Sub-shot-noise measurement with fiber-squeezed optical pulses

K. Bergman, C. R. Doerr, H. A. Haus, and M. Shirasaki

Department of Electrical Engineering and Computer Science and Research Laboratory of Electronics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139

Received October 6, 1992

A novel scheme employing two pulses separated by a short time delay is used to cancel the phase noise from guided-acoustic-wave Brillouin scattering in a fiber ring interferometer. The dual-pulse-excited fiber ring is used to generate squeezed vacuum that, when injected into a measuring Mach–Zehnder interferometer, improves its sensitivity by 3 dB beyond the shot-noise limit.

A squeezed vacuum can enhance the sensitivity of an interferometric measurement limited by shot noise. By injecting a squeezed vacuum into the unexcited port of a phase-measuring device, and by orienting the squeezed vacuum so that its quiet quadrature is along the signal direction, the signal-to-noise ratio is improved. This was shown theoretically[1,2] and demonstrated experimentally for measurements of phase modulation with a Mach–Zehnder interferometer,[3] polarization rotation,[4] and index modulation.[5]

The generation of squeezed light was first demonstrated in 1985 by Slusher *et al.*,[6] and they were closely followed by other researchers.[7,8] Squeezing in optical fibers with the Kerr effect [$\chi^{(3)}$] was pioneered by Shelby *et al.*[9] Squeezing with pulses within an interferometric geometry, first proposed by Shirasaki and Haus,[10,11] naturally separates the pump from the generated squeezed vacuum. This scheme leads to two important consequences: the pump power may be reused in full, and the classical noise of the pump may be subtracted successfully even at low frequencies.[12] When the squeezed vacuum is injected into the measurement device that uses all the original pump power, the signal-to-noise ratio is improved absolutely.

Although squeezing has been demonstrated with a fiber ring interferometer,[12,13] it has been limited by the classical noise termed guided-acoustic-wave Brillouin scattering[14–16] (GAWBS). In this process the propagating light in the fiber is scattered by thermally induced vibrations of the fiber cylinder, thereby acquiring phase-noise sidebands. The vibrational modes range in frequency from approximately 20 MHz to 1 GHz. Even if the measurement window is chosen at lower frequencies, the noise may be convolved into the window through coherent mixing in the balanced homodyne detection normally used to observe the squeezed vacuum noise along its quadrature directions.[16–18] The measurements reported in Ref. 12 were performed with a fiber that exhibited particularly low GAWBS at the measurement window. Since the level of GAWBS can be much higher with other fibers and at different measurement windows, it is essential that means be developed to eliminate its effect on the squeezing.

The GAWBS noise may be overcome by employing a method proposed by Shirasaki and Haus,[19] the experimental results of which are described in this Letter. The fiber ring is excited by two consecutive pulses separated by a time interval shorter than the inverse bandwidth of the GAWBS. Before detection, one of the local-oscillator pulses is π phase shifted with respect to the second pulse. Since the two pulses experience the same phase noise, each pulse contributes to the detection noise current but with an opposite sign. The GAWBS phase-noise contribution to each of the two detectors is nulled. Following the balanced subtraction the laser classical noise is canceled, and only the quantum noise remains.

In the experimental configuration shown in Fig. 1 the laser source is a 1.32-μm mode-locked Nd:YAG laser emitting 100-ps pulses at a 100-MHz repetition rate. Each input pulse is separated into two pulses delayed by 500 ps with respect to each other, which are coupled into the fiber ring interferometer composed of 50 m of polarization-maintaining fiber and a 3-dB coupler. The coupling loss to the fiber is approximately 10%. A portion of the reflected dual-pulse pump is picked off to be used as the dual-pulse local oscillator by an 85/15 fiber coupler (but all the pump power could be reused, in principle, with a nonreciprocal optical circulator). A π phase shift is then imposed on one of the local-oscillator pulses with a polarization-maintaining fiber phase modula-

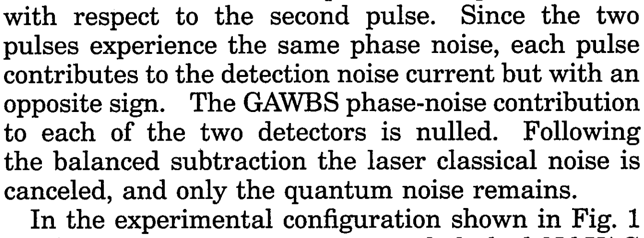

Fig. 1. Experimental configuration of the scheme used to cancel the GAWBS-induced phase noise. Two consecutive pulses delayed by 500 ps enter the fiber ring. One pulse is π phase shifted with respect to the second pulse in the local-oscillator path.

0146-9592/93/080643-03$5.00/0

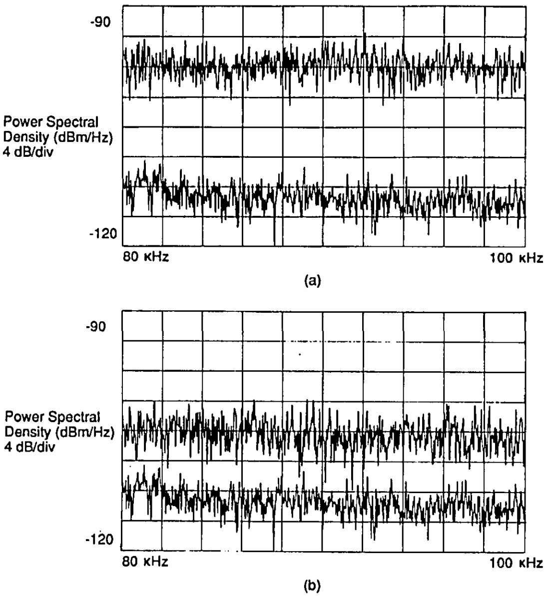

Fig. 2. Power spectra from the balanced detection showing cancellation of excess phase noise. In (a) the maximum projected noise is the sum of antisqueezing and the GAWBS; in (b) with the π-phase-modulation scheme 8 dB of GAWBS noise is canceled.

tor driven by a 1-GHz microwave signal with phase control and synchronization to the mode-locked pulse repetition rate. The fiber-to-fiber insertion loss for the modulator is 3 dB.

With the fiber used in this experiment, Fujikura panda with a pure silica core, we measured a significantly larger amount of excess noise due to GAWBS at the low-frequency measurement window (40–90 kHz) than with the fiber used in Ref. 12. The GAWBS noise measured with the homodyne detection may be quantified by a parameter μ, defined as the ratio between the GAWBS contribution to the current noise spectrum and the in-phase quantum noise contribution.[17] The detailed derivation of μ from first principles is given in Ref. 17. For this fiber and measurement frequency the window μ is approximately 50, and for this value the expected observable squeezing would be negligibly small if no suppression scheme were employed.

We determine the successful cancellation of the GAWBS phase noise by measuring the maximum noise quadrature output from the balanced homodyne detection. In Fig. 2 we show the power spectral density measured at low frequencies (80–100 kHz) with 20-Hz resolution and a 40-ms integration time. The total average power in the fiber ring for this measurement was 350 mW, which corresponds to 1.6 rad of peak nonlinear phase shift accumulated by each pulse. In both Figs. 2(a) and 2(b) the lower trace is the shot-noise level obtained when the squeezed vacuum input port is blocked. The data in Fig. 2 were not averaged because of the drifting relative phase between the local oscillator and noise signal. The shot-noise level has been verified independently with a 0.1-dB accuracy after 100 averages and by cross checking the level with direct laser excitation and with white-light sources.[12] The common-mode rejection of the balanced receiver is 40 dB, and the shot-noise level was achieved above 35 kHz. The upper trace in Fig. 2(a) is the maximum quadrature noise projected after unblocking the squeezed vacuum path arm and turning off the rf driver to the π phase modulator. This level, 18 dB above the shot-noise level, is produced by the noise contributions from the quantum antisqueezing and from the GAWBS-induced phase noise. In Fig. 2(b), taken with the π phase modulator on, the upper trace contains mostly the quantum antisqueezing contribution (9 dB) and a small amount of uncanceled GAWBS noise (1 dB). The magnitude of the amplified quantum noise is determined analytically[11] from the approximated peak nonlinear phase shift, and the remaining noise is attributed to GAWBS. Thus approximately 8 dB of excess phase noise has been successfully canceled by the dual-pulse π-phase-modulation scheme. From the magnitude of the uncanceled GAWBS noise we determine that the μ value has been reduced to approximately 5.

In Fig. 3 the same experimental apparatus is shown but with an appended Mach–Zehnder interferometer. The interferometer is simply composed of two 50/50 antireflection-coated beam splitters and two mirrors, one mounted on a piezoelectric transducer (PZT). The total size of the Mach–Zehnder interferometer is small (5 cm × 5 cm) to minimize the relative arm length drift rate. The interferometer can remain stable at a biased phase without active stabilization for ~2 min. We bias the Mach–Zehnder interferometer at the $\pi/2$ operation point and modulate the phase at 50 kHz by dithering the PZT-mounted mirror. The dithered mirror is translated by ~0.1 μm to generate a reference signal at the measurement frequency. The reflected dual-pulse pump is reused as the measuring probe in the interferometer. With the squeezed arm blocked, the balance detection output spectrum consists of the 50-kHz phase-modulation signal accompanied by the shot-noise background. This shot-noise-limited measurement is the power spectrum trace shown in Fig. 4(a) taken in units of dBm/Hz between 49 and 51 kHz (2.5-Hz resolution and 400-ms integration time) with 600 mW (2.7 rad peak nonlinear phase shift) of average power in the fiber ring. Now we unblock the squeezed vacuum port and project the squeezed noise quadrature direction along the measured signal. The background noise level drops by approximately 3 dB, as seen in Fig. 4(b), enhancing the signal-to-noise ratio be-

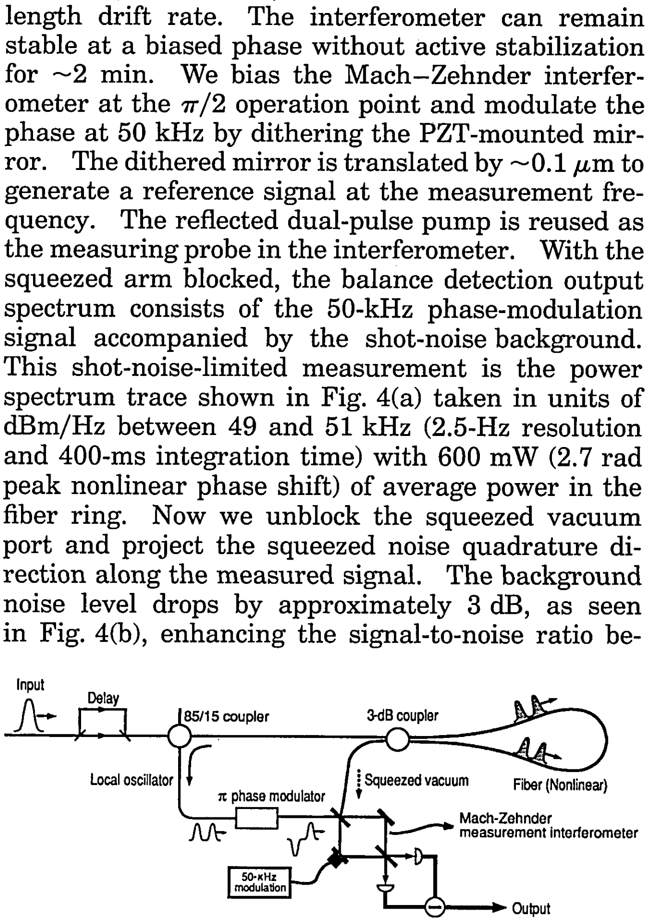

Fig. 3. Configuration used for the sub-shot-noise phase measurement at 50 kHz. The reflected pump is partly reused as the measurement probe in a Mach–Zehnder interferometer.

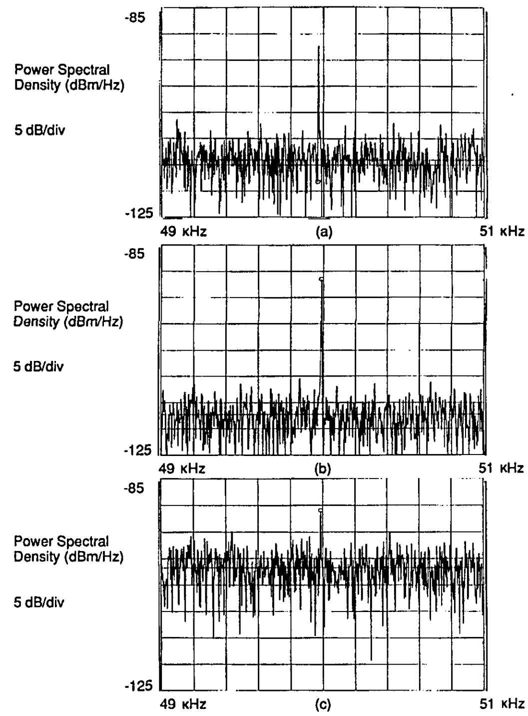

Fig. 4. Experimental results demonstrating signal-to-noise ratio improvement beyond the shot-noise limit. (a) The 50-kHz signal with shot noise, (b) the same signal measured with squeezed noise projection for 3-dB improvement, (c) the signal immersed in 12 dB of (excess) antisqueezing noise.

yond the shot-noise limit. The expected amount of squeezing with a $\mu = 5$ value for this input power level is 3.4 dB. In Fig. 4(c) we show the effect of projecting the antisqueezing quadrature along the signal direction. The resulting signal-to-noise ratio is severely degraded, burying the 50-kHz signal in an additional 12 dB of antisqueezing noise. Without the π phase modulation, the amplified noise is 21 dB above the shot-noise level.

The asymmetry between the amount of squeezing and antisqueezing can be attributed to two effects. First, the Gaussian shape of the pump pulse causes the squeezing in the center of the pulse to be larger and oriented at a different angle than the squeezing at the wings of the pulse. The different orientations of the squeezing ellipses along the pulse degrade the amount of measured squeezing, compared with what it would be if the pump were a square pulse.[11] Second, additional asymmetry is caused by incomplete subtraction of the GAWBS noise.

The squeezing level could be improved with higher input pump power, a more complete suppression of the GAWBS noise, and a constant nonlinear phase across the pulse envelope. One technical limitation is the sinusoidal driving signal to the phase modulator. While the two pulse centers are π phase shifted with respect to each other, the wings obtain a slightly different phase owing to the sinusoidal shape of the index modulation. The total amount of uncanceled power is approximately 5%.

In conclusion, we have demonstrated the successful cancellation of GAWBS-induced phase noise that has previously plagued squeezing in fiber experiments. The generated squeezed vacuum from the nonlinear fiber ring interferometer was utilized in improving the measurement sensitivity of a phase measurement by 3 dB beyond the shot-noise limit. The separation of the squeezed vacuum from the pump field by the interferometric geometry permitted the balanced subtraction of the local-oscillator noise at low frequencies (50 kHz). This allowed the sensitivity improvement to be measured at such a low-frequency window, an important frequency range for practical high-sensitivity measurement instruments.

The authors thank Lincoln Laboratories for providing the balanced receiver and signal analyzer used in the experiment. We are also grateful for the generous support of Draper Laboratories and Kevin Champagne. K. Bergman gratefully acknowledges fellowship support from AT&T Bell Laboratories. This research was supported in part by Fujitsu Laboratories, Ltd., the U.S. Office of Naval Research (contract N00014-92-J-1302), and the National Center for Integrated Photonics Technology (subcontract 542383).

M. Shirasaki is also with Fujitsu Laboratories, Ltd., Kawasaki, Japan.

References

1. C. M. Caves, Phys. Rev. D **23,** 1693 (1981).
2. R. S. Bondurant and H. J. Shapiro, Phys. Rev. D **30,** 2548 (1984).
3. M. Xiao, L. Wu, and H. J. Kimble, Phys. Rev. Lett. **59,** 278 (1987).
4. P. Grangier, R. E. Slusher, B. Yurke, and A. LaPorta, Phys. Rev. Lett. **59,** 2153 (1987).
5. P. Kumar, J. Huang, and O. Aytur, Proc. Soc. Photo-Opt. Instrum. Eng. **1376,** 192 (1990).
6. R. E. Slusher, L. W. Hollberg, B. Yurke, J. C. Mertz, and J. F. Valley, Phys. Rev. Lett. **55,** 2409 (1985).
7. M. Xiao, L. Wu, and H. J. Kimble, Phys. Rev. Lett. **53,** 278 (1987).
8. M. W. Maeda, P. Kumar, and J. H. Shapiro, Opt. Lett. **12,** 161 (1987).
9. R. M. Shelby, M. D. Levenson, S. H. Perlmutter, R. G. DeVoe, and D. F. Walls, Phys. Rev. Lett. **57,** 691 (1986).
10. M. Shirasaki and H. A. Haus, in *Nonlinear Guided-Wave Phenomena: Physics and Applications,* Vol. 2 of 1989 OSA Technical Digest Series (Optical Society of America, Washington, D.C., 1989), p. 232.
11. M. Shirasaki and H. A. Haus, J. Opt. Soc. Am. B **7,** 30 (1990).
12. K. Bergman and H. A. Haus, Opt. Lett. **16,** 663 (1991).
13. M. Rosenbluh and R. M. Shelby, Phys. Rev. Lett. **66,** 153 (1991).
14. R. M. Shelby, M. D. Levenson, and P. W. Bayer, Phys. Rev. B **31,** 5244 (1985).
15. S. H. Perlmutter, M. D. Levenson, R. M. Shelby, and M. B. Weissman, Phys. Rev. B **42,** 5294 (1990).
16. R. M. Shelby, P. D. Drummond, and S. J. Carter, Phys. Rev. A **42,** 2966 (1990).
17. K. Bergman, H. A. Haus, and M. Shirasaki, Appl. Phys. B **55,** 242 (1992).
18. A. J. Poustie, Opt. Lett. **17,** 574 (1992).
19. M. Shirasaki and H. A. Haus, Opt. Lett. **17,** 1225 (1992).