Soliton squeezing in microstructure fiber

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We demonstrate, for the first time to our knowledge, the generation of squeezed light by means of soliton self-phase modulation in microstructure fiber. We observe and characterize the formation of solitons in the microstructure fiber at 1550 nm. A maximum squeezing of 2.7 dB is observed, corresponding to 4.0 dB after correcting for detection losses. The dependence of this quantum-noise reduction on various system parameters is studied in detail. Features of the microstructure fiber can be exploited for generation of low-energy continuous-variable entangled pulses for use in all-fiber teleportation experiments. © 2002 Optical Society of America

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Recent experiments with microstructure fibers[1] (MFs) have demonstrated that one can achieve dramatic nonlinear effects,[2–5] even in short lengths of fiber. MFs combine a small core area with engineerable dispersion characteristics and single-mode behavior over a wide wavelength range. These properties allow one to modify the behavior of solitons propagating in this fiber in interesting ways. Hence, one would expect that such a versatile nonlinear medium would also have advantageous applications in quantum optics, such as generating squeezed light and quadrature entanglement via soliton self-phase modulation.[6]

In this context, MFs offer the advantage of being able to support very low-energy solitons, which can be used for implementing teleportation schemes based on bright entangled states.[7] Properly designed MFs could give soliton energies of a few picojoules at 1550 nm. Such fibers would then allow one to build a compact and robust source of bright squeezed light having low average power, which would permit homodyne measurement of the resulting fields, thus permitting experimental realization of the teleportation schemes.[6,7] In this Letter we report, for the first time to our knowledge, the generation of squeezed light in MFs. To accomplish this task we have studied in detail the behavior of solitons in MFs, paying particular attention to nonlinear effects that hinder the observation of a high degree of squeezing.

The MF used in our experiments was fabricated at Bell Labs, Lucent Technologies.[2] It consists of an $\simeq$1.7-μm-diameter silica core surrounded by a hexagonal array of $\simeq$1.4-μm-diameter air voids. Two samples of the fiber from different batches, which show different nonlinear propagation properties, were used in the experiments. By studying the nonlinear propagation of pulses in the first sample (MF A), which is 0.7 m long, we find that 200-fs FWHM solitons have measured peak powers of 230 and 290 W for the two polarization modes of the fiber. Nonlinear propagation measurements in the second sample (MF B), which is 3.18 m long, led to a peak power of 310 W for 200-fs solitons, with no measurable difference between the two polarization modes of the MF. These measurements of the soliton peak power are consistent with those estimated from the fiber's nonlinear coefficient and the group-velocity-dispersion coefficient extrapolated from Ref. 2, which are $\gamma \simeq 50\ \mathrm{W}^{-1}\ \mathrm{km}^{-1}$ and $\beta_2 \simeq -130\ \mathrm{ps}^2/\mathrm{km}$ at 1550 nm, respectively. These parameters lead to an estimated peak power of 200 W for 200-fs FWHM solitons. Based on the measured peak powers, we calculate that the soliton period is $\simeq 0.14$ m for the lower-energy soliton in MF A and $\simeq 0.10$ m in MF B. The fiber is also strongly birefringent and polarization maintaining (PM); we measured the group delay between the two polarization modes to be $\simeq$8 ps/m in both samples. When we compare the measured parameters of the MF with manufacturer data for the standard PM fiber (e.g., 3M, Inc., FPSM 7811), we find that both the soliton peak power (1100 W for the 3M fiber) and the soliton period (1.19 m for the 3M fiber) are several times (almost 1 order of magnitude) smaller. We also used sample B for measuring the attenuation coefficient of the MF with a cutback technique, which gave a value of (0.6 ± 0.2) dB/m at 1550 nm.

For the experiments described in this Letter we use a nonlinear fiber Mach–Zehnder polarization interferometer[8] in which a pulse undergoing nonlinear propagation is mixed with a weak dispersive pulse to align the squeezed quadrature with the mean field, as shown schematically in the top inset of Fig. 1. This setup, when compared with similar experiments for

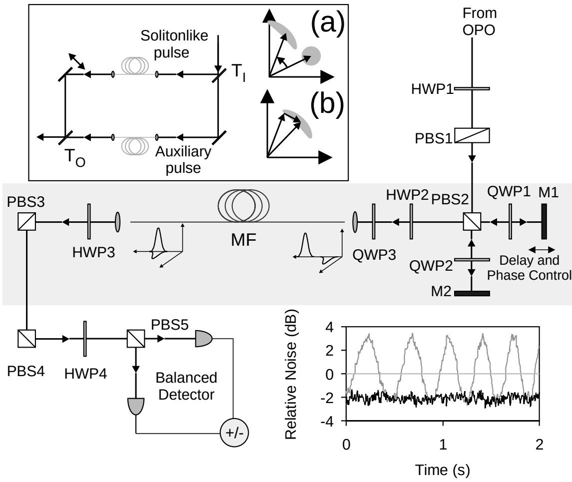

Fig. 1. Schematic of our experimental setup. OPO, optical parametric oscillator; HWP1–HWP4, half-wave plates; QWP1–QWP3, quarter-wave plates; PBS1–PBS5, polarizing beam splitters; M1, M2, mirrors. Top inset, schematic of the equivalent Mach–Zehnder interferometer and graphic illustration of the mechanism leading to amplitude squeezing. (a) Amplitude-dependent phase shift deforms the solitons' symmetrical quantum-noise distribution. (b) A properly phased auxiliary pulse can be used to align the squeezed quadrature with the mean field. Bottom inset, photocurrent-noise spectral density at 20.5 MHz normalized to the shot-noise level (0 dB). The pulse energy in the strong arm was 1.3 times the soliton energy, and 0.35 m of MF B was used; $T_I = 0.09$ and $T_O = 0.065$. All traces were averaged five times.

generating amplitude squeezing with asymmetric Sagnac loops,[9,10] gives us greater control of the phase and amplitude of the two interfering pulses.

The experimental setup is shown in Fig. 1. The light source is a tunable optical parametric oscillator (Coherent, Inc., Model Mira-OPO) emitting a train of pulses at a wavelength of 1550 nm with a 75-MHz repetition rate and an approximately 200-fs (FWHM) pulse width. The pulses are sech shaped and nearly Fourier-transform limited (time–bandwidth product $\simeq 0.4$). An interferometer is formed between polarizing beam splitters PBS2 and PBS3, wherein the two arms of the interferometer separately contain the two polarization modes of the MF. The splitting ratio of the input and output beam splitters of the equivalent Mach–Zehnder interferometer (see the top inset in Fig. 1), T_I and T_O, can be changed by rotation of PBS1 and half-wave plate HWP3, respectively. By setting $T_I \ll 0.5$, we have a strong pulse traveling in one arm of the Mach–Zehnder interferometer and a weak auxiliary pulse in the other. We can change the optical length of one of the two arms by moving M1, which allows us to compensate for the accumulated group delay between pulses propagating in the two polarization modes of the MF. In addition, a piezoelectric control on M1 allows fine tuning of the relative phase between the pulses. At the output of the interferometer the combined pulse, reflected by PBS3, is reflected off another polarization beam splitter (PBS4) to ensure high polarization purity while minimizing optical losses. The emerging pulse train is then analyzed in direct detection with a balanced pair of detectors (Epitaxx ETX500). The total measured detection efficiency is 78%.

In the bottom inset of Fig. 1 we show a typical plot of the direct-detection-noise spectral density as the relative optical phase of the strong pulses with respect to the weak pulses is scanned. For some phases the direct-detection noise at the output of the interferometer falls below the shot-noise limit (0-dB line); i.e., it is amplitude squeezed. We obtained the bottom trace by locking the phase to a value that maximizes the squeezing. The traces shown are an average of five consecutive scans over a 10-s period, demonstrating the stability of our experimental setup. We made two sets of measurements to study the dependence of the maximum squeezing [quantum-noise reduction (QNR)] on two critical system parameters, the input splitting ratio, T_I, and the MF length, L. In Fig. 2 we present plots of the QNR, obtained from squeezing scans like that shown in the bottom inset of Fig. 1, versus the energy of the strong pulse (expressed in terms of the squared soliton number, N^2) for three different values of T_I. For these measurements, we used 0.7 m of MF A, corresponding to $\simeq 4.7$ soliton periods. We chose the output splitting ratio, T_O, to maximize the QNR, and an optimal value of $\simeq 10\%$ was found. The

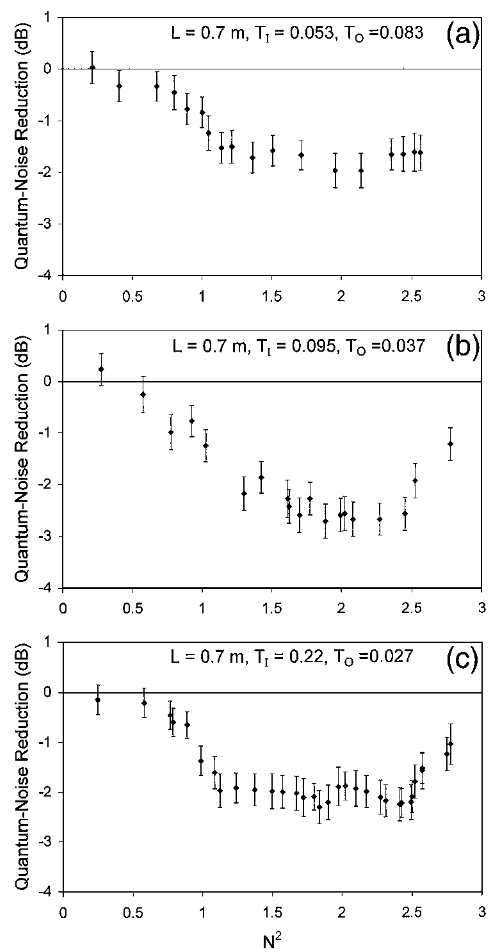

Fig. 2. Plots of experimental quantum-noise reduction in 0.7 m of MF A as a function of the energy of the strong pulse expressed in terms of squared soliton number N^2.

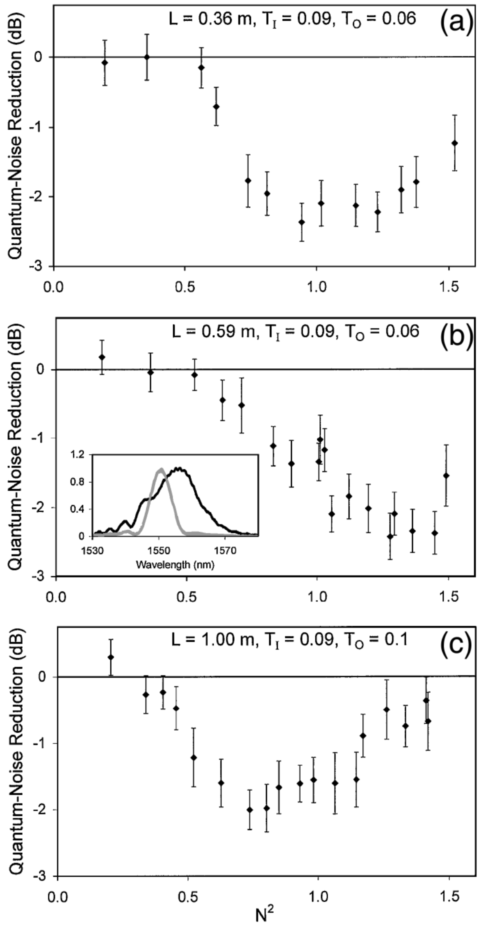

Fig. 3. Plots of the experimental QNR in MF B as a function of the energy of the strong pulse (expressed in N^2) for different fiber lengths L. The inset in (b) shows the normalized spectra for the $N^2 \simeq 1.4$ pulse (dark trace) and the weak pulse (light trace) at the output of the MF, showing the self-frequency shift that is due to the Raman effect.

existence of such an optimal value can be understood by consideration of the interplay between the noises of the strong and the weak pulses; the latter also undergoes slightly nonlinear propagation in the fiber before being mixed with the strong pulse at the output beam splitter of the interferometer.[8] In Fig. 3 we report plots of the QNR versus the energy of the strong pulse (again, expressed in N^2) for lengths L of 0.36, 0.59, and 1.0 m of MF B, corresponding to approximately 3.6, 5.9, and 10 soliton periods. In each case we chose T_I and T_O to maximize the QNR.

The data presented in Figs. 2 and 3 can be compared with similar results obtained from standard PM fiber.[8] We find that both the PM fiber and the MF have similar QNR versus pulse-energy and QNR versus fiber-length behavior. In both cases the maximum noise reduction occurs for five to six soliton periods of propagation in the fiber. This feature cannot be explained in terms of the theory presented in Ref. 8. We believe that the inclusion of effects such as the Raman self-frequency shift of the pulse [see the inset in Fig. 3(b)] and the third-order dispersion in the fiber is required for clarification of the origin of this feature. A significant difference between the MF and the PM fiber results can be seen in the high-energy behavior ($N^2 > 2$); in the MF case the QNR drops suddenly. We attribute the drop in the QNR to the process of third-harmonic generation (similar to that reported in Ref. 5), which was observed to get strong at those higher pulse energies. In the MF we observed a maximum squeezing of 2.7 ± 0.3 dB (as shown in Fig. 2), which corresponds to 4.0 ± 0.4 dB when the effect of detection losses is taken out. The latter value should be compared with 6.3 ± 0.6 dB of squeezing reported in the PM fiber case.[8] The difference is, in part, due to distributed losses in the MF, which amount to ≃10% in 0.7 m of MF. We have carried out a numerical simulation of the effect of distributed losses,[11] which shows that the inclusion of loss alone is not enough to explain the differences between the squeezing results in the two types of fiber. Other nonlinear processes, such as Raman scattering and third-harmonic generation, that have been observed in MFs must also be included.

In conclusion, we have demonstrated a nonlinear fiber Mach–Zehnder interferometer that uses microstructure fiber for the production of amplitude-squeezed light. The unique properties of this fiber allow observation of quantum-noise reduction at significantly lower average powers and with much shorter fiber lengths than those required when one is using standard communication fibers.

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