal-to-noise ratio set by the shot-noise limit. Squeezed vacuum is phase-sensitive vacuum noise such that in one phase (with respect to a reference signal) the fluctuations are greater than in the other quadrature direction. It has been shown theoretically[3–6] and experimentally[7,8] that the measurement sensitivity is improved with the injection of squeezed vacuum into the interferometer's unexcited port if the squeezed vacuum is oriented with its reduced (squeezed) quadrature along the desired signal direction.

Quadrature squeezing of quasi-cw radiation has been achieved by several laboratories.[9–13] Shelby *et al.*[14] have demonstrated squeezing in fibers using the $\chi^{(3)}$ of the fiber. However, noise from forward scattering of thermally excited guided acoustic modes known as guided-acoustic-wave Brillouin scattering,[15] whose spectrum ranges from approximately 10 MHz to 10 GHz, greatly diminished the amount of observed squeezing at those frequencies. Squeezing with pulses of high peak power offers greater nonlinearity, as was realized by Yurke *et al.*[16] and demonstrated by Slusher *et al.*[17] Recently, Shirasaki and Haus[18] proposed the use of pulses for squeezing in a nonlinear Mach–Zehnder interferometer.

Figure 1 reviews briefly the theory of pulsed squeezing in a nonlinear Mach–Zehnder interferometer containing symmetrical Kerr media as described in Ref. 18. At the pump port, the temporal segment of the pulse radiation is represented by a phasor in the phasor plane, and the rms vacuum fluctuations that accompany the pump (Wigner representation), which are phase incoherent, are represented by a circle along the locus of the half-power points. Vacuum fluctuations enter into the unexcited port. After the beam splitter, the excitation is symmetric, and the noise in the two arms is uncorrelated. The Kerr medium distorts the noise into an ellipse (under the linearization approximation) tangent to circles of constant phase that appear as parallel lines (within the same approximation). The output beam splitter adds and subtracts the incoming signals, delivering the unchanged phasor with the elliptic fluctuation locus into one output port and squeezed vacuum without signal into the other output port. The pump can be reused as the local oscillator in a balanced homodyne detector. In the figure we have suppressed the signal-induced phase shifts. These are canceled in the detector circuit.

If other than square pulses are used for the pump, the degree of squeezing varies with time delay through the pulse. The axes of the different squeezing ellipses do not coincide, and thus the output current of the detector does not achieve the full squeezing. A comparison of the noise reduction obtained by using square pulses and Gaussian pulses is shown in Fig. 3 of Ref. 18. The squeezing obtained with Gaussian pulses saturates at approximately 7 dB.

The present Letter describes the first experimental demonstration of the scheme of Ref. 18. We employ optical pulses in a fiber ring interferometer geometry rather than cw excitation in a traveling-wave configuration. The use of pulses enhances the fiber nonlinearity and raises the stimulated Brillouin scattering threshold. The ring interferometer replaces the Mach–Zehnder interferometer and is insensitive to changes in the linear index due to temperature

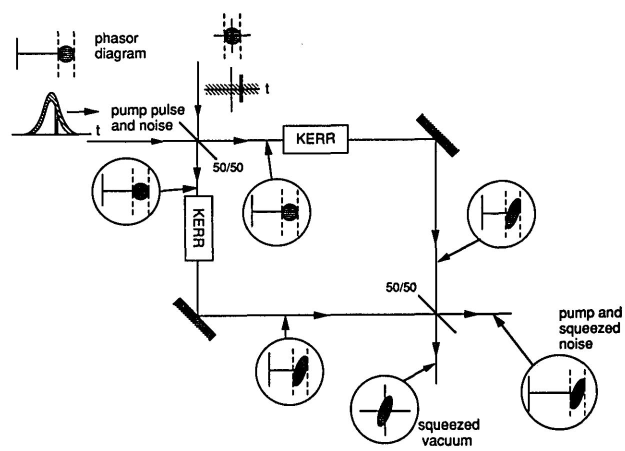

Fig. 1. Explanation of squeezing and pump separation in the nonlinear Mach–Zehnder interferometer.

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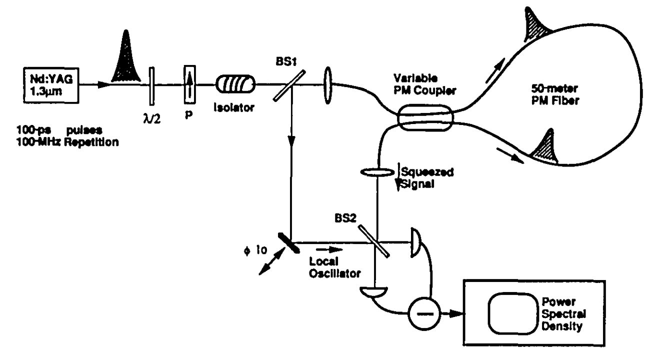

Fig. 2. The experimental configuration.

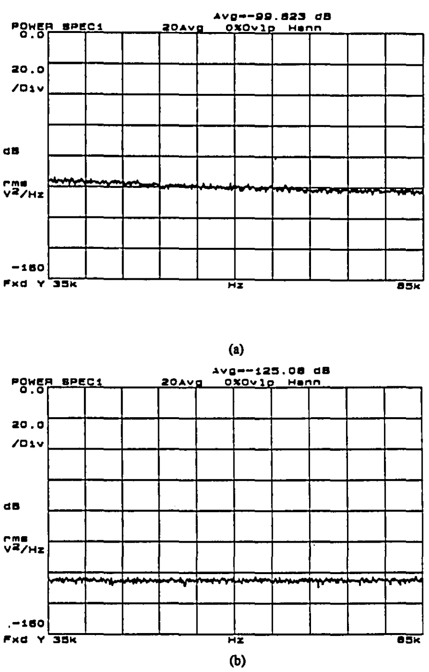

Fig. 3. Laser spectrum from 35 to 85 kHz in units of decibel-meters per hertz taken (a) with one homodyne detector blocked and (b) following the balanced subtraction.

changes and other environmental effects. The ring is also balanced nonlinearly since the two equal counterpropagating pulses obtain the same nonlinear phase shifts.

The experimental setup is shown in Fig. 2. A mode-locked Nd:YAG laser delivered 100-ps pulses at 1.3 μm at a repetition rate of 100 MHz. The $\lambda/2$ plate and the polarizer (P) were used as a variable attenuator. The ring reflector is formed of 50 m of polarization-maintaining (PM) fiber (generously provided to us by Alcoa Fudjikura). A variable PM coupler that can be adjusted to a 50/50 ratio to within 0.2% was fusion spliced to the PM fiber by Draper Laboratories. The reflected pump is picked off with a 90/10 beam splitter (BS1) and used as the local oscillator in a homodyne detection. Careful temporal and spatial alignment of the local oscillator and the squeezed signal pulse were performed at the 50/50 beam splitter (BS2). Both the local oscillator and the signal are incident upon a dual-detector balanced receiver (built at Lincolon Laboratories). The homodyne detection is used to subtract coherently the fluctuations caused by the local oscillator pulse and allow phase-sensitive detection of the squeezed signal pulse.

The output of the balanced detector is fed to a power spectrum analyzer (Hewlett-Packard model 3462A). The analyzer has a real-time bandwidth of 10 kHz and a measured noise floor of approximately −155 dBm/Hz, which is 15 dBm below the balanced receiver's noise floor level. By blocking the input to one of the two detectors, we determined the upper bound on the common-mode rejection ratio to be 24 dBm. In Fig. 3 we display the power spectral density (PSD) trace of the laser between 35 and 85 kHz. Figure 3(a) shows the spectrum with one of the balanced receiver's detectors blocked, and Fig. 3(b) is the difference current spectrum with both detectors unblocked. Figure 3(b) is in fact the shot-noise spectrum. These measurements were taken with an integration time of

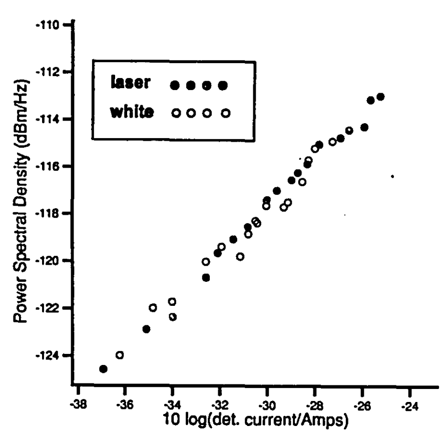

Fig. 4. Shot-noise calibration using both white light and direct laser excitation.

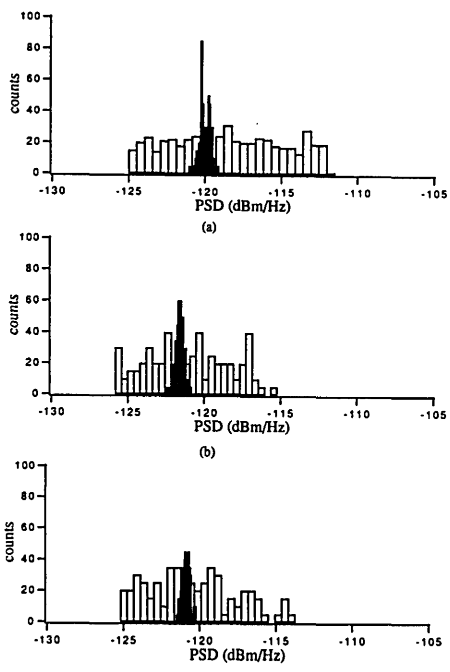

Fig. 5. Experimental results. Shown are counts of PSD readings at three power levels [110, 60, and 85 mW in each ring direction for (a), (b), and (c), respectively]. The black bars are counts taken with local oscillator alone; the white bars are the counts taken with the squeezed signal arm open.

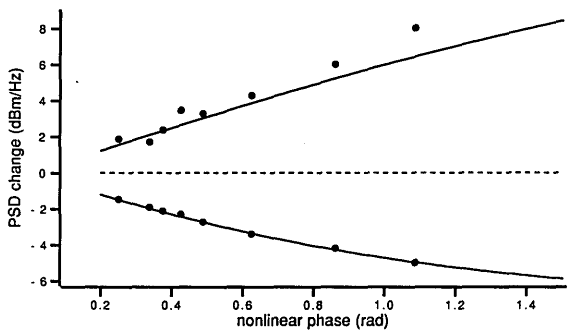

Fig. 6. Maximum and minimum values of the PSD readings extracted from measurements at several power levels between 20 and 110 mW. The shot-noise level is set at 0 dB. The traces are horizontally adjusted for best fit.

16 ms and a 62.5-Hz resolution. Below 35 kHz the laser noise could not be adequately subtracted, and above 85 kHz the slow detectors stopped responding.

In the experiment it was important to establish the shot-noise level accurately. Both white light (from two flashlights) and direct excitation by the laser were used. As can be seen from Fig. 4, for equal detector current, the two measurements gave good agreement. Also, the shot-noise level was predicted theoretically and agreed satisfactorily with the measured value.

The phase shift between the pump and the squeezed light varied on a long-term scale, drifting one cycle in approximately 2 s. The spectrum was measured between 39 and 41 kHz, with an integration time of 400 ms and a resolution of 2.5 Hz. Since we have not yet stabilized against the long-term fluctuations, the data were taken by collecting samples at a constant laser pump power and counting the number of samples of a particular spectral density. By collecting enough samples, one detects the noise levels for all possible phase adjustments. Typical collections of data, taken with 110, 60, and 85 mW of average power in each direction in the fiber ring, are displayed in Figs. 5(a), 5(b), and 5(c), respectively. The counts shown by the black bars are the shot-noise calibration counts taken with the squeezed signal arm blocked. The counts shown in white were taken with the squeezed arm open. In Fig. 6 we show the measured maximum and minimum PSD levels taken with the average power in each direction of the ring ranging from 20 to 110 mW. The two solid curves are the theoretically predicted upper and lower bounds on the squeezed noise with Gaussian pulses. The shot-noise level is set at 0 dB, and the detector efficiencies are assumed ideal. The horizontal axis is the estimated value of the peak phase shift Φ (Ref. 18) produced by the pump in the fiber. For an average power of 110 mW (in each ring direction), the estimated nonlinear phase shift is 1.5 rad. Because this value is not known precisely, the horizontal scale was adjusted for a best fit, thus taking into account the optical losses and the detector's quantum efficiencies (estimated at 80%).

Figure 6 shows that squeezing of over 5 ± 0.3 dB was achieved. The plot for the maximum and minimum measured values is not symmetric with respect to the shot-noise line, as it would be if one had squeezing with a square pulse. The shift is upward because of the different orientations of the squeezing ellipses, as pointed out above. Had we used solitons for squeezing, these effects would be absent, and the ideal limit could be approached more closely. We plan to carry out the experiment with solitons in the 1.55-μm regime.

In conclusion, we may state that we have observed substantial squeezing by this new method of interferometric squeezing using pulses in a fiber ring. The pump can be reused as a local oscillator. In principle, if one used nonreciprocal coupling of the pump one could recover it fully; in our case 81% of the pump was sacrificed. In our experiment, noise is reduced at low frequencies, frequencies that are particularly appropriate for interferometric measurements that are usually performed with modulations of the mirror position or the like at these frequencies. Therefore we believe that this method, or methods like it, will find use for high-precision interferometric measurements.

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