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Generation of polarization squeezed light with an optical parametric amplifier at 795 nm

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ABSTRACT

We report the experimental demonstration of polarization squeezed beam at 795 nm by combining a quadrature amplitude squeezed beam with an in-phase bright coherent beam. The quadrature amplitude squeezed beam is generated by a degenerate optical parametric amplifier based on a PPKTP crystal. Stokes operators $\hat{S}_2$ squeezing of −3.8 dB and $\hat{S}_3$ anti-squeezing of +5.0 dB have been observed. This polarization squeezed beam resonant to rubidium D_1 line has potential applications in quantum information networks and precision measurement beyond the shot noise limit.

1. Introduction

As an important nonclassical light field, the squeezed light has been widely used in the fields of quantum teleportation [1–3], quantum dense coding [4–6], quantum storage [7–9], gravitational wave detection [10–12] and etc., since it is experimentally generated in 1985 [13]. In the field of squeezed light, in addition to quadrature squeezed light, photon number squeezed light and intensity difference squeezed light, the recently developed polarization squeezed light has also been widely concerned. The polarization squeezed light can be understood as a linear polarized coherent light, whose orthogonal vacuum channel is filled by a squeezed vacuum. In the field of quantum storage, the polarization squeezed light can directly interact with the spin wave of atomic ensemble [14]. In addition, the polarization squeezed light can also improve the sensitivity of the magnetic field measurement [15]. At present, the sensitivity of magnetometer based on atomic spin effect reaches 0.16 $fT/Hz^{1/2}$ [16], which is close to the shot noise limit. To further improve the sensitivity, two fundamental quantum noises must be considered, including atomic spin projection noise and polarization noise of the light field. The polarization squeezed light can realize the sensitivity of the magnetic field measurement beyond the shot noise limit.

In 1993, Chirkin et al. [17] first characterized the polarization state of the two-mode field by the Stokes operators and discussed the concept of polarization squeezing for continuous variable (CV). After then, many groups carried out related experimental research. For now, there are three schemes to realize the polarization squeezed light. The first scheme is based on the Kerr nonlinearity of the fiber [18–20]. Using this scheme, up to 5.1 dB of pulsed polarization squeezing at 1497 nm was observed [20]. The second scheme is based on the polarization self-rotation (PSR) effect of atomic ensemble [21–23]. Via PSR, −3 dB of CV polarization squeezing has been observed for D_1 transitions using ^{87}Rb vapor [23]. The experimental system for this scheme is quite simple, but the squeezing degree strongly depends on the frequency detuning relative to the atomic transition. This leads to a bad tunability. The last scheme is based on the second-order nonlinear effect of nonlinear crystal [15,24–27]. Compared with results base on PSR effect of atomic ensemble, the generated polarization squeezed light with this scheme has the advantage of good tunability and higher squeezing degree. In 2016, Wu et al. [27] generated −4.0 dB of polarization squeezed light at 795 nm by combining two quadrature amplitude squeezed optical beams on a polarization beam splitter (PBS) cube. This is the maximum polarization squeezing observed at this wavelength. However, this scheme needs two optical parametric amplifiers (OPA), which increases the complexity and cost of the system.

In this paper, we generated the CV polarization squeezed light resonant with the Rb D_1 line by combining the amplitude squeezed beam with an orthogonally polarized bright coherent beam. A 3.8 dB polarization squeezing with Stokes operator $\hat{S}_2$ is achieved. Although the squeezing degree is a little bit lower compared with Wu et al.'s work [27], the experimental system is greatly simplified. This polarization squeezed light at Rb D_1 line has huge potential in precise measurement of magnetic field.

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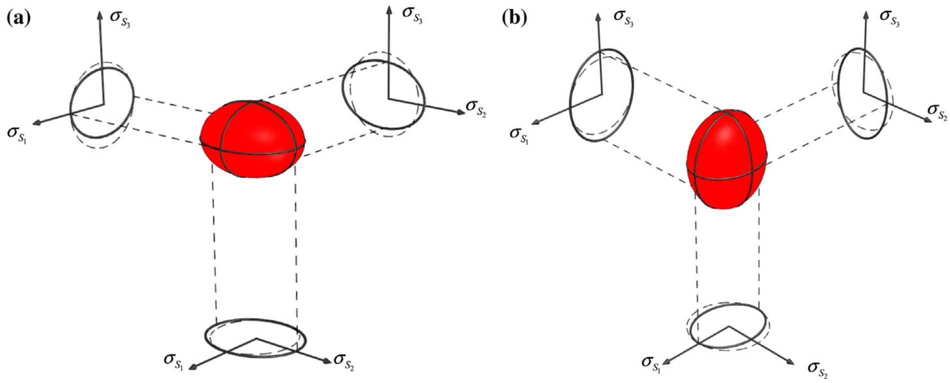

Fig. 1. Representations of quantum polarization states for the generated polarization squeezed beam for (a) $\hat{S}_2$ is anti-squeezed and $\hat{S}_3$ is squeezed; (b) $\hat{S}_2$ is squeezed and $\hat{S}_3$ is anti-squeezed. For both (a) and (b), $\hat{S}_0$ and $\hat{S}_1$ is QNL. The red ellipsoid is the squeezed noise ball, the three ellipses are the projections at each plane. The dashed circle represents the noise of coherent state and the solid one shows the squeezing results.

2. Polarization squeezing

The polarization state of a light beam can be described by four Stokes operators ($\hat{S}_0$, $\hat{S}_1$, $\hat{S}_2$, and $\hat{S}_3$) on a Poincaré sphere [17]. $\hat{S}_0$ represents the intensity of the beam, the other three Stokes operators characterize the polarization and form a Cartesian axis system. $\hat{S}_1$, $\hat{S}_2$ and $\hat{S}_3$ stand for horizontally, linearly at 45°, and right-circularly polarized, respectively. Following the references [28] and [29], the Stokes operators can be expanded in term of the annihilation $\hat{a}$ and creation $\hat{a}^\dagger$ operators of the horizontally (H) and vertically (V) polarized modes. The results are as follows:

$$\hat{S}_0 = \hat{a}_H^\dagger \hat{a}_H + \hat{a}_V^\dagger \hat{a}_V, \qquad \hat{S}_1 = \hat{a}_H^\dagger \hat{a}_H - \hat{a}_V^\dagger \hat{a}_V$$

$$\hat{S}_2 = \hat{a}_H^\dagger \hat{a}_V e^{i\theta} + \hat{a}_V^\dagger \hat{a}_H e^{-i\theta}, \qquad \hat{S}_3 = i\hat{a}_V^\dagger \hat{a}_H e^{-i\theta} - i\hat{a}_H^\dagger \hat{a}_V e^{i\theta} \tag{1}$$

Where θ is the relative phase between H and V polarized modes. If the quantum noise of these orthogonally polarized modes is uncorrelated, the variances of Stokes operators are given by

$$V_0 = V_1 = \left\langle \alpha_H^2 (\delta \hat{X}_H^+)^2 \right\rangle + \left\langle \alpha_V^2 (\delta \hat{X}_V^+)^2 \right\rangle$$

$$V_2(\theta = 0) = V_3(\theta = \frac{\pi}{2}) = \alpha_V^2 \left\langle (\delta \hat{X}_H^+)^2 \right\rangle + \alpha_H^2 \left\langle (\delta \hat{X}_V^+)^2 \right\rangle$$

$$V_3(\theta = 0) = V_2(\theta = \frac{\pi}{2}) = \alpha_V^2 \left\langle (\delta \hat{X}_H^-)^2 \right\rangle + \alpha_H^2 \left\langle (\delta \hat{X}_V^-)^2 \right\rangle \tag{2}$$

Here, $\delta \hat{X}_{H,V}^+$ and $\delta \hat{X}_{H,V}^-$ are the quadrature amplitude and phase noise operators of two orthogonally polarized modes, respectively. According to Eq. (2), there are two methods to realize the polarization squeezed beam. One is to combine two quadrature squeezed beam on a PBS. The other is to combine the quadrature squeezed beam with a coherent beam. Actually, Wu et al. discussed simultaneous squeezing of stokes operators S_1, S_2 and S_3 [27] with the first method. However, all it costs is the utilization of two OPA cavities. It is not an easy work to simultaneously control two OPAs. Compared with their setup, we only use one OPA cavity to realize the polarization squeezed beam. In our experiment, we combine an s-polarized dim amplitude squeezed beam with a p-polarized strong coherent beam on a PBS cube. In this case, the phase difference between two beams is locked to 0. We assume the intensity of amplitude squeezed beam is much weaker than the coherent beam, and then α_V^2 is negligible. According to Eq. (2), we expect the variances of the stokes operators to be: $V_0 = V_1 = 1$, $V_2 < 1$ and $V_3 > 1$, where the quantum noise limit (QNL) is normalized to be 1. This means that the stokes operator $\hat{S}_3$ is squeezed and $\hat{S}_2$ is anti-squeezed, whereas $\hat{S}_0$ and $\hat{S}_1$ are QNL. If the phase difference is locked to $\pi/2$, the variances of these operators turn into: $V_0 = V_1 = 1$, $V_2 > 1$ and $V_3 < 1$.

Although the polarization squeezed beam can be produced by combining two quadrature squeezed beam or combining a quadrature squeezed beam with a coherent beam, it is quite different from quadrature squeezed beam. For instance, in quadrature squeezing, the conjugate variables never commute, whereas in polarization squeezing, there may be situation when conjugate Stokes operators may commute leading to simultaneous squeezing in all stokes operators, inferred from Eq. (2). Besides, for describing quadrature squeezed state, 2D phase-space is enough. For polarization squeezed states, the concept of Poincaré sphere is inapplicable and a 3D Stokes space is required. Fig. 1 shows the representations of quantum polarization states for the generated polarization squeezed beam for the two circumstances. Fig. 1(a) represents the circumstance for the phase difference of $\pi/2$, and Fig. 1(b) is the result for the phase difference of 0.

3. Generation and detection of polarization squeezing

The schematic of experimental setup is shown in Fig. 2. The fundamental source is a continuous-wave Ti:Sapphire laser (M squared Ltd), whose spectrum covers 700–1000 nm. In this experiment, the wavelength of the laser is adjusted to 794.975 nm. At this wavelength, we can tune the laser continuously and observe the saturation absorption spectroscopy (SAS) of D_1 line of ^{85}Rb and ^{87}Rb atoms. The laser can be tuned continuously above 8.5 GHz. Here, to simplify the experimental setup, we just run the laser to be resonant with atomic transitions. In the future experiment, we hope that the generated squeezed beam can interact with atomic ensemble of Rb atoms, then we need to lock the laser to transitions of D_1 line of Rb atoms with feedback control loops.

An isolator and phase-type electro-optic modulator (EOM) are used at the output of the laser. Although the follow-up enhancement cavities are bow-tie configuration, the feedback is serious and an isolator is required. The EOM is utilized to realize the Pound Drever–Hall locking of all the enhancement cavities. Then the main laser is divided and injected into three enhancement cavities, including a second-harmonic generation (SHG) cavity, an optical parametric amplifier (OPA) cavity and a mode-cleaner (MC) cavity. Two PPKTP crystals (Raicol Crystals Ltd.) with a poling period of 3.15 μm are positioned at the center of the concave mirrors for SHG and OPA cavities. The PPKTP crystals are placed in copper-made ovens, whose temperature was actively stabilized to about 53 °C for optimization. PPKTP is chosen due to a high nonlinearity together with a relatively good transmission at 397.5 nm. These three cavities are all designed in a uniform bow-tie configuration, which have lengths of about 600 mm and a distance of around 120 mm between the two concave mirrors. This gives a beam waist of ∼40 μm at the central of the crystals. The transmissivity of the input coupler of SHG cavity is 10% at 795 nm. For OPA cavity, the transmissivity of the output coupler is 11.5%. The detailed parameters of these three cavities can be seen in our previous paper [29]. The MC is used to filter the spatial mode of the local beam, ensuring a high interference visibility in the homodyne detection.