A Novel Method for Polarization Squeezing with Photonic Crystal Fibers

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Abstract: Photonic Crystal Fibers can be tailored to increase the nonlinear Kerr effect while producing small amounts of excess noise. Using these features we create polarization squeezed states with higher purity than is obtained in standard fibers. We produce squeezed states in counter propagating pulses along the same fiber axis to achieve near identical dispersion properties. This enables the production of polarization squeezing through interference in a polarization type Sagnac interferometer. We observe Stokes parameter squeezing of -3.9 ± 0.3 dB and anti-squeezing of 16.9 ± 0.3 dB. The purity of the squeezed state is notably higher than using standard fibers.

OCIS codes: (270.0270, 270.6570, 270.2500, 270.5290, 060.5295).

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1. Introduction

Generation of squeezed light in glass fibers has, to date, been greatly affected by large phase noise from molecular vibrations, defects in the amorphous silica and Guided Acoustic Wave Brillouin Scattering (GAWBS) [1, 2, 3, 4]. Photonic Crystal Fibers (PCFs) represent a promising new technology to reduce this noise. Due to higher nonlinearities of PCFs the fiber length can be drastically reduced compared to standard fibers. The excess noise originating from GAWBS is thus reduced since it scales linearly with the length of the fiber. Furthermore, tailoring the cross-sectional geometries of these novel waveguides [5] and, thus, their vibrational properties [6], may lead to a further reduction of GAWBS. The microstructuring of a PCF may act as a phononic attenuator thus preventing the excitations of low frequency GAWBS fluctuations. Therefore these PCFs are excellent candidates for the production of purer squeezed states which is of crucial importance for numerous quantum communication and information protocols [7].

The optical Kerr effect $(\chi^{(3)})$ in silicon glass fibers links the fluctuations in the intensity to changes in the refractive index. This leads to correlations between the amplitude and the phase quadratures, thereby generating quadrature-squeezing. However, the nonlinear processes that occur in optical fibers do not preserve the minimum uncertainty states, as huge amount of phase noise is added. Note that since the Kerr effect conserves the photon number, the amplitude fluctuations remain at the shot noise level. This prevents direct detection of the quadrature-squeezing. However, this problem can be overcome by using a nonlinear optical loop mirror (NOLM) [8, 9, 10, 11] or generating polarization squeezing. The quantum polarization states can be described by its three Stokes observables [12, 13] obeying the standard commutation relations for angular momenta. The polarization of a gaussian state is limited by quantum noise and therefore polarization squeezing is associated with the squeezing of Stokes parameters to be below the fluctuations of the standard quantum noise limit (QNL). This was first suggested in the work by Chirkin et al. in 1993 [14], where the Heisenberg uncertainty relations for the Stokes operators were derived. Note that if the light is classically $\hat{S}_3$ polarized, the ”dark” polarization plane is spanned by the $\hat{S}_1$ and $\hat{S}_2$ parameters, and the squeezing and anti-squeezing of the quantum polarization can be investigated in this plane. Using this fact, there is a clear analogy between polarization squeezing and quadrature squeezing [15, 16].

Polarization squeezing is a two-mode squeezing process, in which two modes are interfered [1, 2, 17, 18, 19, 20]. The interference visibility is therefore a very crucial parameter for the production efficiency of polarization squeezing. In a previous experiment on the production of polarization squeezing in orthogonal polarization modes of a PCF the efficiency was degraded due to the different dispersion properties of the two fiber axes. The spectral evolution of the

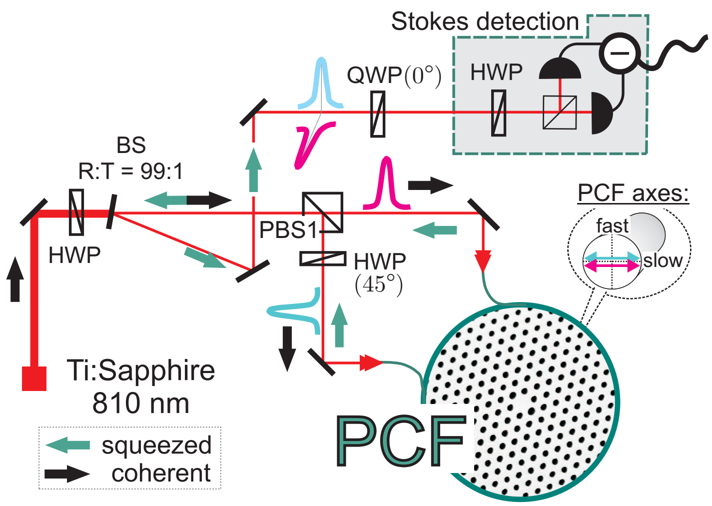

Fig. 1. Schematic of the experimental squeezing setup. BS: beam splitter PBS: polarizing beam splitter. HWP: half-wave plate. QWP: quarter-wave plate.

orthogonal bright pulses was different, thus the pulses evolving along different fiber axes could not interfere perfectly and therefore the amount of squeezing decreased with increasing pump power [21]. In the present paper we report on the generation of polarization squeezing with PCFs using an improved method. Namely, in order to avoid different dispersion effects for each mode, we employed counter propagating pulses along the same fiber axis to achieve identical dispersion properties. This improved method also simplifies the experimental setup, since no birefringence compensator is needed.

2. Experimental procedure

The schematics of the experimental setup is depicted in Fig.1. We use a single mode polarization maintaining NL-PM-750 PCF (Crystal Fibre A/S) with a zero dispersion wavelength at 750 nm. The PCF uses a micro-structured cladding region with air holes to guide light in the pure silica core. The PCF supports a mode with an effective mode field diameter of $1.8 \pm 0.2\,\mu$m, which yields an enhanced effective nonlinearity due to the strong light localization. Ultra short laser pulses with approximately 120 fs pulse duration are used to exploit the $\chi^{(3)}$ nonlinearity of the fiber. The pulses are generated with a commercial Tsunami Ti:Sapphire laser from Spectra Physics Inc. at a wavelength of 810 nm. The pulse repetition rate is 82 MHz and the average output power is approximately 2 W.

A linearly polarized beam is equally divided into both ends of the PCF which is placed in a polarization type Sagnac interferometer. For the in- and out-coupling of the optical field we use aspheric lenses with numerical apertures of 0.41 and a focal length f = 4.5 mm. The half-wave plates (HWPs) are aligned such that the polarization of the two counter propagating beams are aligned along the same axis of the polarization maintaining PCF. This was validated by monitoring the dark port of the PBS1 and we found that it never exceeded more than 2% of the beam intensity (This is an essential point of the setup in order to have identical spectra of both pulses). After recombination of the two beams, they are directed to the Stokes detection scheme via a 99:1 beam-splitter (BS). Here the two pulses pass through a quarter wave-plate (QWP) which turns the polarization mode into a $\hat{S}_3$ circular polarized mode. The squeezing and anti-squeezing is then simply measured in the $\hat{S}_1$ - $\hat{S}_2$ dark plane. The Stokes parameters in that plane can be accessed by rotating the HWP and subtracting the resulting photo currents of the two outputs of the PBS. This measurement is equivalent to a balanced homodyne detection, where the bright excitation acts as the local oscillator for the orthogonally polarized dark mode. The spectral densities of the resulting difference currents are measured with an electronic spectrum analyzer (ESA).

2.1. *Visibility and spectral evolution*

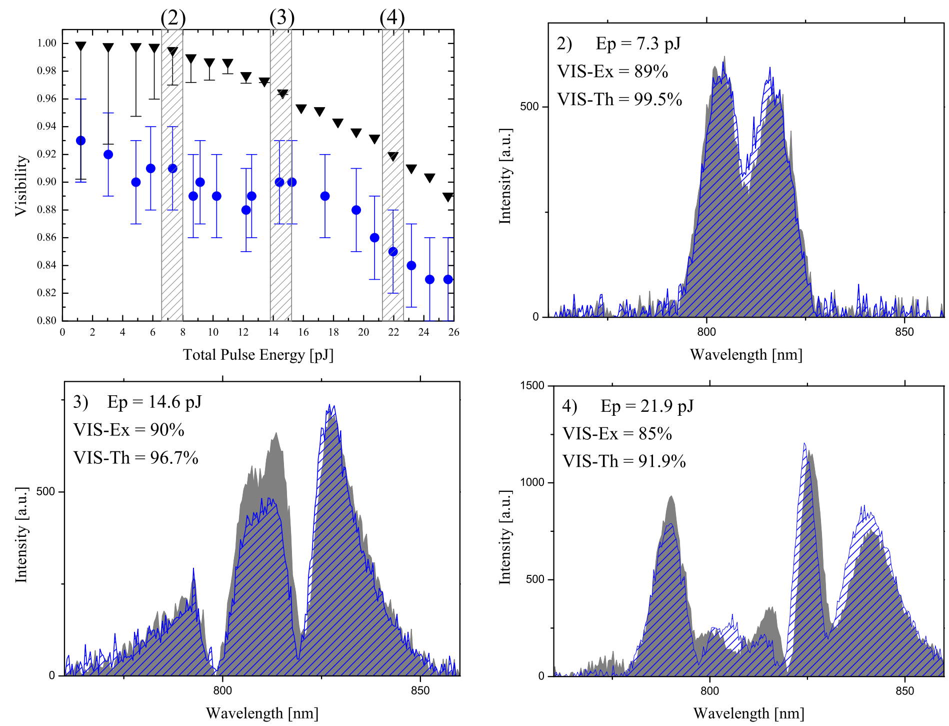

Fig. 2. Visibility as function of total pulse energy. The blue circles show the experimentally measured visibility whereas the black triangles show the theoretical maximum for the corresponding spectra. The error-bars for the theoretical visibility are due to the low power in the pulses, low signal to noise ratio. The marked areas (2)-(4) are pulse energies for which the measured output spectra the are shown in detail: (2) 7.3 pJ, (3) 14.6 pJ and (4) 21.9 pJ. The gray and blue shaded areas are the s- and p-polarized outputs from PBS1, respectively. (NL-PM-750 fiber, 810 nm center input wavelength.)

Since the dispersion parameters of the orthogonal fiber axes are different, the spectral evolution of the orthogonal polarized pulses will also be different. As a consequence the pulses evolving along different fiber axes do not interfere perfectly and the amount of detectable squeezing will decrease with increasing pump power. In our previous work this effect prevented the efficient generation of polarization squeezing [21]. Here we observe that the spectral evolution of the two counter propagating pulses on the same optical axis is very similar, which is due to the identical dispersion response. Spectral evolutions for different pulse powers are shown in Fig. 2. Note that the error-bars for the measured visibility are given by the precision of our measurement device, which is approximately 4-5%. We observe that with increasing pulse energy, spectral broadening occurs. The spectral broadening is due to a complex interaction of several linear and nonlinear effects; dispersion, self-phase modulation and Raman scattering [22]. Because of the these effects, the spectra gets therefore more complex and the spectral overlap between the pulses decreases. We have calculated an upper bound of the visibility for various pulse powers. Fig. 2 shows the measured and theoretical visibility as a function of the power of the pump. It can be seen that the theoretical values for the visibility are about 5%-9% higher than the experimentally measured. This is mainly because the theoretical values assume perfect temporal and spatial overlap, which is not perfectly realized in the experiment. However, compared to our previous work, where the spectral overlap between the corresponding pulses was very low, we have with this new experimental procedure increased the spectral overlap of the pulses.

Nevertheless there is a drawback with the present setup. The interference contrast (visibility) of the two Kerr squeezed modes is extremely sensitive. In conventional single-pass fiber squeezing experiments the spatial mode-matching comes for free and the temporal mode-matching is normally controlled with a feedback loop. In our experiment the in-coupling into the individual fiber ends are not identical and imperfect, the out-coupling angle can therefore slightly differ. This will lead to a noticeable difference in the temporal and spatial overlap of the counter propagating pulses. Also mechanical fluctuations of the PCF ends lead to imperfect mode matching, since the fiber ends fluctuate independently.

For this experiment glass ferules with ca. 1.5 mm diameter have been cleaved to the PCF ends to enhance the in- and out-coupling. Therefore we have to exclude the possibility that the ferules corrupt the optical mode. By measuring squeezing and also visibility without these ferules we always stayed clearly below the results which were measured using the ferules. This is probably due to mechanical vibrations which effect the in and out-coupling into the bare PCF more than using glass ferules. Furthermore due to spectral broadening, as show in Fig. 2, imperfect optical components, especially the HWPs, can have slightly different effects on wave component. We believe that these are the dominant factors for the difference in the maximally theoretical possible and experimentally measured visibility.

2.2. Measurement of polarization squeezing

The measured squeezing and anti-squeezing versus total pulse energy are plotted in Fig. 3. With increasing pulse energy the squeezing increases until a certain point after which the squeezing decreases. The measured noise even exceeds the shot noise level for higher pulse energies. This excess noise is mainly composed of GAWBS, Raman scattering as well as uncorrelated modes which were created by nonlinear four-wave-mixing processes. We observed a maximal squeezing of -3.9 ± 0.3 dB with an excess noise of 16.9 ± 0.3 dB (Fig.3). Note that the squeezing behavior is investigated in the anomalous dispersion regime at a wavelength of 810 nm. All measurements were performed at a detection frequency of 17 MHz. The variances have all been corrected for dark-noise of the detectors, which is more than 13 dB below the QNL. Each trace depicted in Fig. 3 is normalized to the QNL. The measurements are performed with a resolution bandwidth of the ESA set to 300 kHz and with a video bandwidth of 300 Hz. The calibration of the QNL is done by sending a coherent beam with equal power to that of the squeezed beam into the Stokes measurement.

The total detection efficiency of our experiment is given by: $\eta_{total} = \eta_{prop}\eta_{det}\eta_{vis}$, where $\eta_{prop} = 0.95 \pm 0.01$ is the propagation efficiency from the fiber to the detectors, $\eta_{det} = 0.95 \pm 0.05$ is the quantum efficiency of the photo-detectors and η_{vis} range from $(0.86)^2 \pm 0.02$ to $(0.92)^2 \pm 0.02$ is the visibility in our Stokes measurements (see Fig. 2). The purity $\mathscr{P}$ of the squeezed state is calculated as $\mathscr{P} = \left[\Delta^2\hat{S}(\mathrm{sqz}) \cdot \Delta^2\hat{S}(\mathrm{antisqz})\right]^{-1/2}$. Corrected for linear losses and interference losses between the polarization modes, the maximum inferred squeezing is -8.7 ± 0.3 dB and the anti-squeezing is 18.5 ± 0.3 dB. Comparing the purity (Fig. 3) to the

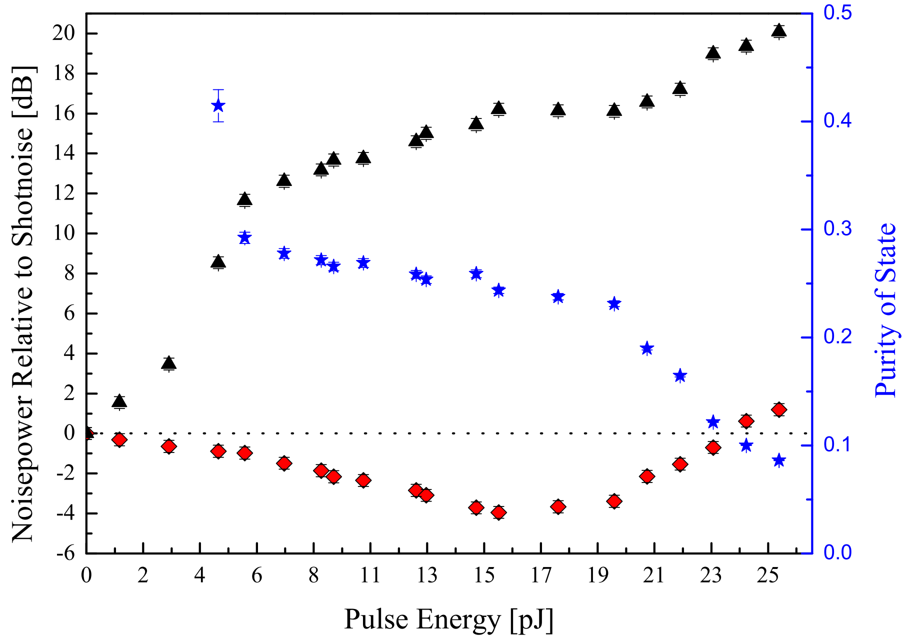

Fig. 3. Measured noise power versus the optical pulse energy. Red squares and black triangles show squeezing and anti-squeezing, respectively (left scale). We observed a maximal squeezing of -3.9 ± 0.3 dB with an anti-squeezing of 16.9 ± 0.3 dB. The blue stars show the purity of the squeezed state (right scale). All data is measured at a frequency of 17 MHz. The squeezing is only corrected for electronic detector noise which is 13 dB below the shot noise.

purity of squeezed states generated with standard fibers [1], the purity of our squeezed state is notably higher, approximately 3-4 times, although we could not reach the same amount of squeezing as in the work by R. Dong *et. al.* [1]. We attribute this increase in purity to the increased effective nonlinearity, which has the consequence that the fiber length is much shorter then in standard fiber squeezing experiments, which in return reduces the scattering of acoustic modes in the fiber [6].

3. Conclusion

We have demonstrated the generation of polarization squeezed light using a PCF. We generated -3.9 ± 0.3 dB squeezing and 16.8 ± 0.3 dB anti-squeezing. We successfully exploited a Sagnac-loop type setup with counter propagating pulses along the same fiber axis. Compared to our previous work, where the spectral overlap between the corresponding pulses was very low, we have with this experimental procedure increased the spectral overlap and also increased the amount of measured squeezing. However, the interference contrast of the two Kerr squeezed modes is highly sensitive to imperfect optical components and mechanical fluctuations of the PCF ends. The future task is to achieve a constant high visibility to produce a reliable and simple source for bright entangled states.

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