Photon-number squeezing in the normal-dispersion regime

Dmitriy Krylov and Keren Bergman

Department of Electrical Engineering, Princeton University, J303, E-Quad, Olden Street, Princeton, New Jersey 08544

Yinchieh Lai

Institute of Electro-Optical Engineering, National Chiao-Tung University, Hsinchu, Taiwan

Received March 3, 1999

We experimentally demonstrate the generation of amplitude-squeezed light in the normal-dispersion regime and measure by direct detection 1.7 ± 0.1 dB (33%) and, with correction for linear losses, 2.5 ± 0.2 dB (47%) of noise reduction below the shot-noise level. The dependence of the noise behavior on dispersion is investigated both experimentally and theoretically.

OCIS codes: 270.6570, 270.5530, 270.1670.

Significant progress in producing amplitude-squeezed optical soliton pulses with a new experimental scheme has recently been achieved. This scheme, originally proposed[1] and later generalized by Werner,[2] is based on nonlinear pulse propagation in an asymmetric fiber interferometer and is potentially capable of producing large squeezing levels in excess of 10 dB. A high-energy ($N > 1$) soliton pulse propagating in fiber has its noise properties modified owing to the Kerr nonlinearity in such a way that correlations develop between the quantum amplitude and the phase fluctuations. Interference of this high-energy pulse with a much weaker pulse will, for appropriate choices of pulse energies and propagation distances, act to project the squeezed component of the quantum noise onto the amplitude fluctuations.[3] The amplitude-squeezed or the photon-number-squeezed noise can be directly measured by a single detector. In an experimental demonstration of this scheme Krylov and Bergman recently reported a 5.7-dB (73%) reduction, or a 6.2-dB reduction (76%) after correcting for linear losses, in photon-number fluctuations below the shot-noise level, with 180-fs high-energy soliton pulses centered at 1550 nm in a highly asymmetric Sagnac interferometer geometry.[4]

Soliton pulses have the distinctive property of acquiring a uniform nonlinear phase shift across the temporal envelope, which provides for the most-efficient projection and measurement of squeezing. It is, however, not required by the quantum theory of nonlinear pulse propagation that one have a soliton pulse to observe amplitude-noise reduction, and thus the practical scope of the photon-number-squeezing experiments in optical fibers can be significantly extended. It has been predicted by Werner and Friberg that squeezing can be observed in the normal-dispersion regime with the maximum observable noise reduction limited by dispersion-induced temporal broadening.[2,5] For high pulse energies, squeezing levels of as much as 6 dB have been predicted for relatively short fiber lengths corresponding to only several dispersion lengths.[2] In this Letter we experimentally demonstrate the presence of amplitude squeezing in the normal-dispersion regime by use of a highly asymmetric Sagnac loop geometry and measure a maximum of 1.7 ± 0.1 dB (33%) of photon-number squeezing below shot-noise level. Correcting for linear system losses, we estimate the actual amplitude squeezing to be 2.5 ± 0.2 dB (47%). We also investigate the dependence of noise behavior on dispersion both experimentally and theoretically and find the results to be in good qualitative agreement.

The experimental setup is shown in Fig. 1. A Spectra-Physics Opal laser is used as a source of 140-fs (FWHM) sech-shaped optical pulses at a repetition rate of 82 MHz. We can vary the central wavelength of the generated pulses in the 1.4–1.6-μm range by controlling the phase-matching conditions in the nonlinear lithium triborate (LBO) crystal by automatically changing the crystal temperature and the grating angle. We can make slight adjustments to the temperature of the LBO crystal manually to control the spectral bandwidth of the generated pulses and ensure that they are transform limited. We use an asymmetric Sagnac loop configuration in which the light is split by a 94/6 free-space beam splitter and then coupled from both ends into a 1.5-m section of the

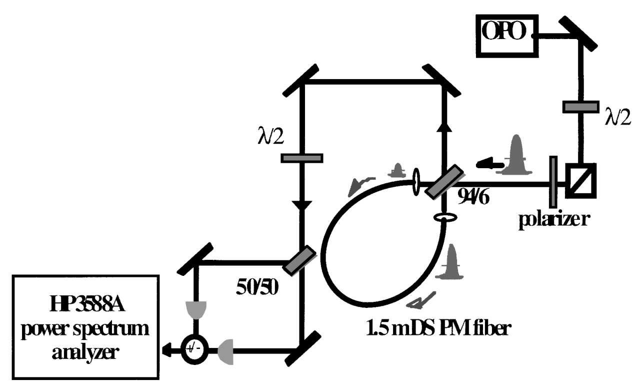

Fig. 1. Experimental setup: OPO, optical parametric oscillator; $\lambda/2$'s, half-wave plates; DS PM, dispersion-shifted polarization-maintaining.

0146-9592/99/110774-03$15.00/0

dispersion-shifted polarization-maintaining optical fiber with a 6-μm core diameter and a zero-dispersion point at 1562 nm. The dispersion of this fiber was carefully measured for the range of the relevant wavelengths by use of a Michelson interferometer apparatus.[6]

The two parts of the initial pulse counterpropagate in the fiber and reinterfere at the beam splitter. The photocurrent fluctuations associated with the resulting pulse exhibit either noise reduction or noise amplification, depending on the input pulse energy, fiber length, and splitting ratio. These fluctuations are then measured by a balanced receiver (Epitaxx ETX-1000T photodiodes) followed by a Hewlett-Packard HP3588A power spectrum analyzer operated in a zero-span regime centered around 5 MHz with a resolution bandwidth of 17 kHz. We use the subtraction mode of the receiver for shot-noise calibrations, and the summing mode is used for direct detection of the amplitude fluctuations.

We performed several calibrations in fiber as well as in free space, as described in Ref. 4, to establish accurately the shot noise and the other relevant noise levels to within 0.1 dB. All the values were shown to be consistent with the ones reported in Ref. 4. The photodiodes were independently calibrated to have their responsitivities matched and their saturation levels accurately established at 26 mW, which corresponds to approximately 70 mW of input optical power into the fiber Sagnac interferometer.

The experimental results are shown in Fig. 2, in which the squeezing (noise power normalized to the shot-noise level) is plotted versus the optical power entering the loop for wavelengths of 1490, 1505, and 1525 nm. The dispersion parameter β'' of the fiber for these wavelengths was measured to be 4.85, 3.85, and 2.55 ps^2/km, respectively. The third-order dispersion parameter β''' was measured to be approximately 0.08 ps^3/km over the range of wavelengths used in the experiment. For all three wavelengths we observe the characteristic oscillations of the noise levels to above and below the shot-noise level, exhibiting the so-called squeezing resonances and antisqueezing peaks. Figure 2 also demonstrates the dependence of squeezing on dispersion. As the effective length of the fiber is varied in units of dispersion length, we observe a change in the frequency of the noise-level oscillation and the locations of the squeezing resonances. The largest noise reduction is observed at 1490 nm, at which we directly measure 1.7 $\pm$ 0.1 dB (33%) of squeezing for the input optical power of 51 mW into the interferometer, which corresponds to $N = 5.2 \pm 0.05$ in soliton units. Even though there are no solitons in the normal-dispersion regime, N is still a convenient parameter to use when one is dealing with the normalized nonlinear Schrödinger equation, as discussed below. Taking into account the 80% overall efficiency, which includes the mode mismatch at the output beam splitter and the 95% detector quantum efficiency, we estimate the total noise reduction to be 2.5 $\pm$ 0.2 dB (47%). We note that additional power-dependent nonlinear losses, which potentially are due to the geometry of the dispersion-shifted polarization-maintaining fiber, were observed and may have further limited the observed squeezing.

To establish the correct behavior of the noise fluctuations for the different values of the dispersion parameter we performed several numerical simulations based on the previously developed backpropagation method.[7,8] Since the pulses that were used in the experiment had a spectral bandwidth of 17 nm, the change in β'' across the spectrum of the pulse is significant compared with the absolute value of β'', and therefore third-order dispersion had to be taken into account in this low-group-velocity dispersion regime. Raman effects were not included in the simulations and are part of work in progress.[9]

The classical propagation equation for an optical pulse in the normal-dispersion regime of optical fiber is[9]

$$\frac{\partial}{\partial z} U(z, t) = -\frac{i}{2}\beta'' \frac{\partial^2}{\partial t^2} U(z, t) + \frac{1}{6}\beta''' \frac{\partial^3}{\partial t^3} U(z, t) + i\gamma |U(z, t)|^2 U(z, t), \qquad (1)$$

where $U(z, t)$ is the normalized optical field envelope function; z is the propagation distance; t is the time deviation from the pulse center; β'' and β''' are the group-velocity dispersion and the third-order dispersion parameters, respectively; and γ is the Kerr nonlinearity parameter, which for the fiber used in the experiments is estimated to be 3.4 $km^{-1}\ W^{-1}$. Quantization is performed based on the linearization approximation and the conservation of commutation relations.[8] Quantum noise is then treated as a perturbation to the classical solution to Eq. (1), $U_0(z, t)$, and its evolution is described by

$$\frac{\partial}{\partial z} \hat{u}(z, t) = -\frac{i}{2}\beta'' \frac{\partial^2}{\partial t^2} \hat{u}(z, t) + \frac{1}{6}\beta''' \frac{\partial^3}{\partial t^3} \hat{u}(z, t) + 2i\gamma |U_0(z, t)|^2 \hat{u}(z, t) + i\gamma {U_0}^2(z, t)\hat{u}^+(z, t), \qquad (2)$$

where $\hat{u}(z, t)$ is the quantum-perturbed optical field operator, which represents the quantum noise. The classical solution $U_0(z, t)$ is obtained numerically for both

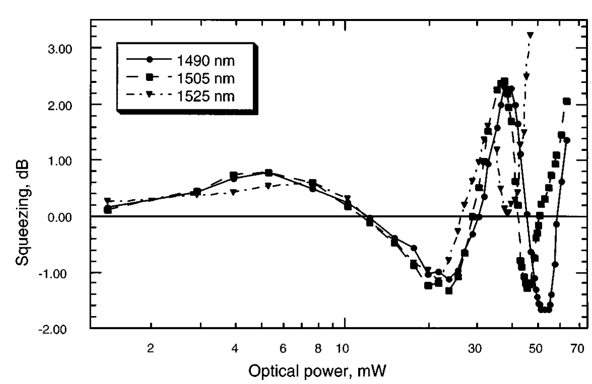

Fig. 2. Relative noise power fluctuations versus input optical power for three wavelengths.

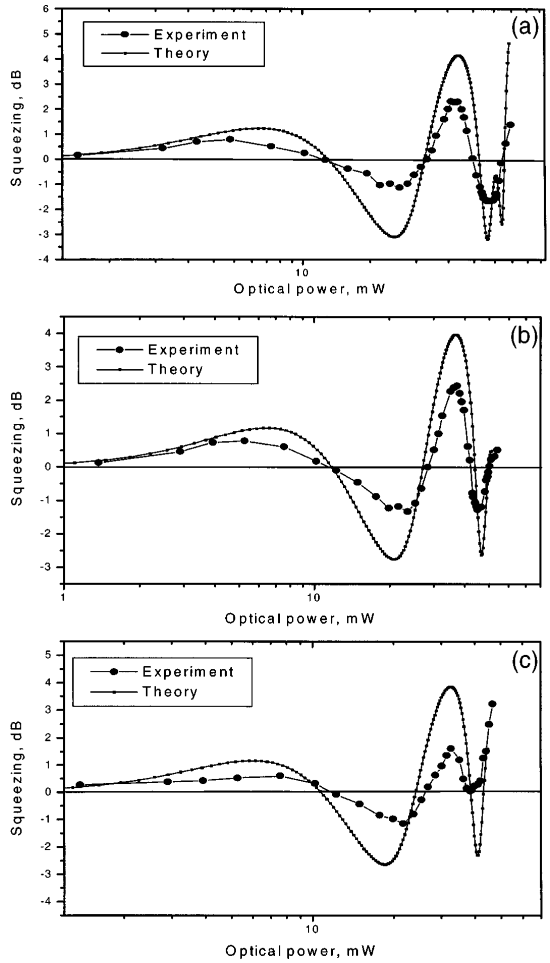

Fig. 3. Numerical simulation plots for a 140-fs pulse propagating through (a) 1.1, (b) 0.875, and (c) 0.580 dispersion lengths in the normal-dispersion regime, with the corresponding experimental plots of squeezing versus input optical power at 1490, 1505, and 1525 nm.

arms of the interferometer. The two counterpropagating pulses are then interfered, and the result is used as the initial condition for the backpropagation routine. The photon-number variances at the input and the output of the experiment are calculated by numerical solution of the linearized equation for the adjoint system $u^A(z, t)$,[7]

$$\frac{\partial}{\partial z}\hat{u}^A(z, t) = -\frac{i}{2}\beta''\frac{\partial^2}{\partial t^2}\hat{u}^A(z, t) + \frac{1}{6}\beta'''\frac{\partial^3}{\partial t^3}\hat{u}^A(z, t) + 2i\gamma|U_0(z, t)|^2\hat{u}^A(z, t) - i\gamma {U_0}^2(z, t)\hat{u}^{A*}(z, t)\,. \quad (3)$$

Squeezing can then be calculated as the ratio between the variance in the photon number of the signal at the output of the interferometer and that at the input.

The results of the simulations are shown in Fig. 3. The numerical calculations were performed with normalized units, where the propagation distance was measured in units of dispersion length and the soliton parameter N was used to scale the optical power entering the fiber interferometer. With such scaling, the different wavelengths correspond to propagation of the pulses through different effective lengths of fiber. Thus the experimental results at 1490, 1505, and 1525 nm correspond to propagation distances of 1.1, 0.875, and 0.580 dispersion length units. Figure 3 shows the noise behavior as a function of the input optical power in milliwatts, where we used the standard definition of the soliton N parameter for convenience to scale the numerical results correctly and consistently.[9] One can see that the numerical and the experimental results are in good qualitative agreement in terms of the locations of the squeezing and antisqueezing regions. The discrepancy in the actual squeezing values most likely is due to the absence of Raman effects in the simulation.

In conclusion, we have experimentally demonstrated a practical scheme for producing amplitude-squeezed light in the nonsoliton regime and measured 1.7 ± 0.1 dB (2.5 ± 0.2 dB after correcting for losses) of quantum-noise reduction. Numerical simulations of the experiments were performed, and the results were found to be in good qualitative agreement with the experiments.

This work was supported by the U.S. Office of Naval Research (grant N00014-96-0773). D. Krylov's e-mail address is krylov@ee.princeton.edu.

References

1. M. J. Werner, in *Digest of 1997 OSA Annual Meeting* (Optical Society of America, Washington, D.C., 1997), p. 142.
2. M. J. Werner, Phys. Rev. Lett. **81,** 4132 (1998).
3. D. Levandovsky, M. Vasilyev, and P. Kumar, Opt. Lett. **24,** 89 (1999).
4. D. Krylov and K. Bergman, Opt. Lett. **23,** 1390 (1998).
5. M. J. Werner and S. R. Friberg, Phys. Rev. Lett. **79,** 4143 (1997).
6. B. C. Collings, K. Bergman, S. T. Cundiff, S. Tsuda, J. N. Kutz, J. E. Cunningham, W. Y. Jan, M. Coch, and W. H. Knox, IEEE J. Quantum Electron. **3,** 1065 (1997).
7. Y. Lai, J. Opt. Soc. Am. B **10,** 475 (1993).
8. Y. Lai and S.-S. Yu, Phys. Rev. A **51,** 817 (1994).
9. G. P. Agrawal, *Nonlinear Fiber Optics*, 2nd ed. (Academic, San Diego, Calif., 1995).