Generation of Polarization Squeezing with Periodically Poled KTP at 1064 nm

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We report the experimental demonstration of directly produced polarization squeezing at 1064 nm from a type I optical parametric amplifier (OPA) based on a periodically poled KTP crystal (PPKTP). The orthogonal polarization modes of the polarization squeezed state are both defined by the OPA cavity mode, and the birefringence induced by the PPKTP crystal is compensated for by a second, but inactive, PPKTP crystal. Stokes parameter squeezing of 3.6 dB and anti squeezing of 9.4 dB is observed.

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I. INTRODUCTION

The quantum properties of polarization states of light have recently received a great deal of attention. It is not only interesting from a fundamental point of view, but also has some practical relevance since it facilitates the execution of various quantum communication protocols. A future quantum information network will probably consist of nodes of atoms, where the quantum information is processed, linked by optical channels [1]. The transfer of quantum information from atoms to atoms and photons to atoms is made possible using the quantum properties of the different polarization states [2].

Several methods for generating polarization squeezed states have been proposed and experimentally realized. For example, making use of the nonlinearity provided by Kerr-like media, such as in nonlinear fibers and atomic media, or by combining a quadrature squeezed beam generated by an optical parametric amplifier (OPA) with a bright coherent beam on a polarizing beam splitter (PBS) [2] [10, 11, 12, 13, 14, 15, 16, 17].

In the works by Heersink et al. [12, 13], polarization squeezed light was generated by combining two orthogonally polarisation components inside a spatial mode supported by a fiber. It means that the polarization squeezed state was directly generated in the nonlinear medium. In contrast, in previous approaches where optical parametric amplification has been used, the polarization squeezing was produced by combining a coherent beam with a quadrature squeezed beam on a polarizing beam splitter. This method is limited by the losses of the beam splitter and imperfect spatial mode overlap in the beam splitter. In this paper we overcome this problem by injecting the coherent beam into the cavity along with the squeezed beam but in an orthogonal polarization mode. Since both beams are supported by the same spatial cavity mode the spatial overlap between them is perfect, and thus the polarization squeezing is optimized. Also in this paper we demonstrate for the first time squeezing at 1064 nm using periodically poled KTP. This crystal has proven to be superior for squeezed state generation due to the absence of nonlinear absorption effects. It has been used to squeeze light at 532 nm [13], 795 nm [19, 20], 860 nm [21] and 946 nm [22] but so far not at 1064 nm.

II. POLARIZATION SQUEEZING

The polarization state of light can be described by the four Stokes operators \( \hat{S}_0, \hat{S}_1, \hat{S}_2 \) and \( \hat{S}_3 \), where \( \hat{S}_0 \) represents the beam intensity whereas \( \hat{S}_1, \hat{S}_2 \) and \( \hat{S}_3 \) characterize its polarization and form a cartesian coordinate system. If the Stokes vector points in the direction of \( \hat{S}_1, \hat{S}_2 \) or \( \hat{S}_3 \) the polarized part of the beam is horizontally, linearly at 45°, or right-circularly polarized, respectively [3, 4]. It is well known that the polarization of a light beam is a property which is limited by quantum noise and that it is possible to achieve polarization states below the standard quantum noise limit (QNL). This was first suggested in the work by Cirkin et al. in 1993 [2], where the Heisenberg inequalities for the Stokes operators were derived by making use of their cyclical commutation relations:

\[
V_i V_j \geq \varepsilon_{ijk} |\langle \hat{S}_k \rangle|, \tag{1}
\]

where \( i, j, k = 1, 2, 3 \). This means that intrinsic quantum fluctuations of the different Stokes operators exist. The variances of the Stokes operators, \( V_i = \langle \hat{S}_i^2 \rangle - \langle \hat{S}_i \rangle^2 \), can be expressed in terms of the amplitude and phase quadrature operator variances, \( V_{\pm} \), where \( \pm \) refers to squeezing and anti-squeezing of the s- and p-polarized states, respectively. Assuming that the s- and p-polarized states are uncorrelated it can be shown that the variance of the different Stokes operators are given by [4]:

\[
V_0 = V_1 = \alpha_s^2 V_s^+ + \alpha_p^2 V_p^+ \\
V_2(\theta) = \cos^2(\theta) (\alpha_s^2 V_s^+ + \alpha_p^2 V_p^+) \tag{2}
+ \sin^2(\theta) (\alpha_s^2 V_s^- + \alpha_p^2 V_p^-) \\
V_3(\theta) = V_2(\theta - \pi/2),
\]

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where $\theta$ is the phase between the s-polarized and p-polarized beams and $\alpha_s, \alpha_p$ are the classical amplitudes. In our experiment we use a phase difference of $\theta = 0$.

In the case of an s-polarized bright amplitude squeezed beam and vacuum in the orthogonal polarization mode we expect the variances to be: $V_0 = V_1 < 1$ and $V_2 = V_3 = 1$, where we have normalized the QNL and amplitudes. Note that this is not polarization squeezing, but simply amplitude squeezing. The generation of polarization squeezing requires the presence of vacuum squeezing along with a bright beam. For example, considering the case of a dim s-polarized squeezed beam and a strong p-polarized coherent beam the expected variances will be: $V_0 = V_1 = 1$, $V_2 < 1$ and $V_3 > 1$ (see Eq.\,[1]), and thus the state is polarization squeezed.

The polarization states can also be visualized in a 3-dimensional diagram, the so-called Poincaré sphere. The mapping of the state onto the Poincaré sphere provides the full characterization. A recent example of such a mapping of the polarization state was demonstrated by Marquardt et al.\,[7]. The polarization plane on which the classical stokes parameter is perpendicular defines the polarization squeezing of the state in case of large coherent excitation\,[13]. Therefore, if the light is classically $S_1$ polarized, the “dark” polarization plane is spanned by the $S_2$ and $S_3$ parameters, and the squeezing and anti-squeezing of the quantum polarization is to be found in this plane. Using this simple observation, the analogy between polarization squeezing and quadrature squeezing is obvious\,[8, 9].

### III. GENERATION AND DETECTION OF POLARIZATION SQUEEZING

Our squeezing setup is depicted in Fig.\,[1] and consists of an empty cavity, an optical parametric amplifier and a detection scheme. The laser source, a cw solid-state monolithic YAG laser, Diabolo from Innolight, provides 800 mW at 532 nm and 450 mW power at 1064 nm. The 1064 nm beam from the laser is directed through an empty ring cavity, a so-called mode-cleaner (MC), which filters out the intensity and frequency noise of the laser above the bandwidth of the MC. In addition the MC defines a high quality spatial TEM$_{00}$ mode. A bandwidth of 2.7 MHz is measured and a transmission greater than 90% is obtained for the TEM$_{00}$ mode.

We used a bow-tie shaped cavity for the OPA in order to avoid possible destructive interference that may result from a double passed linear cavity. Furthermore the circulating beam encounters the passive loss in the crystal only once per round trip. The nonlinear crystal used is a 1x2x10 mm$^3$ type I periodically poled KTP (PPKTP) crystal manufactured by Raicol Inc. Our bow-tie cavity consists of two curved mirrors of 25 mm radius of curvature and two plane mirrors. Three of the mirrors are highly reflective at 1064 nm, $R > 99.9\%$, while the output coupler has a transmission of $T = 15\%$. The transmittance of the mirrors at the pump wavelength, 532 nm, is more than 95%. The crystal is placed in the smallest beam waist, which is located between the two curved mirrors. In order to maximize the conversion efficiency, corresponding to an optimization of the Boyd-Kleinmann factor\,[23], a beam waist of 20 $\mu$m is chosen. This was enabled by using a cavity length of about 145 mm and setting the distance between the two curved mirrors to be 28 mm. The OPA has a measured finesse of approximately 20, a free spectral range (FSR) of 2 GHz and a cavity bandwidth of 100 MHz. From the finesse of the cavity we deduced an overall intra-cavity loss of $L = 1.0 \pm 0.2\%$.

We use the half-wave plate in front of the OPA to inject a beam that has components of both s- and p-polarization, where the s-polarized beam is a seed for the squeezed beam, and the p-polarized beam is the coherent beam. Due to the birefringence of the nonlinear crystal the s- and p-polarization is not simultaneously resonant. A difference between the s- and p-polarization resonances is measured to 0.5 FSR at a crystal temperature of 32°C, which is the optimal phase-matching temperature. By changing the temperature of the crystal to 24°C a simultaneous resonance of the s- and p-polarization could be enabled. However, this temperature lies outside the phase-matching bandwidth of the nonlinear crystal, which was measured to be approximately 5°C. We therefore use a second, but identical, PPKTP crystal for compensating the birefringence. We tune the temperature of the second crystal so that the s- and p-polarization are simultaneously resonant. The cavity was locked to resonance using the Pound Drever Hall locking technique\,[24].

Depending on the relative phase between the pump and the seed, the seed is either amplified or de-amplified. We measure a maximum amplification of 14 and a de-amplification of 0.38. The relative phase is locked to de-amplification in order to generate an amplitude quadra-
ture squeezed beam. This beam is then directed to the polarization measurement scheme [22].

In order to perform the measurement of the Stokes operators the state propagates through a sequence of waveplates and is subsequently projected on a PBS. The intensities of the two outputs are then measured and by subtracting the resulting photocurrents any Stokes parameter can be accessed. If the waveplates are aligned so that the polarization state is unchanged \( S_1 \) is accessed. To measure \( \hat{S}_2 \) the polarization of the beam was rotated by 45° with a half-wave plate, and if, in addition to the half wave plate rotation, a quarter wave plate introduces a \( \pi/2 \) phase shift between s- and p-polarization, \( \hat{S}_3 \) is measured. The spectral densities of the resulting difference currents are measured with an electronic spectrum analyser (ESA).

The measurements were performed at a detection frequency of 14 MHz. The detectors used are designed to be resonant at 14 MHz having a 1 MHz bandwidth. The variances have all been corrected for dark-noise of the detectors, which is more than 12 ± 0.2 dB below the QNL, and thus had a negligible effect on the noise spectrum. Each trace depicted in Fig. 2 is normalised to the QNL and measured with a resolution bandwidth (RBW) of the ESA set to 300 kHz and with a video bandwidth (VBW) of 300 Hz. The calibration of the QNL is done by operating the OPA without the pump. We then adjusted the seed power to be equal to that of the squeezed beam to ensure an efficient \( \eta \) of 300 Hz. The calibration of the QNL is done by operating the OPA without the pump. We then adjusted the seed power to be equal to that of the squeezed beam when the pump is turned on.

The total detection efficiency of our experiment is given by: \( \eta_{\text{total}} = \eta_{\text{prop}} \eta_{\text{det}} \eta_{\text{OL}} \), where \( \eta_{\text{prop}} = 0.97 \pm 0.02 \) is the propagation efficiency from the cavity to the detectors, \( \eta_{\text{det}} = 0.95 \pm 0.02 \) is the quantum efficiency of the photo-detectors, \( \eta_{\text{av}} = T/(T + L) = 0.94 \) is the quantum escape efficiency and \( \eta_{\text{OL}} \) is the overlap efficiency. Since both the seed and coherent beam are injected into the cavity the efficiency is \( \eta_{\text{OL}} \approx 1 \). The total detection efficiency of our system is therefore \( \eta_{\text{total}} = 0.87 \pm 0.02 \).

We first measured the polarization state of a single bright amplitude squeezed beam without a coherent beam in the orthogonal polarization mode. This is achieved by injecting all the OPA seed light into the squeezed p-polarization mode and subsequently measuring the amplitude of output with a single detector. The variance of the measurement outcomes is displayed in Fig. 2a, and we see that amplitude squeezing of -3.6 ± 0.2 dB relative to the QNL, while the \( \hat{S}_1 \) operator is anti-squeezing +9.4 ± 0.2 dB relative to the QNL. Taking into account the detection efficiency, we infer squeezing and anti-squeezing values of -4.6 ± 0.4 dB and +10.0 ± 0.4, respectively.

IV. SUMMARY

We have demonstrated the generation of polarization squeezed light using periodically poled KTP. We generated -3.6 ± 0.2 dB squeezing in \( S_2 \) and +9.4 ± 0.2 dB anti-squeezing in \( S_3 \) using a dim amplitude squeezed beam combined with a coherent beam. To ensure an efficient spatial mode overlap between the coherent state and the squeezed state, both modes were defined in the same cavity in orthogonal polarization modes. We also produced bright amplitude squeezing and measured -3.8 ± 0.2 dB squeezing. To our knowledge this is the first demonstration of squeezing at 1064 nm using PPKTP.

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