Propagation of quantum properties of sub-picosecond solitons in a fiber

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Abstract: We present new results on photon number squeezing of spectrally filtered solitons in fibers. The impact of frequency low-, high-, and bandpass filtering on noise reduction has been measured as a function of fiber length for 130-fs pulses close to the soliton energy. For short fibers our results agree qualitatively with theoretical predictions. For longer fibers, however, the measured squeezing increases to an unexpectedly large value. Spectral filtering of a strongly Raman-shifted, higher energy pulse squeezed the directly detected photocurrent fluctuations down to 3.8±0.2 dB (59%) below the shot noise level. The measured noise reductions are broadband from 5 to 90 MHz.

OCIS code: (270.6570) Squeezed states; (270.5530) Pulse propagation and solitons; (190.4370) Nonlinear optics, fibers; (270.5290) Photon statistics

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1. Introduction

More than a decade ago the Kerr nonlinearity of optical fibers was demonstrated to lead to quadrature squeezing of cw [1] and more recently pulsed light. [2-6] Recently, a new and unexpected squeezing mechanism in fibers has been discovered, first for picosecond, [7] then for femtosecond solitons. [8] Nonlinear propagation in a fiber and subsequent spectral filtering squeezes the photon number uncertainty of the pulses. Noise reductions of 2.3 dB and 3.2 dB below shot noise have been reported for the picosecond and the femtosecond solitons respectively. [7,8] Numerical simulations of squeezing by spectral filtering based on the positive-P-representation predicted oscillations in noise reduction as a function of fiber length. [9] With pulses launched into the fiber at energies required for a fundamental soliton, the maximum squeezing is calculated to be 6.5 dB below shot noise. [10] With the Raman effect included, squeezing is expected to be reduced by 1.7 dB for 1.8-ps (FWHM) pulses at room temperature. [10] The latter prediction was found by varying the filter bandwidth and propagation distance from zero to 4 soliton periods. Recently, oscillations in noise reduction as a function of propagation distance have been also predicted and explained in a linearized approach using a back propagation method. [11]

This paper reports on first experiments investigating the quantum noise reduction by spectral filtering as a function of fiber length. The experimental data are in good qualitative agreement with theory for fiber lengths of up to a few soliton periods. [9-11] In this setup the best squeezing is observed for a fiber length of more than 100 soliton periods. This is in contrast to what can be extrapolated from the only theoretical model, so far, dealing with longer fibers, [11] which does not yet include the Raman self-frequency shift. A strong asymmetry is observed in the spectral distribution of the quantum noise for longer fiber lengths, and in the long propagation limit this asymmetry is accompanied by a further improvement of squeezing when the pulse energy is increased above the fundamental soliton energy. This leads to the strongest squeezing ever achieved for sub-picosecond pulses. Our experimental observation for long fibers is different from the predictions for ps-pulses in short fibers which included the Raman effect and which show the noise reduction to saturate at energies above the fundamental soliton energy. [10] Since the Raman effect seems to play a dominant role in the measurements as indicated by the pronounced spectral asymmetry of the noise, we feel that it may also be responsible for the increase of squeezing in the long fiber experiment although this is not explained by the results of the theoretical calculations for shorter fibers and ps-pulses.

2. Experimental setup

The experimental setup (Fig.1) is similar to the one reported earlier. [8] A modelocked Chromium-YAG-laser is used as a soliton source, [12] producing stable bandwidth-limited 100-200-fs pulses at a repetition rate of 163 MHz. Care had to be taken to ensure that no multiple pulses were travelling inside the cavity. [12] Part of the output pulse train was focused on a fast photodiode and the corresponding frequency comb was monitored by a 6.5-GHz spectrum analyzer. Constant height of the individual spikes in the spectrum, separated by the laser repetition rate, indicated that no satellite pulses were present more than 200 ps away from the main pulse. For detection of short-distanced satellite pulses, a spectrometer was operated at high sensitivity. The lack of oscillations in the pulse spectrum excludes any satellite pulses.

Pulses are launched into a single mode polarization maintaining optical fiber (3M, FS-PM-7811) with a mode field diameter of 5.5 µm. Comparing the input and output spectral and temporal pulse widths for different fiber lengths, the fundamental soliton energy of 130-fs pulses was determined to be 54±2 pJ. This corresponds to a photon number of 4.1×10^8 in each

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pulse. A group velocity dispersion of β_2=-10.5±0.5 fs^2/mm at 1505 nm was found independently by fitting numerical pulse propagation data to experimentally observed pulse broadening at low energies.

In order to minimize reflection losses from the fiber end a single-sided AR-coated gradient index lens was index-matched to the fiber. Spectral filtering was done with the beam dispersed by a diffraction grating and focused onto a variable slit consisting of two knife edges. Each knife edge could be moved individually in order to realize variable low-, high-, and band-pass filters. The spectral 90/10 transmission steepness of the edge filter was limited to 0.9 nm by the resolution of the grating setup.

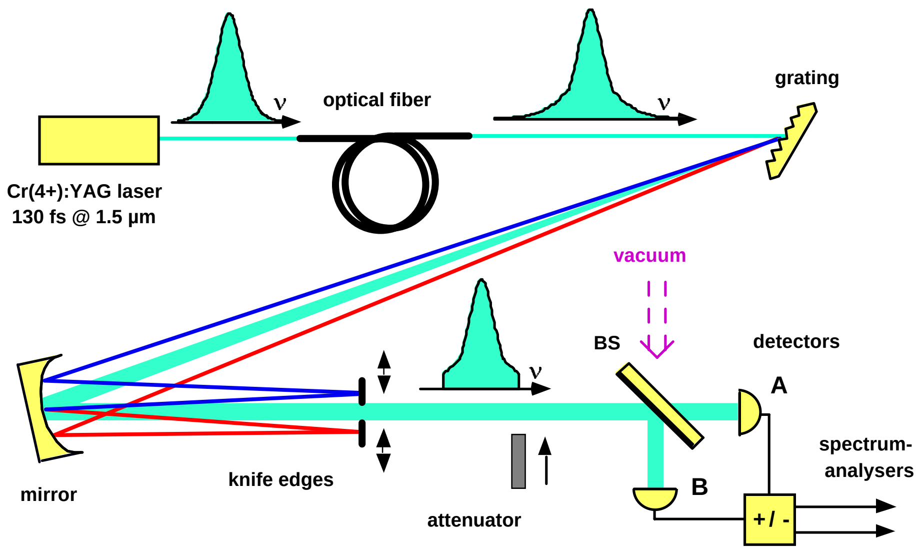

Fig. 1. Setup for the detection of sub-shot noise spectrally filtered solitons.

The transmitted light is detected by a balanced two-port detector consisting of one InGaAs photodiode (Epitaxx ETX-500T) in each output port. Their quantum efficiency was at 89-92% depending on wavelength. The DC photocurrents measured at the two detection ports A and B (Fig. 1) were monitored by digital voltmeters. The AC photocurrents from the two photodiodes were analyzed at frequencies ranging from 5 to 90 MHz. For pulses at the soliton energy, the quantum noise power was more than 12 dB above the electronic dark noise in a frequency span from 5 to 20 MHz. Particular care was taken to avoid saturation of the detector electronics by the strong signal at the laser repetition rate and its higher harmonics. The sum and difference of the rf photocurrent fluctuations are recorded by two spectrum analyzers, and their noise levels are displayed simultaneously on an oscilloscope screen. The sum of the photocurrent fluctuations represents the photon number fluctuations whereas their difference was used for the shot noise calibration. With an amplitude modulated diode laser, the two-port detector was balanced to an extinction ratio better than -30 dB in the 10-90 MHz frequency window.

The shot noise level of the photon number fluctuations has been established in three mutually independent ways: One was by dividing the sum by the difference fluctuations, both corrected for electronic dark noise and also corrected for a small difference in the gain of sum and difference output port. The shot noise level was checked independently by measuring the noise reduction introduced by attenuation of the optical signal right after the fiber. The noise reduction is verified to scale as required for quantum noise. At last, the shot noise level was determined in a third independent way by replacing the grating by a mirror and thus

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excluding any spectral filtering. All three methods gave the same shot noise level within 0.2 dB.

3. Noise reduction as a function of fiber length

In a first series of measurements we investigated the dependence of amplitude noise reduction as a function of fiber length. For all data points, the laser output pulses were centered at 1503.5±1.5 nm with spectral width and pulse duration kept constant at 18.5±0.7 nm (FWHM) and 130±5 fs (FWHM) respectively. The energy of the pulses launched into the fiber was 52±1 pJ and therefore close to the energy required for a soliton. The measurement procedure was the following: At a fixed fiber length a frequency high-pass and a low-pass filter were applied, respectively, at either side of the spectrum. The resulting photocurrent fluctuations were measured at 20 MHz and were recorded for different cut-off wavelengths. Fig. 2a shows results for a fiber length of 2.9 m. As reported earlier the spectral noise distribution appears to be asymmetric with respect to the center wavelength of the pulses, both in the amount of

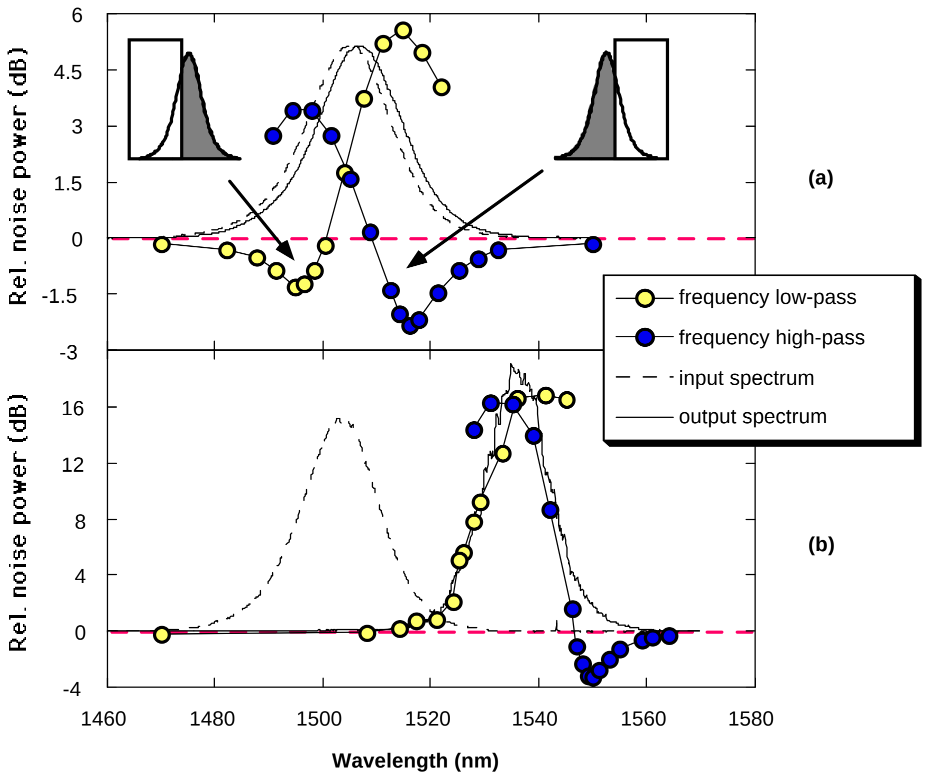

Fig. 2. Noise levels (relative to shot noise) in low- and high-pass filtering for different cut-off wavelengths. The fiber length for the data plotted here was fixed at 2.9 m (a) and 90 m (b). For comparison, input and output pulse spectra are shown.

maximum squeezing as well as in wavelength position. [8] Other results are displayed in Fig. 2b for a significantly longer fiber of 90 m. In that case, the asymmetry is much stronger than for the short fiber: squeezing is no longer observed for frequency low-pass filtering of the Raman shifted pulse, whereas frequency high-pass filtering squeezes the photocurrent fluctuations down to 3.2±0.2 dB below shot noise. This implies a noise reduction of 4.5±0.5 dB if linear detection losses are taken into account (grating efficiency: 94%, losses at mirrors and beamsplitters: 5%, detector quantum efficiency: 92%). In contrast, strong excess noise is observed if filters cut out about half of the spectrum. The tiny residual signal at the initial wavelength is barely visible on the scale of Fig. 2b. Cutting it off does not change the noise level as indicated. Similar data were taken at different fiber lengths. The maximum squeezing in each of these measurements is plotted in Fig. 3 along with the corresponding fiber length, both for high-pass (blue circles) and for low-pass filtering (yellow circles). Using an optimized band-pass filter instead of single edge filters improved the squeezing only for fiber lengths smaller than 3 m (green triangles).

At a fiber length of 2.4 m and 2.9 m we find pronounced maxima in squeezing of 1.3±0.1 dB and 2.3±0.1 dB (1.7±0.2 dB and 3.0±0.3 dB if corrected for linear losses) for the low-pass and the high-pass filtering respectively. The maxima might correspond to the first half-period of the oscillations predicted by theory. [9-11] The fiber length at the squeezing maxima corresponds to 3.0±0.3 and 3.6±0.4 soliton periods for blue- and red-filtered pulses (frequency low- and high-pass filtering) respectively, values coming close to the theoretical prediction for non-Raman-shifted pulses. For longer fibers, there is no clear evidence for oscillations by the data points. In the limit of fibers much longer than the soliton period, substantially higher squeezing is observed than for short fibers if the red wavelength components are filtered (Fig. 2a,b and Fig. 3). In contrast, squeezing is reduced for the blue-filtered solitons with increasing fiber length and vanishes after propagation along more than 10 soliton periods (Fig. 3). In this case, the spectral noise distribution looks similar to the one shown in Fig. 2b and the minimum noise for frequency low-pass filtering occures when the knife edge is completely moved out of the beam. The residual squeezing at 8.2 m is most likely explained by a small amount of frequency high-pass filtering at the detectors due to their finite dimension.

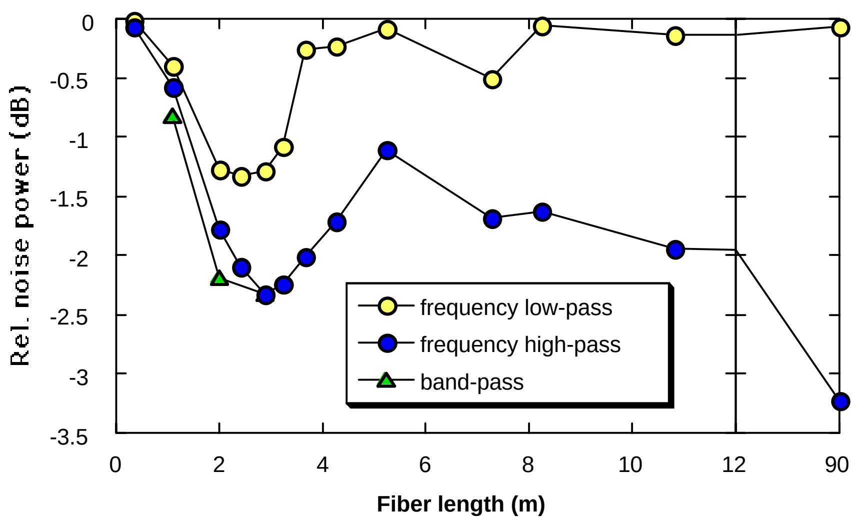

Fig. 3. Photon number squeezing by low-, high-, and band-pass filtering for different fiber lengths.

For pulses with a symmetric input spectrum (Fig. 2a,b) the Kerr effect can only produce a symmetric spectral noise distribution. [9,10] In contrast, the Raman effect asymmetrically transfers photons from the short to the long wavelength side of the spectrum and therefore should lead to an asymmetric spectral noise distribution [8] as also supported by the numerical calculations. [10] As a consequence, we believe the Raman effect to explain the measured asymmetry increasing with fiber length.

A model, that does not include the Raman effect, predicts that squeezing should be best during the initial propagation. [11] In contrast, the experimental data show that squeezing increases for long fibers and we conclude that the Raman effect might improve the squeezing. Further theoretical studies are needed.

In the limit of vanishing propagation distance, the squeezing decreases and approaches the shot noise level as expected both for high- and low-pass filtering, thus providing yet another check of the shot noise level.

4. Measurement of broadband noise reduction

The phase matching bandwidth of the Kerr effect is supposed to be in the Petahertz regime, [13] the Raman bandwidth has been measured to extend to about 10 THz. [14] Therefore fiber squeezing associated with the Kerr and the Raman nonlinearities should be broadband in spectrum. This has been verified for different fiber lengths, filter configurations, and pulse energies. As an example, Fig. 4 shows the directly detected photocurrent fluctuations in a frequency window ranging from 5 to 90 MHz. The noise reduction is well below 3 dB all over the frequency span. For frequencies higher than 60 MHz the trace becomes noisy due to reduced photodetector sensitivity. As the laser source is pulsed at a repetition rate of 163 MHz, noise from frequency sidebands up to the optical bandwidth are demodulated into the measured frequency window. Therefore, the measured noise floor represents the coherent sum of the noise in all 81.5-MHz intervals up to about 2 THz.

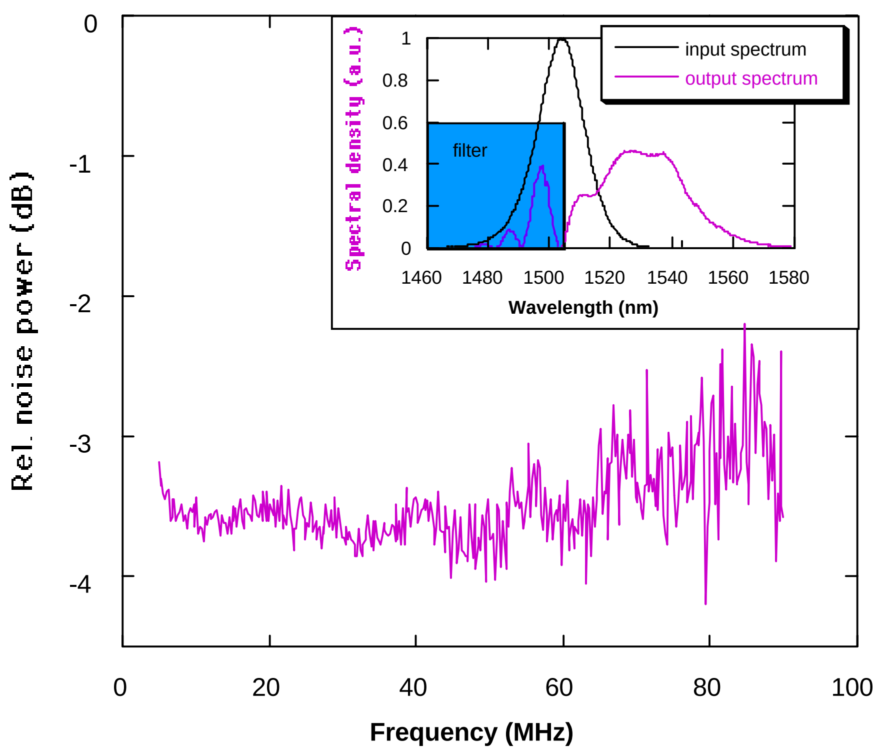

Fig. 4. Broadband noise reduction. Fiber length, pulse energy, and pulse width were at 3 m, 128 pJ, and 140 fs respectively. Input and output spectra as well as filter position are shown in the insert.

The maximum squeezing observed so far for spectrally filtered solitons has been obtained in the regime of strongly Raman-shifted pulses. 135 fs-pulses with energies of about 85 pJ were launched into 90 m of fiber. During propagation, pulses at energies above the soliton energy are known to split into a pulse close to the input wavelength and a soliton-like Raman pulse, which is red-shifted along the fiber. [15] In the experiment discussed here the Raman shift was 80 nm with only a small portion of the pulse staying unshifted. A spectral band-pass filter was adjusted such that it removed both this unshifted part of the pulse and red wavelength components above 1605 nm of the Raman pulse containing 4.2% and 1.9% of the total photon number respectively. As a result the photocurrent fluctuations (measured at 20 MHz) were squeezed to 3.8±0.2 dB (59%) below shot noise. The overall detection efficiency was 76% including 89% detector quantum efficiency, 90% grating efficiency, and 5% losses at mirrors and beamsplitters, implying a total squeezing of 6.4±0.8 dB (77%). Varying the low-and high-pass filter cut-off frequencies resulted in a noise distribution similar to the one shown in Fig. 2b with its asymmetry even more pronounced.

By comparison of these results with the 90-m data of Fig. 2b and Fig. 3 we find that for the long propagation distance, the measured noise reduction improves as the pulse energy is increased. Recent theoretical calculations which include the Raman effect predict a saturation in squeezing towards higher energy pulses in short fibers. [10] For long fibers however, no theoretical predictions are presently available for pulses with energies different from the soliton energy and including the Raman effect. Therefore, it is not clear at this point, whether the measured improvement is due to the Kerr nonlinearity with the Raman effect just degrading squeezing for frequency low-pass filtering or whether it is caused by the Raman nonlinearity again degrading squeezing for low-pass filtering but also improving it for high-pass filtering. The latter conjecture that the Raman effect helps the squeezing is supported by the arguments given in Section 3 and might be checked by repeating the experiments descibed here with longer pulses which are less affected by the Raman nonlinearity. [13]

5. Conclusion

In summary, we have experimentally shown that squeezing by spectral filtering depends critically on the nonlinear propagation distance. The oscillatory behavior predicted in the numerical and analytical models [9-11] is qualitatively supported by the experiment for a short fiber. For a long fiber and a corresponding strong Raman self-frequency shift, the measured squeezing increases, in contrast to what is expected from theory. In this regime we have achieved the best squeezing up to date both for fs-pulses and for solitons. Due to aliasing of higher frequency noise into the measured frequency window the measured squeezing-bandwidth product should be the largest ever observed. The measurement of potentially even higher noise reduction for stronger Raman-shifted pulses was hindered by the limited wavelength range of the InGaAs photodiodes. From a theoretical point of view the question is still open whether the Raman effect may support squeezing. Therefore, in order to explore the full potential of noise reduction by spectral filtering, the quantum theory including the Raman effects [9,10] should be applied to long propagation distances.

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