Squeezing in a fiber interferometer with a gigahertz pump

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We report 5.1 dB of squeezing from a fiber interferometer pumped with a 1-GHz pulse source that successfully eliminates guided-acoustic-wave Brillouin scattering in significant frequency regimes. The pulse source is a diode-pumped Nd:YLF laser actively mode locked at 1.314 μm. The squeezing results are consistent with the limits imposed by the Gaussian pulse shape and the detection quantum efficiency.

Squeezing in optical fibers[1] is greatly facilitated by the extraordinarily low insertion loss of fibers, long interaction lengths, high power densities, and good mode overlap. Squeezing in fibers employs the third-order susceptibility, $\chi^{(3)}$, through the nonlinear process of self-phase modulation and requires no phase matching, in contrast to squeezing in parametric amplifiers or oscillators that employ $\chi^{(2)}$.[2–4] The broadband nature of the Kerr nonlinearity permits the use of short pulses with high peak power, and large nonlinear phase shifts are easily attained.[5] The use of short pulses also avoids the power threshold set by stimulated Brillouin scattering in the backward direction.

The first reported experimentally measured squeezed noise level from a fiber[1] was smaller than predicted. The researchers who divided their cw pump power among 20 frequency components to overcome stimulated Brillouin scattering discovered a new noise source that severely limited the squeezing. The noise originated from scattering of the pump in the forward direction by thermally induced index fluctuations of the fiber and was termed guided-acoustic-wave Brillouin scattering (GAWBS).[6,7] The pump accumulated phase-noise sidebands with peaks that ranged in frequency from 20 MHz to 1 GHz and corresponded to the acoustic excitations of the fiber cylinder. Although GAWBS-induced noise is phase noise, which is close to being orthogonal to the squeezed quadrature, the squeezing is sufficiently hampered that none could be observed at frequencies that overlapped with the GAWBS excitations. The squeezing was observed at frequencies between GAWBS peaks, but the measured amount was small because of the limited power available with a cw source.

When pulses are used to achieve a larger squeezing coefficient the GAWBS peaks generated by each Fourier component of the mode-locked pulse train appear as sidebands of the Fourier components. The detection process convolves the spectrum.[8,9] It becomes difficult and sometimes impossible to measure squeezing between GAWBS peaks of the convolved spectrum. The exact form of the resultant noise spectrum is highly dependent on the particular fiber type and jacket as well as on the repetition rate of the input pulse train. If the repetition rate is sufficiently high, however, i.e., higher than the bandwidth of the GAWBS, there is no overlap of the noise between adjacent harmonics, and the resultant spectrum has a shape similar to that obtained with a cw pump repeated at every harmonic.[10] Squeezing measurements can then be performed between GAWBS peaks while the advantage of pulsed excitation, namely, no stimulated Brillouin scattering with large nonlinear phase shifts, is maintained. In this Letter we report on such squeezing experiments performed with a mode-locked 1-GHz repetition-rate laser source.

The experiments are performed with a fiber ring interferometer that is used to separate the pump from the squeezed noise, a scheme that was first proposed by Shirasaki and Haus.[5] Once separated, the pump power may be reused in full as the local oscillator in a separate measuring instrument employing the squeezed vacuum to improve the signal-to-noise ratio. Previous squeezing experiments implemented this scheme with pulses of megahertz-range repetition rates in both the positive and the negative (soliton) dispersion regimes of the fiber.[11–13] The results obtained in Ref. 11 were achieved with a particular fiber whose GAWBS excitations left low noise in the 40–90-kHz detection regime. We also demonstrated sub-shot-noise-limited measurement in an experiment in which the GAWBS noise was coherently canceled.[14] The present experiment is an alternative, simpler approach to the GAWBS suppression.

Our laser source, developed by us in collaboration with Spectra-Physics, is a diode-pumped Nd:YLF laser that is designed to lase at 1.314 μm. The cavity has an optical length that corresponds to approximately a 1-ns round-trip time and is actively mode locked with a TeO_2 amplitude modulator. The laser output is a steady 1-GHz pulse stream with 550 mW of average power, providing a clean and stationary second-harmonic autocorrelation trace, as shown in Fig. 1. The pulse width is 17 ps, assuming a Gaussian profile.

In the experimental configuration illustrated in Fig. 2 the pump passes through an isolator and a variable attenuator and is then coupled into a 90/10 polarization-maintaining (PM) fiber coupler. The 90% output port of the coupler is fusion spliced to the fiber ring interferometer, which is composed of

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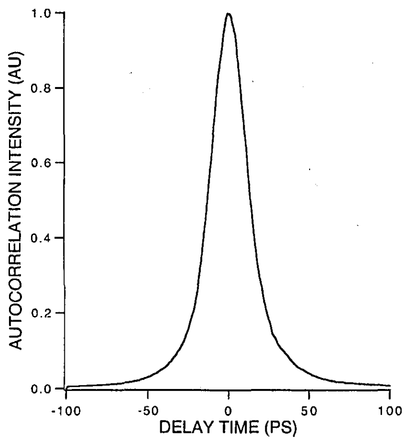

Fig. 1. Autocorrelation trace of the gigahertz source output pulse. The FWHM is 15 ps, assuming a sech profile.

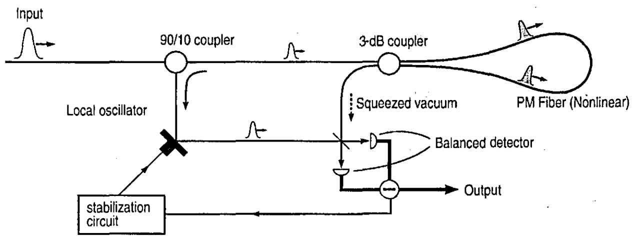

Fig. 2. Experimental configuration used to measure squeezing with a 1-GHz pump.

a 50/50 PM fiber coupler and 90 m of PM fiber (Fujikura sm.13-p). Before the interferometer was connected, the splitting ratio of the 50/50 coupler, which is crucial to the separation of the squeezed vacuum, was tested and determined to be accurate to within 0.2%. Since the local-oscillator power is larger than the squeezed-signal power by a factor of approximately 3000 the imperfect splitting ratio of the coupler can be neglected.

Both the local-oscillator and squeezed-signal pulses propagate through the entire nonlinear fiber loop and are therefore well matched temporally in phase and shape. An additional phase correction, done with a simple time delay, must be imparted on the local oscillator for projection of the squeezed quadrature. By varying this phase, we can measure the squeezed-noise quadrature as well as the orthogonal antisqueezed-noise quadrature that also contains the GAWBS noise.

We measured the shot-noise level by blocking the squeezed-signal port and reading the power spectral density of the difference current. To ascertain that blocking the signal port results in shot noise and that no excess noise is contributed by the system, we also calibrated the shot-noise level obtained with direct laser excitation of the balanced detectors. We can determine the shot-noise level for a given detector current within an accuracy of 0.1 dB. Two separate receivers were used, one designed for high frequencies (5–90 MHz) and the second for low frequencies (dc to 100 kHz). With the high-frequency receiver unit the shot-noise level was verified for the full bandwidth, and a linear response was measured for detector currents between 5 and 50 mA. With the second, low-frequency unit, shot-noise-limited detection was achieved at frequencies greater than 50 kHz, and the linear detection regime ranged from 200 μA to 40 mA. At less than 50 kHz the laser's relaxation-oscillation noise band, which peaks at 40 kHz, could not be fully canceled.

For an initial measurement, we compare the GAWBS spectrum obtained with the pulsed input with that obtained with a cw input of equal average power. The power level used was 20 mW, sufficiently low to render a negligibly small nonlinear phase. Since the GAWBS magnitude for this pulse width scales with the average power[8,9] the two spectra should be identical if there is indeed no overlap of GAWBS noise in the pulsed case. In Fig. 3 the GAWBS spectrum obtained with the 1-GHz pulsed input is shown from 5 to 90 MHz. The curve is identical to that obtained with a cw input, indicating that the pulse repetition rate is sufficiently high to avoid any substantial overlap of the GAWBS noise peaks. The shot-noise-level curve is approximately 1 dB less than the background level between the GAWBS peaks and follows the same frequency response.

With the high-repetition-rate source, measurements free of GAWBS noise can be performed at low frequencies, below the onset frequency of the first GAWBS peak, and at higher frequencies between GAWBS peaks. We stabilized the relative phase between the local-oscillator and squeezed-vacuum signals along the squeezed quadrature direction with a feedback loop, as in Ref. 15. The low-frequency squeezing results were measured between 80 and 100 kHz for a range of input powers. With the maximum input average power of 210 mW in each of the counterpropagating fields in the ring, 5.1 dB of noise reduction was achieved. This power level is equivalent to a nonlinear phase shift of 4.2 rad. The shot-noise level was approximately 17 dB greater than the thermal noise floor of the detectors and amplifiers.

The 5.1 dB of squeezing can be explained solely by the overall quantum efficiency of the homodyne detection, estimated to be 85%, and by the Gaussian shape of the pulses. Since the pulses are not rectangular the intensity-dependent nonlinear phase shift is not constant across the temporal profile of the

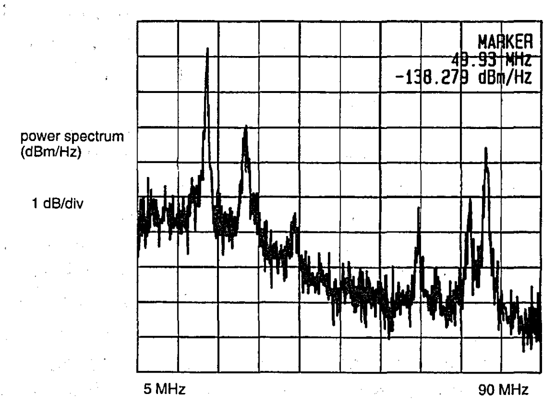

Fig. 3. GAWBS power spectrum (shown from 5 to 90 MHz) obtained with the balanced homodyne receiver by measurement of the amplified noise quadrature. The input average power of the 1-GHz mode-locked pulses is 20 mW.

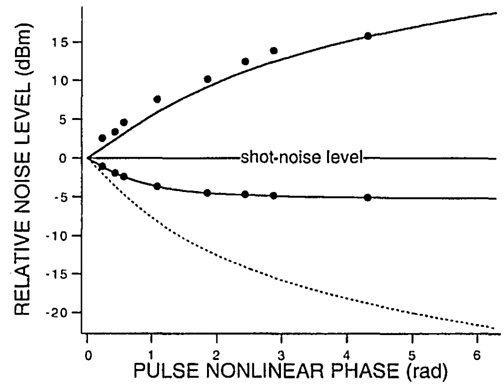

Fig. 4. Squeezing and antisqueezing magnitudes (filled circles) measured between 80 and 100 kHz for a range of input average powers (maximum was 440 mW) plotted along the analytical predictions with the assumptions of Gaussian pulse shape and 85% detection quantum efficiency (solid curves). The dashed curve is the expected optimum squeezing with perfect detection and ideal local-oscillator phase bias.

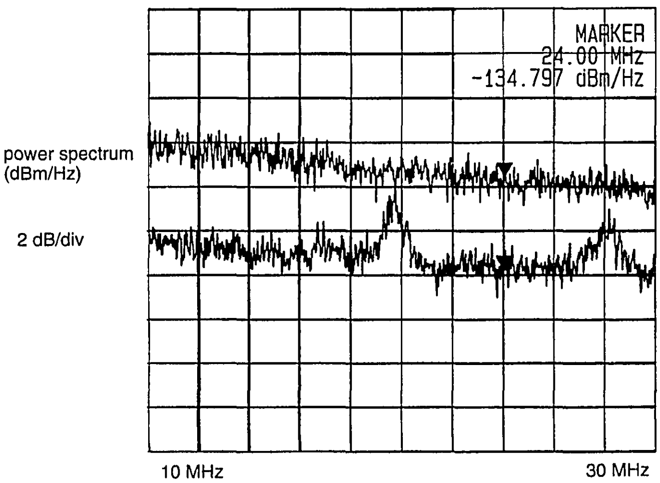

Fig. 5. Squeezing measured between GAWBS peaks from 10 to 30 MHz with 440 mW of average power. The upper curve is the shot-noise level, and the lower curve is the squeezed-noise level. At frequencies corresponding to GAWBS excitations the squeezing is destroyed.

pulse. The result is a varying squeezing magnitude and phase across the pulse profile. In the experiment the local oscillator is provided with a fixed correction phase shift across the pulse profile, leading to an imperfect projection of the squeezed signal and a limit on the maximum measurable noise reduction.[5] In Fig. 4 we illustrate the fit of the squeezing and the antisqueezing levels (indicated by filled circles) obtained with a range of input power levels to the analytical projection (solid curves) obtained with the assumption of Gaussian pulses and an 85% quantum efficiency. Also shown (dashed curve) is the ideal squeezing measurement with a matching Gaussian bias phase and perfect efficiency.

Figure 5 shows the results for the measurement taken from 10 to 30 MHz with approximately 440 mW of average power in the ring. The upper curve is the shot-noise level, and the lower curve is the squeezed quadrature noise projection. From the squeezing curve it is clear that, at the narrow frequency intervals intercepted by the two GAWBS peaks, squeezing is destroyed. The lowest squeezing level obtained outside the GAWBS is approximately 4 dB less than shot noise, which is limited by the electronics, namely, the nonlinear response of the balanced receiver with low detector currents.

In conclusion, we have shown that squeezing free of GAWBS noise in fibers is possible with a high-repetition-rate pulsed source. The 5.1 dB of noise reduction below the shot-noise level is limited only by the pulse shape and the quantum efficiency of the detection. Except in the case of narrow-frequency windows that include GAWBS noise peaks, measurements can be performed within a significant portion of the total bandwidth. The important low-frequency kilohertz regime is available, with limitation set by only classical laser noise. A diode-pumped fiber laser, for example, is expected to be nearly shot-noise limited at kilohertz frequencies.

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