Letter
Fibre-optic photon-number squeezing in the normal group-velocity dispersion regime

F. KÖNIG†, S. SPÄLTER†, I. L. SHUMAY†, A. SIZMANN†, TH. FAUSTER† and G. LEUCHS†
† Lehrstuhl für Optik, Physikalisches Institut der Universität Erlangen-Nürnberg, Staudtstr. 7/B2, D-91058 Erlangen, Germany
‡ Lehrstuhl für Festkörperphysik, Institut für Angewandte Physik der Universität Erlangen-Nürnberg, Staudtstr. 7/A3, D-91058 Erlangen, Germany

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Abstract. The nonlinear optical Kerr effect, acting on optical pulses in fibres, creates spectral sidebands and noise correlations between these sidebands. The reduction of photon-number fluctuations of these pulses below the shot-noise limit by spectral filtering is well established in the anomalous dispersion regime which allows for soliton formation. Here it is demonstrated that a significant quantum-noise reduction with spectral filtering can also be reached for pulses in the normal dispersion regime. The filter function was optimized and the power dependence of the noise reduction was investigated. The best squeezing result is $(1.2 \pm 0.2) \text{dB}$ (corresponding to $(2.6 \pm 0.7) \text{dB}$ inferred for 100% detection efficiency).

1. Introduction

Nonlinear optical pulse evolution in the presence of group-velocity dispersion (GVD) is an important issue in many applications such as fibre-optic communication [1], signal processing [2] and quantum measurement [3]. Spectral filtering of these pulses proved to be important for overcoming the Gordon–Haus limit [4–6] for noise reduction in the anomalous dispersion regime [7–10] and furthermore one may hope to realize optical functional elements [11]. Solitons occurring in the anomalous GVD regime do not disperse and therefore have a high peak power during the full length of propagation. Experiments on the noise characteristics of spectrally filtered solitons suppressed classical 1/f laser noise by 23 dB [10]. In the quantum regime, where noise reduction may lead to sub-Poissonian photon statistics, the measurements showed 2.3 dB of squeezing with 2.7 ps pulses [7] and up to 3.8 dB with 130 fs pulses [9]. On the other hand, the regime of normal GVD does not allow for bright solitons. There the effects of GVD and self-phase modulation (SPM) add and broaden the temporal pulse shape. This leads to a reduction of nonlinear effects. However, for pulses with high enough peak intensity the nonlinear effects are sufficient for observation of sub-Poissonian noise without the assistance of soliton-like dynamics.

So far the only pulsed squeezing experiments that have been performed with normal or zero dispersion fibres are quadrature-squeezing experiments with...
heterodyne measurements of the signal [12–14]. In contrast, no photon-number noise-reduction experiments in the normal GVD regime have yet been reported in the literature [15]. This letter presents results on sub-Poissonian photon-number noise generated in fibres of normal dispersion (-132 ps nm\(^{-1}\) km\(^{-1}\)) using 29 fs laser pulses. On the theoretical side, for the normal dispersion regime numerical simulations have been carried out. These calculations using the Raman-modified quantum nonlinear Schrödinger equation predict a noise reduction below the shot-noise level of up to 2.1 dB for picosecond pulses at energies corresponding to \(N \in [0.7, 1.2]\) in soliton parameters [16].

2. Experimental configuration

The experimental configuration is shown in figure 1. The laser system was a Kerr-lens mode-locked Ti:sapphire laser pumped by a frequency-doubled Nd:YVO\(_4\) laser (Spectra Physics Millennia series) with 3.7 W of output power. The laser emitted 29 fs pulses (FWHM) centred at 808 nm with a repetition rate of 87.2 MHz. Assuming a hyperbolic-secant shape for the pulses the time-bandwidth product was estimated to be 0.38, which is significantly larger than the value of 0.31 for unchirped pulses. This suggests that the pulses were slightly chirped. With optimum dispersion compensation shorter pulses can be achieved. The pulses were launched into 2 m of polarization-preserving single-mode fibre (fused silica containing 12 wt.% Ge, Fibercore HB800). We determined the field-mode diameter to be 4.8 \(\mu\)m. The dispersion of this fibre is -132 ps nm\(^{-1}\) km\(^{-1}\) at the centre wavelength of 808 nm [17]. From the literature we estimated the nonlinear refractive index \(n_2\) to be approximately \((3.5 \pm 0.4) \times 10^{-16} \text{ cm}^2 \text{ W}^{-1}\) [18]. We found the same value within the error bar using a numerical propagation calculation. This simulation, with \(n_2\) being the only free parameter, yielded the experimentally observed spectral broadening at several input energies. The linearly polarized output from the laser was rotated by a half-wave plate so as to couple to only one main axis of the fibre. A telescope expanded the output beam diameter. The light was then dispersed by a grating (600 grooves/mm, blaze

![Figure 1. Outline of the experimental apparatus (BS= beamsplitter). The spectral pulse evolution is indicated for the propagation through the fibre and the spectral filter.](image-url)
wavelength $750\text{nm}$, Jobin Yvon). The dispersed beam was focused on a slit formed by two knife edges. The slit served as a spectral band-pass filter, but could also be used as a low- or high-pass filter. A subsequent beamsplitter directed the light onto a balanced two-port detector. At each port there were two silicon-PIN photodiodes (Siemens SFH217) operating in parallel in order to avoid saturation effects. The rf current of the photodiodes was resonantly enhanced at about $21\text{MHz}$ and attenuated at $87.2\text{MHz}$, the repetition rate from the laser. Thereby the signal-to-noise ratio improved without saturating the amplifier. Two spectrum analysers (HP8590L) recorded simultaneously the sum and the difference, respectively, of the amplified ac photocurrents at $21\text{MHz}$ with a resolution bandwidth of $300\text{kHz}$. While the sum photocurrent corresponds to the intensity fluctuations of the light, the difference represents the shot-noise level. Independently the shot-noise level was determined by attenuating the light with neutral density filters as in [8] and [9]. As a test of the detector balance, the laser beam was electro-optically amplitude modulated and sent onto the balanced two-port detector. By adjusting the electronics an extinction ratio between sum and difference levels larger than $25\text{dB}$ was achieved. The overall quantum efficiency of the fibre-output coupler, the grating and the balanced two-port detector with opened filter was determined to be $(54 \pm 2)\%$. The losses include a photodiode quantum efficiency of $81\%$ and an $80\%$ grating efficiency. Additional losses are due to beamsplitters and Fresnel reflections. All mirrors were highly reflecting mirrors and most of the lenses were antireflection coated.

3. Measurements

When ultrashort pulses are propagating in an optical fibre, there are different competing effects changing the pulses both in the time and spectral domain. The most important effects for ultrashort pulses are the dispersion, the Kerr and the Raman effect. These effects may be characterized by the length scales over which the pulses are modified significantly [2]. A short length corresponds to a strong effect. A Gaussian pulse broadens by a factor of $2^{1/2}$ after one dispersion length. After one nonlinear length the maximum nonlinear phase shift within a pulse amounts to $1\text{rad}$. For our experiment the shortest scale is the dispersion length, being only about $6\text{mm}$. This means that the pulse spreads out during the first few centimetres of the fibre and different wavelength components separate in space and time. Pump and Stokes wavelengths disperse and therefore stimulated Raman scattering is ineffective. Consequently we could not observe any self-frequency shift even at a fairly high pulse energy of $1.4\text{nJ}$. The length scale of the Kerr nonlinearity is power dependent and ranges from $33$ to $7\text{mm}$ for $84$ to $360\text{pJ}$ pulses, respectively. This is comparable to the dispersion length and shows the relative importance of the Kerr effect. We observed spectral broadening up to three times the initial spectral width at the highest energy of $1.4\text{nJ}$. Taking together both effects, the dispersion and the nonlinearity, the pulse broadens after propagating a few dispersion lengths so much that the nonlinearity becomes negligible. Beyond this point the pulse continues to disperse and the spectrum and the spectral noise properties remain unchanged. In our experiment the fibre was $2\text{m}$ long, much longer than the characteristic length scales. Most of the fibre was therefore merely used as a waveguide. When the shot-noise limited laser pulses are launched into the fibre, the spectral quantum statistics of the light is
modified in the first few centimetres. This can be investigated with a subsequent spectral filter. Since the Kerr effect and dispersion act symmetrically on the pulse envelope, the filter for optimum noise reduction will be a symmetric filter. Similar to the experiments in the anomalous GVD regime an optical band-pass filter was applied. It was checked experimentally that best squeezing is achieved for a band-pass filter positioned at the centre of the spectrum. In the measurement of the quantum-noise reduction two parameters were varied systematically, the filter width and the pulse energy.

3.1. Variation of filter width

The first type of experiment was to find the optimum filter width for maximum squeezing. Input and output spectra for an input pulse energy of 360 pJ are displayed in figure 2(a). With the band-pass filter centred around the maximum of

![Figure 2](image)

Figure 2. (a) Input (thin line) and output (thick line) spectra at a pulse energy of 360 pJ. (b) Intensity-noise power at 21 MHz relative to shot noise versus filter bandwidth for the input pulses from (a). Open circles, triangles and diamonds correspond to a squeezing measurement without, with 46% and with 71% attenuation at 360 pJ input energy. The data are corrected for the degradation of squeezing due to the 46% and 71% attenuation. The full circles indicate data taken without attenuation at an input energy of 135 pJ.
the pulse spectrum we changed the spectral width of the filter and observed the photon-number fluctuations at 21 MHz. Results are displayed in figure 2(b) for the same input-pulse energy (open marks). For extremely narrow filter widths the level of fluctuations lay clearly above the shot-noise level. Increasing the filter width reduced the noise below the shot noise. Input-power fluctuations were transferred to the spectral sidebands and these were removed by the band-pass filter. With the filter being wide open the fluctuations approached the shot-noise level reproducing the statistics of the incident laser radiation. For spectral filter widths of more than 22 nm an attenuator was inserted in front of the balanced detector in order not to saturate the photodiodes (triangle and diamond marks). The measurements were taken 10 dB above the electronic noise background and corrected for the noise as in [8] and [9]. The maximum observed squeezing was $(1.15 \pm 0.10)$ dB. At this point the spectral filter width was about 20.3 nm corresponding to half the spectral FWHM of the output pulse. In other words about 60% of the pulse energy was blocked by the filter.

The vanishing noise reduction for very narrow filter widths indicates that narrow spectral intervals across the pulse carry fluctuations above shot noise. Then sub-Poissonian statistics are only possible through noise correlations between spectral components [19]. For large filter widths the measurement included all these correlations and thereby reached shot noise.

For comparison figure 2(b) displays a second data series measured with a reduced pulse energy of 135 pJ (full circles). The dependence of noise reduction on filter width is similar to the measurement at higher energy with the squeezing being generally less.

3.2. Variation of input energy

In the second type of experiment the dependence of maximum noise reduction on the input energy was measured. The input energy was varied at the fibre input coupler and for each energy the filter bandwidth was optimized for minimum fluctuations. The result is shown in figure 3. The squeezing improves gradually with increasing input-pulse energy. The best squeezing observed was $(1.2 \pm 0.2)$ dB, corresponding to $(2.6 \pm 0.7)$ dB if corrected for linear losses in

![Figure 3. Relative noise powers of the measured photocurrent, each at the optimum filter position, versus pulse energy.](image-url)
the set-up. The maximum squeezing seemed to be limited only by the onset of photodiode saturation. The measured energy dependence of the squeezing was in qualitative agreement with the prediction of the theoretical calculation [16]. However, the absolute value was larger than the simulation, carried out for picosecond pulses, indicates. For comparison figure 4 shows the data from figure 3 corrected for finite detection efficiency together with the results from the theoretical calculation. For the data in figure 3 the filter transmitted at most 50% of the pulse energy for all input energies. The requirement for strong filtering indicates that only in the very centre of the pulse spectrum there are regions of anticorrelated noise. A notch filter centred in the spectrum would therefore yield strong excess noise.

4. Conclusion

Kerr squeezing of the photon number in the normal dispersion regime was demonstrated using spectral filtering and the optimum filter width was found. The evolution of squeezing at the optimized width was observed as the input-pulse energy was increased. The relative noise power decreases gradually showing a significant noise reduction. The behaviour is qualitatively explained by the simulation in [16]. However, the absolute size of squeezing seems to be larger than predicted for unchirped picosecond pulses. Two possible reasons are the much shorter femtosecond pulses or the frequency chirp in each pulse. The optimum band-pass filter has a lower transmission than the one found in the anomalous dispersion regime [7].

Acknowledgments

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References


[15] During the preparation of this publication we were informed that preliminary measurements of photon-number squeezing with picosecond pulses were achieved by S. R. Friberg. They were briefly discussed at the International Quantum Electronics Conference: Friberg, S. R., and Werner, M. J., 1998, International Quantum Electronics Conference IQEC '98, 5–8 May, San Francisco, CA, Paper OTHH3.


