Efficient polarization squeezing in optical fibers

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We report on a novel and efficient source of polarization squeezing using a single pass through an optical fiber. Simply passing this Kerr squeezed beam through a carefully aligned $\lambda/2$ waveplate and splitting it on a polarization beam splitter, we find polarization squeezing of up to $5.1 \pm 0.3$ dB. The experimental setup allows for the direct measurement of the squeezing angle.

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The budding field of quantum information holds promise to revolutionize communication. In particular the field of quantum information with continuous variables has received much attention in the last decades with the realization, for instance, of quantum teleportation, quantum cryptography and dense coding. Most of these protocols require the use of squeezed (or entangled) states of light that are generally detected using a strong local oscillator, which makes the scalability of quantum networks difficult. Recently, polarization squeezing has attracted much attention as it can be measured in direct detection, making it especially attractive for cryptography and other quantum communication applications. Furthermore the fluctuations of the polarization variables can be mapped onto the collective fluctuations of an atomic ensemble, paving the way to quantum memory.

To date polarization squeezing has been achieved using the nonlinear interactions in Optical Parametric Amplifiers, optical fibers and atomic media. In this paper we present the results of a novel and efficient method of bright pulse polarization squeezing generation using the Kerr effect in an optical fiber. This setup is greatly simplified relative to other schemes and leads to high squeezing levels. Further, this method enables us to completely characterize all quadratures of the state exiting an optical fiber. In particular we measured the angle by which the squeezed uncertainty region has been rotated by the nonlinear Kerr effect.

It has been known for a long time that the optical Kerr effect in glass fiber can generate quadrature squeezing. This third order nonlinear effect ($\chi^3$), also referred to as Self Phase Modulation produces an intensity dependent change in the refractive index. The squeezing generation can be understood by a single mode picture represented in Fig. 1(a): since different amplitudes experience different rotations in phase space, the fluctuation circle (corresponding to shot noise) of the input field is transformed into an ellipse. The squeezed quadrature is rotated by the angle $\theta_{sq}$ relative the amplitude quadrature. Since the Kerr effect conserves photon number, the amplitude fluctuations remain at the shot noise level preventing direct detection of the squeezing.

Polarization squeezing overcomes this problem. It can be generated by overlapping two quadrature squeezed beams produced in the two orthogonal polarization modes of the fiber, visualized by $\hat{a}_x$ and $\hat{a}_y$ in Fig. 1(b). This setup, seen in Fig. 2, is similar to our previous experiment producing polarization squeezing, where instead two amplitude squeezed beams were generated. These were produced in an asymmetric Sagnac interferometer in which a strong Kerr squeezed pulse is transformed into amplitude squeezing by interference with a weak auxiliary pulse; squeezing by this principle can also be achieved using a Mach Zehnder interferometer. This interference of a strong squeezed and a weak "coherent" beam however gives rise to a loss in squeezing due to the dissimilarity of the pulses. In this paper’s setup we avoid this destructive effect by mutually interfering two strong Kerr squeezed pulses in a Stokes measurement, with the potential to measure more squeezing. Formally this interference of equally squeezed pulses is reminiscent of earlier experiments producing vacuum squeezing. Further advantages of the present setup is a greater robustness against input power fluctuations and the ability to measure squeezing at all powers.

To describe the quantum polarization state of a light
Stokes parameters obey the relations:

\[
\begin{align*}
\hat{S}_0 &= \hat{a}_x^\dagger \hat{a}_x + \hat{a}_y^\dagger \hat{a}_y, \quad \hat{S}_1 = \hat{a}_x^\dagger \hat{a}_x - \hat{a}_y^\dagger \hat{a}_y, \\
\hat{S}_2 &= \hat{a}_x^\dagger \hat{a}_y + \hat{a}_y^\dagger \hat{a}_x, \quad \hat{S}_3 = i(\hat{a}_x^\dagger \hat{a}_x - \hat{a}_y^\dagger \hat{a}_y). \quad (1)
\end{align*}
\]

Following the non-commutation of the photon annihilation and creation operators, \(\hat{a}_x\) and \(\hat{a}_y\), these Stokes parameters obey the relations: \([\hat{S}_0, \hat{S}_i] = 0\) and \([\hat{S}_i, \hat{S}_j] = 2i\epsilon_{ijk}\hat{S}_k\) with \(i, j, k = 1, 2, 3\). These relations lead to Heisenberg inequalities for the fluctuations of these parameters that depend on the mean polarization state.\(^7\) For instance, let us consider the situation where the modes \(\hat{a}_x\) and \(\hat{a}_y\) have the same amplitude but phase shifted by \(\pi/2\) (Fig. 1(b)): \(\langle \hat{a}_x \rangle = i\langle \hat{a}_y \rangle = i\alpha/\sqrt{2}\), \(\alpha\) being a real number. This light is circularly polarized \((\hat{S}_1) = (\hat{S}_2) = 0\); \((\hat{S}_3) = (\hat{S}_0) = \alpha^2\) and the only non-trivial Heisenberg inequality is \(\Delta^2 \hat{S}_1 \Delta^2 \hat{S}_2 \geq |\langle \hat{S}_3 \rangle|^2 = \alpha^4\), where \(\Delta^2 \hat{S}_j\) refers to the variance \((\hat{S}_j^2) - \langle \hat{S}_j \rangle^2\). Polarization squeezing is achieved if the variance \(\Delta^2 \hat{S}_0\) (variance of a general Stokes parameter rotated by an angle \(\theta\) in the \(\hat{S}_1\)-\(\hat{S}_2\) plane) is below the shot noise level:

\[
\Delta^2 \hat{S}_0 \leq |\langle \hat{S}_3 \rangle| = \alpha^2 \quad \text{where} \quad \hat{S}_0 = \cos \theta \hat{S}_1 + \sin \theta \hat{S}_2. \quad (2)
\]

To fully characterize the polarization fluctuations, one can express the fluctuations of the Stokes parameters in terms of the noise of the linearly polarized modes \(\hat{a}_x\) and \(\hat{a}_y\). Since the fluctuations are small compared to the mean values \((\delta \hat{a}_x, \delta \hat{a}_y \ll \alpha)\), we find:

\[
\delta \hat{S}_0 = \alpha(\delta \hat{X}_{x,\theta} - \delta \hat{X}_{y,\theta})/\sqrt{2}. \quad (3)
\]

Here \(\hat{X}_{x,y,\theta}\) corresponds to the quadrature rotated by an angle \(\theta\) for \(x\) and \(y\) polarizations, visualized in Fig. 1(b) and Fig. 3. The amplitude and phase quadratures are found for \(\theta = 0\) and \(\theta = \pi/2\).

The mode \(x\) and \(y\) propagate through the same fiber with identical amplitudes. They experience the same nonlinearity, and thus have the same noise quadrature \(\Delta^2 \hat{X}_{x,\theta} = \Delta^2 \hat{X}_{y,\theta} = \Delta^2 \hat{X}_0\). We assume the noise to be uncorrelated since the modes are temporally and spatially separated by the fiber birefringence. With this assumption, the measured noise corresponds to the noise of the rotated quadrature, \(\Delta^2 \hat{S}_0 = \alpha^2 \Delta^2 \hat{X}_0\). Polarization squeezing is seen in a certain quadrature, rotated by the angle \(\theta_{sq}\). This leads to two conclusions: i) we can easily produce polarization squeezing using this setup and, ii) by measuring the fluctuations of the Stokes parameters we can characterize the light state, in particular its quadrature noise \(\Delta^2 \hat{X}_0\).

The experimental setup is seen in Fig. 2. We use a Cr\(^{4+}\):YAG laser emitting 130 fs FWHM pulses at 1497 nm at a repetition rate of 163 MHz. This beam is coupled into the two orthogonal polarization axes of a 13.3 m polarization maintaining fiber (3M FS-PM-7811, 6 \(\mu\)m core diameter). In this manner we generate two independent Kerr squeezed beams in a single pass through a fiber. After the fiber, the pulses’ intensities are adjusted to be identical and they are aligned to temporally overlap. The fiber’s polarization axes exhibit a strong birefringence (beat length 1.67 mm) that must be compensated. To minimize losses at the fiber output, we pre-compensate the pulses in an unbalanced Michelson-like interferometer that introduces a tunable delay between the polarizations.\(^5,12\) At the output, 0.1% of the light is used as an input signal for a control loop which maintains a constant relative phase of \(\pi/2\) between the exiting pulses, producing a circularly polarized beam (not explicitly shown).

![Fig. 2. Experimental setup for efficient polarization squeezing generation.](image)

We measure the noise of a given Stokes parameter with the half waveplate (\(\lambda/2\)) and a PBS. The PBS outputs are measured directly using detectors with Epitaxx-500 photodiodes and a low pass filter (\(\leq 40\) MHz) to avoid AC saturation due to the laser repetition rate. The measurement frequency is 17.5 MHz on a HP8595E spectrum analyzer with a resolution bandwidth of 300 kHz and a video bandwidth of 30 Hz. The difference between the two photocurrents is given by:

\[
i_- \propto \cos 4\Phi \hat{S}_1 + \sin 4\Phi \hat{S}_2 = \hat{S}_{4\Phi}. \quad (4)
\]

where \(\Phi\) is the rotation angle of the waveplate compared to the \(x\) axis. Rotating the waveplate effectively rotates the measured Stokes parameter in the \(\hat{S}_1\)-\(\hat{S}_2\) plane, allowing a complete measurement of the polarization noise. Using the fact that the amplitude fluctuations of the two individual modes \(x\) and \(y\) are at the shot noise level, the Heisenberg uncertainty limit is determined by measuring \(\Delta^2 \hat{S}_1\). This shot noise calibration was checked using a coherent beam with the same amplitude directly from the laser.

A plot of the measured noise as the \(\lambda/2\) waveplate is rotated is seen in Fig. 3. The pulse energy is 83.7 pJ (soliton energy 56±4 pJ). We find an oscillation between very large noise and squeezing, as expected from the rotation of a squeezed state. Plotted on the \(x\)-axis is the projection angle \(\theta\), i.e. the angle by which the state has been rotated in phase space, inferred from the waveplate angle \(\theta = 4\Phi\). For \(\theta = 0\), an \(\hat{S}_1\) measurement, we find a noise value equal to the shot noise. Rotation of the state by \(\theta_{sq}\)
makes the squeezing in the system observable by projecting out only the squeezed axis of the uncertainty ellipse. Further rotation brings a rapid increase in noise as the excess phase noise, composed of the anti-squeezing and classical thermal noise, becomes visible. This is similar to experiments using local oscillators, however here no stabilization is needed after production of the polarization squeezed state. This may be important for experiments with long acquisition times, i.e. state tomography.

![Fig. 3. Noise against phase-space rotation angle for the rotation of the measurement \(\lambda/2\) waveplate for a pulse energy of 83.7 pJ using 13.3 m 3M FS-PM-7811 fiber. Inset: Schematic of the projection principle for angle \(\theta\). Results are corrected for \(-86.1 \pm 0.1\) dBm electronic noise.](image)

The squeezed and anti-squeezed quadratures and the squeezing angle, \(\theta_{sq}\), of this state were investigated as a function of pulse energy (Fig. 4). The maximum observed squeezing is \(-5.1 \pm 0.3\) dB at an energy of 83.7 pJ. Squeezing saturation is seen at high power, likely due to the overwhelming excess phase noise which distorts the uncertainty ellipse. The losses of the setup were found to be 20.5%: 4% from the fiber end, 7.8% from optical elements and 10% from the photodiodes. Thus we have generated a maximum polarization squeezing of \(-8.8 \pm 0.8\) dB. This value agrees better with theoretical predictions. Investigating the squeezing angle, \(\theta\), we find that the rotation of the uncertainty region necessary to observe squeezing decreases with increasing power. This is expected as, despite an increasing anti-squeezing, the amplitude noise of a Kerr squeezed beam remains constant. Saturation is also apparent in \(\theta_{sq}\) making a clean projection of the squeezing difficult. This polarization squeezing setup could be further investigated for different fiber lengths as well as types and theoretical description of the setup could be implemented.

We see potential for further improvement of our \(-5.1 \pm 0.3\) dB squeezing produced in our novel and efficient setup, namely with better photodiodes and an all fiber setup in which losses are minimized. The development of specialty microstructured fibers with lower classical phase noise is expected to also improve our result, bringing us yet closer to the theoretically predicted maximal fiber squeezing. Polarization and quadrature entanglement can be directly produced from this resource, both important tools in many quantum communication protocols.

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