Soliton Squeezing in Microstructure Fiber

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Abstract

We experimentally demonstrate the generation of amplitude-squeezed light by means of soliton self-phase modulation in a microstructure fiber. By injecting 180 fs pulses at 1550 nm into the fiber we observe the formation of solitons. Subsequent mixing of the solitons with weak pulses allows us to measure sub-shot noise amplitude fluctuations; a maximum noise reduction of 2.7 dB is measured without correction for detection losses. Comparison with a similar experiment carried out in standard polarization-maintaining fiber shows that, owing to the high nonlinearity of the microstructure fiber, squeezing is obtained for smaller peak powers and shorter fiber lengths.

Recent experiments using microstructure fibers (MFs) [1] have demonstrated that, even in short fiber lengths, one can achieve dramatic nonlinear effects, such as the generation of supercontinuum [2], a large Raman self-frequency shift for solitons [3], four-wave mixing [4], and third harmonic generation [5]. MFs combine a small core area with single-mode behavior over a wide wavelength range and engineerable dispersion characteristics. By changing the nonlinearity and the dispersion, one can modify the properties of the solitons propagating in the fiber in a completely new way. Hence, such a versatile nonlinear medium can also be used advantageously in quantum optics for generating squeezed light via soliton self-phase modulation. The interest in efficient generation of squeezed radiation in optical-fiber devices is prompted by the possibility of using the resulting highly-squeezed fields to create and distribute continuous-variable entanglement [6] for quantum-communication applications such as teleportation and dense coding [7]. In this context, MFs offer the advantage of being able to support very low-energy solitons, which can be used for experimentally realizing the teleportation schemes that use bright entangled states [8]. Properly designed MFs could give soliton energies of a few pJ at 1550 nm. These fibers would then allow one to build a compact and robust source of bright squeezed light that can be integrated with the existing communication technology, while the small average power would help overcome some of the difficulties associated with the detection and characterization of the resulting quantum states [6].

The MF used in our experiments was fabricated at Bell Labs, Lucent Technologies [2]. It consists of a $\simeq 1.7\,\mu$m-diameter silica core surrounded by a hexagonal array of $\simeq 1.4\,\mu$m-diameter air voids. The attenuation was measured to be 0.4 dB/m at 1550 nm by comparing the insertion losses for two different MF lengths. Estimates of the fiber nonlinear coefficient and the group-velocity dispersion can be extrapolated from Ref. [2], which are given by $\gamma \simeq 50\,\mathrm{W}^{-1}\mathrm{km}^{-1}$ 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. Studying the nonlinear propagation of pulses in the MF we measured that 200 fs long solitons have peak powers of 230 W and 290 W, respectively, for the two polarization modes of the fiber. We believe that the discrepancy between the measured and expected values is mainly due to the uncertainty in the extrapolated value of β_2. Based on these measured peak powers, we calculate that the soliton period is $\simeq 0.15$ m in this MF. The fiber is also strongly birefringent and polarization maintaining; we measured the group delay between the two polarization modes to be 8.6 ps/m. When we compare the measured parameters for the MF with manufacturer data for the standard polarization-maintaining (PM) fiber (e.g., 3M Inc., FPSM 7811), we find that the soliton peak power in our MF is approximately three times lower (1100 W for the 3M fiber) and the soliton period is about seven times shorter (1.19 m for the 3M fiber). All of the experiments reported in this paper were carried out with a 70 cm-long piece of MF. According to our measurements, this corresponds to $\simeq 4.7$ soliton periods, which is close to the optimal squeezing length measured in Ref. [9].

In a previous experiment [9], we generated amplitude-squeezed light by using a nonlinear fiber Mach-Zehnder polarization interferometer. This setup, when compared with similar experiments for generating amplitude squeezing in asymmetric Sagnac loops [10], gives us a greater control of the phase and amplitude of the two interfering pulses. By adding these new degrees of freedom, we were able to study in detail the physical process that leads to quantum-noise reduction. In this paper we describe a modification of our setup, where the PM fiber is replaced with the Lucent MF.

A schematic of the experimental setup is shown in Fig. 1. The light source in our experiment 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 approximately 200 fs (FWHM) pulse width. The pulses are *sech* shaped and nearly Fourier transform limited (time-bandwidth product $\simeq 0.4$). As shown in Fig. 1, an interferometer is formed between the polarizing beamsplitter PBS2 and PBS3, where the two arms of the interferometer correspond to the two polarization modes of the MF. Into one arm we inject strong pulses propagating in the soliton regime, while in the other we inject a weak, dispersive pulse.

The total injected power is controlled by using a half-wave plate (HWP1) while the splitting ratio T_I of the input beamsplitter of the interferometer is set by rotating the polarizing beamsplitter PBS1. Since the pulses propagate with significantly different group velocities in the two polarization modes, they are launched at different times into the fiber in order for them to overlap at the fiber output. The relative delay is introduced by adding separate free-space propagation paths [s(p)-polarization reflects from M1 (M2)] for the two polarization modes in the interferometer. This arrangement also prevents cross interaction between the two pulses, as they are temporally separated during most of the propagation distance in the fiber. In addition, a piezoelectric control on M1 allows fine tuning of the relative phase between the pulses. A half-wave plate (HWP2) and a quarter-wave plate (QWP3) are used to inject the s and p polarized pulses from free space into the correct polarization modes of the fiber. At the output of the fiber, the two pulses are recombined using a half-wave plate (HWP3) and a polarizing beamsplitter (PBS3), allowing us to easily change the output splitting ratio T_O of the interferometer by turning HWP3. The combined pulse, reflected by PBS3, is reflected off another polarization beamsplitter (PBS4) in order to insure a high polarization purity while minimizing optical losses. The emerging 75 MHz pulse train is then analyzed with a balanced detector, made with two matched Epitaxx ETX500 photodiodes. To increase the overall detection efficiency, we use spherical mirrors that bounce back the light reflected from the photodiode surfaces. This configuration yields a total measured detection efficiency of 78%, where the Fresnel loss at the fiber end (5%), propagation losses through various optical elements (5%), and sub-unity photodetector quantum efficiencies (equivalent losses of 13%) are the contributing factors.

In Fig. 2 we report a typical plot of the noise spectral density at 20.5 MHz normalized to the shot-noise level as the relative optical phase of the soliton pulses with respect to the weak pulses is scanned by changing the length of one arm of the interferometer. For some phases the noise falls below the shot-noise level indicating that the output of the interferometer is amplitude squeezed. Noise reduction is measured by averaging the bottom trace of figure 2 obtained by locking the phase to the value that maximizes the squeezing. For these curves the energy of the strong pulse was 1.8 times that of the fundamental soliton, the input splitting was $T_I = 0.095$ and the output splitting was $T_O = 0.035$.

In Fig. 3 we report plots of quantum-noise reduction versus the energy of the strong pulse (expressed in terms of the squared soliton number N^2) for three different input and output splitting-ratio combinations. The data can be compared with similar results obtained in an equivalent length of standard PM fiber as reported in Ref. [9] and we reproduce the relevant plots in Fig. 4. The comparison shows that the two types of fiber have similar quantum-noise reduction vs. pulse energy behavior. A significant difference between the MF and PM-fiber results can be seen in the high-energy behavior, where in the MF the noise reduction drops suddenly. We attribute the drop in the noise reduction to the process of third-harmonic generation (similar to that reported in [5]), which begins to get strong at these pulse energies. We also observe that the noise reduction is maximized for the same values of the input and output splitting ratios as observed in the PM fiber. In the MF we observed a maximum squeezing of 2.7 ± 0.3 dB, corresponding to 4.0 ± 0.4 dB when the effect of detection losses is taken out, which should be compared with 6.3 ± 0.3 dB of squeezing in the PM fiber [9]. This difference in results is, at least in part, due to linear losses in the MF, which amount to $\simeq 5\%$ in 70 cm of MF. To clear this point, a detailed study of the effect of distributed linear losses on the noise propagation in fibers is needed.

In conclusion, we have demonstrated a nonlinear fiber Mach-Zehnder interferometer for the production of amplitude squeezed light using microstructure fiber. The unique properties of this fiber allow the observation of maximium noise reduction at significantly lower power and fiber length than that required with standard communication fibers.

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FIGURES

FIG. 1. A schematic of the experimental setup. The shaded area highlights the components that form the Mach-Zehnder interferometer. HWP, half-wave plate; QWP, quarter-wave plate; PBS, polarizing beamsplitter; M, mirror.

FIG. 2. Photocurrent noise spectral density at 20.5 MHz normalized to the shot-noise level. For the top trace the length of one arm of the Mach-Zehnder interferometer is scanned; for some lengths the noise falls below the shot-noise level. For the bottom trace the length of the interferometer's arm is fixed to obtain maximium squeezing. For these acquisitions the pulse energy was 1.8 times the soliton energy, 70 cm of MF was used, $T_I = 0.095$, and $T_O = 0.035$. All traces are averaged 3 times.

FIG. 3. Plot of experimental quantum-noise reduction in 70 cm of MF as a function of the energy of the strong pulse expressed in terms of squared soliton number N^2. (a) $T_I = 0.053$, $T_O = 0.083$; (b) $T_I = 0.095$, $T_O = 0.037$; (c) $T_I = 0.22$, $T_O = 0.027$. For all data the detection efficiency was 78%.

FIG. 4. Plot of experimental quantum-noise reduction as a function of average power in the soliton arm (squared soliton number N^2) in PM-fiber. (a) 3.4 m of fiber, $T = (0.4 \pm 0.1)\%$; (b) 6.0 m of fiber, $T = (0.11 \pm 0.01)\%$ (triangles), $T = (0.32 \pm 0.01)\%$ (filled circles), $T = (1.0 \pm 0.4)\%$ (squares), and for clarity only one error bar for each data set is displayed; (c) 9 m of fiber, $T = (0.53 \pm .05)\%$. For all data the detection efficiency is 78%.

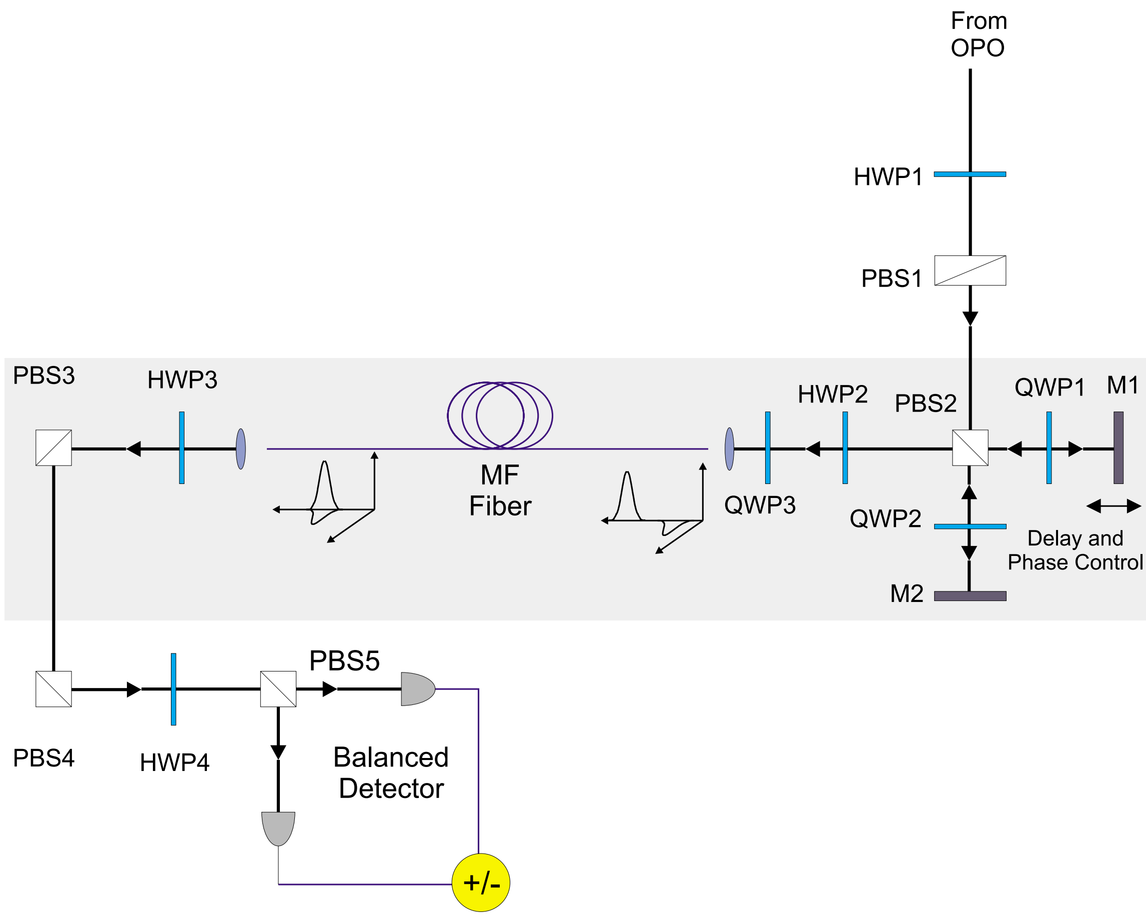

Fig.1 M. Fiorentino et al *"Soliton squeezing…"*

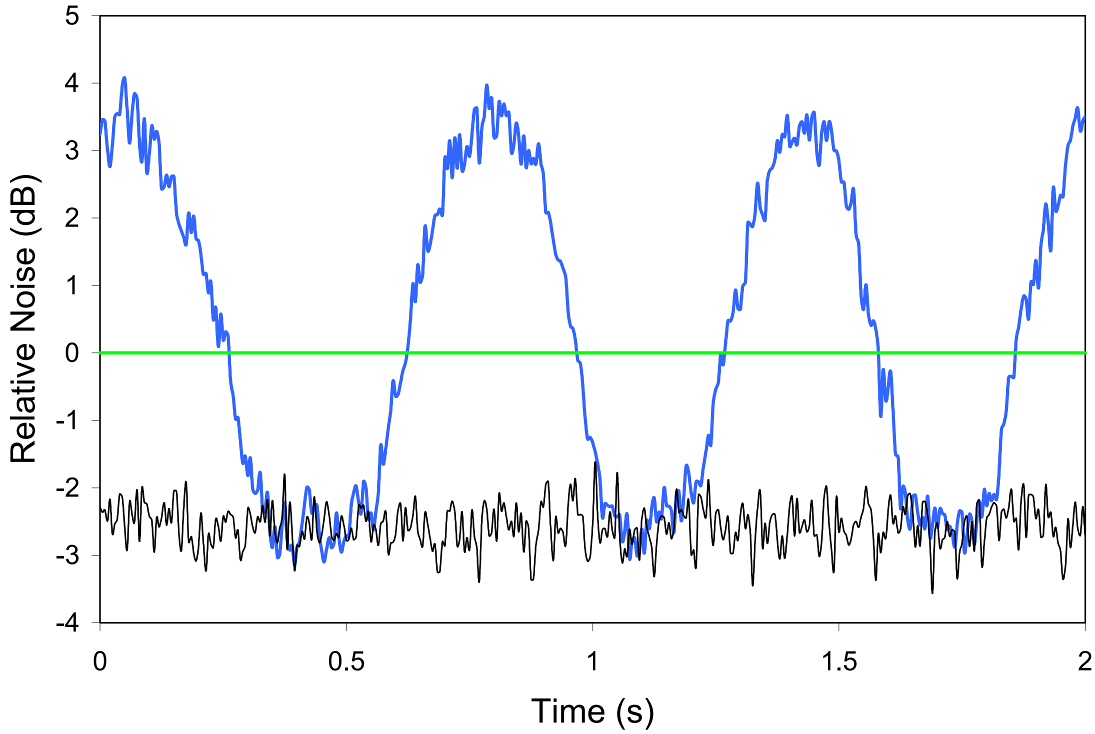

FIG.2 M. Fiorentino et al *"Soliton squeezing…"*

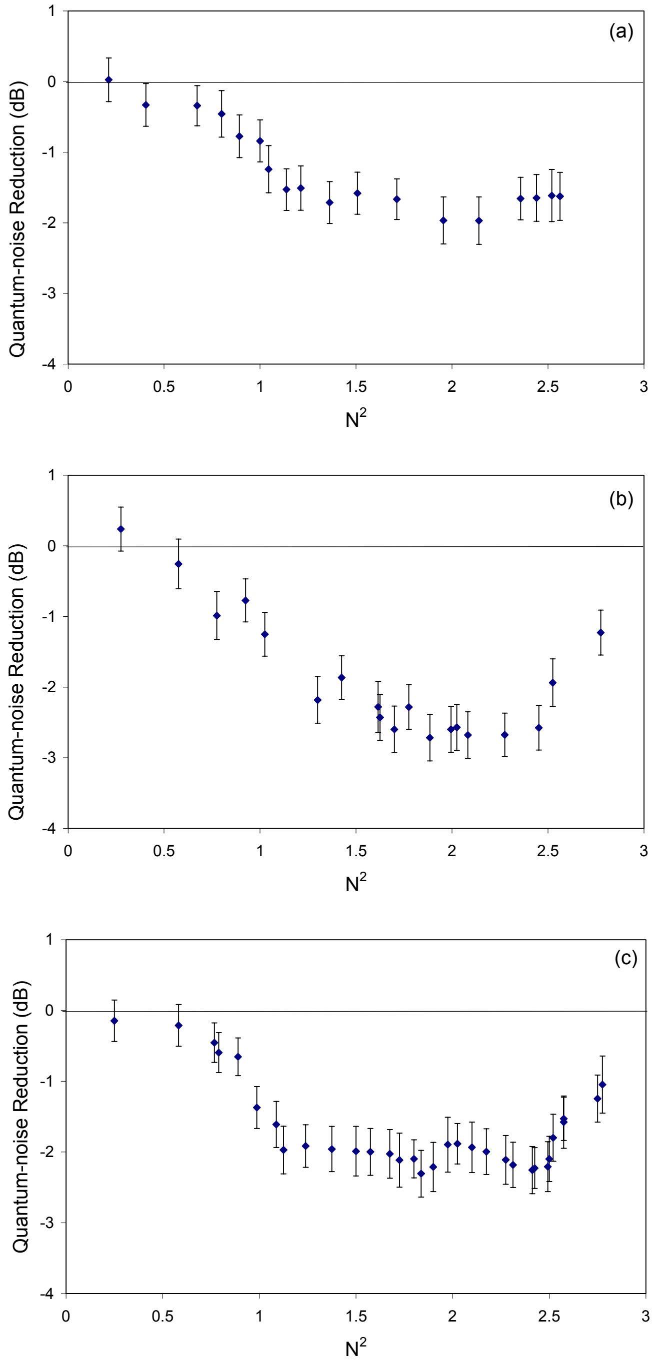

FIG. 3 M. Fiorentino et al *"Soliton squeezing…"*

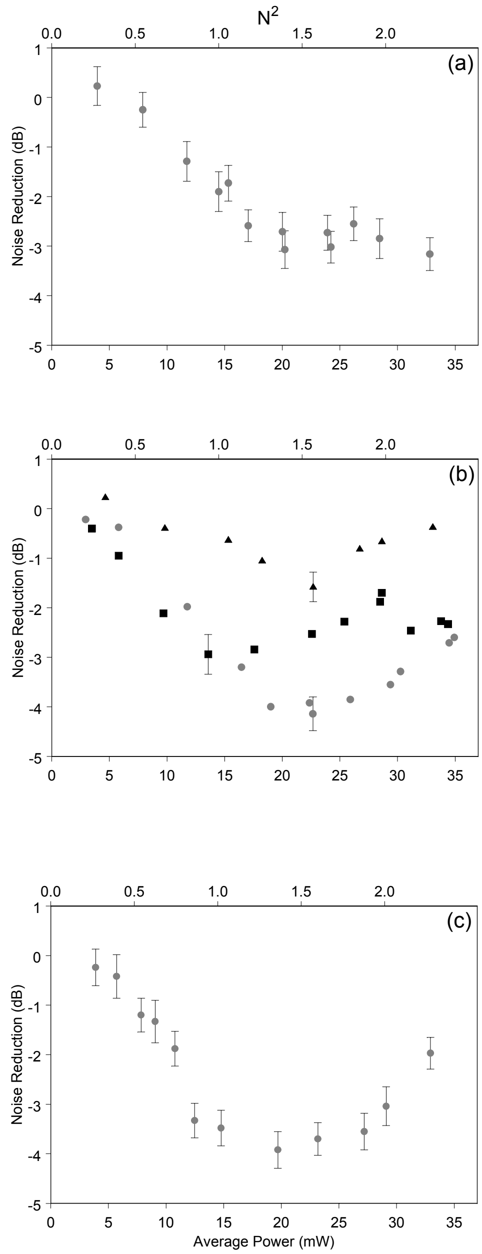

FIG. 4 M. Fiorentino et al *"Soliton squeezing…"*