Generation of entangled TEM_{01} modes with periodically poled $KTiOPO_4$ crystal*

Rong-Guo Yang(杨荣国)[1,2,†], Jing-jing Wang(王晶静)[2], Jing Zhang(张静)[1,2], and Heng-Xin Sun(孙恒信)[1,3]

[1] State Key Laboratory of Quantum Optics and Quantum Optics Devices, Shanxi University, Taiyuan 030006, China
[2] College of Physics and Electronics Engineering, Shanxi University, Taiyuan 030006, China
[3] Institute of Opto-Electronics, Shanxi University, Taiyuan 030006, China

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Spatial quantum optics based on the high-order transverse mode is important for the super-resolution measurement and quantum image beyond the shot noise level. Quantum entanglement of the transverse plane Hermite–Gauss TEM_{01} mode has been demonstrated experimentally in this paper. Two squeezed TEM_{01} modes, which are generated by a pair of degenerate optical parametric amplifiers (DOPA) with the nonlinear crystals of periodically poled $KTiOPO_4$, have been combined to produce TEM_{01} mode entanglement using a beam splitter. The 1.5 dB for the sum of amplitude and 1.2 dB for the difference of phase below shot-noise level is achieved with the measurement system of a Bell state detection.

Keywords: Hermite–Gauss mode, entangled state, degenerate optical parametric amplifier

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1. Introduction

The non-classical states of the squeezed and entangled states are key quantum resources, which have been usually applied to many quantum information protocols, such as sensing and gravitational-wave detection,[1,2] quantum key distribution,[3] quantum communication,[4] quantum secret sharing,[5] noiseless amplification,[6] quantum dense coding,[7] quantum logic operation,[8] and quantum teleportation.[9] In real applications, these valuable quantum resources present the trend, such as low noise, small wastage, high intelligence bandwidth, the ability to encode information into multiple degrees of freedom and high-order transverse mode.[10,11] Squeezing of high-order mode, spatial squeezing, and entanglement have been obtained. The squeezing in the high-order transverse mode has been experimentally obtained by an optical parametric amplifier process in 2007.[12] In 2011, we demonstrated experimentally the transverse plane TEM_{01} Hermite–Gauss quantum squeezing.[13] In 2013, a group from the Australia National University experimentally demonstrated biological measurement.[14] In addition, spatial transverse quantum correlation can be applied to sensitive measurement of minuteness displacement and tilt beyond the standard quantum limit,[15–18] noiseless images amplification.[19,20] In recent years, the techniques of reducing the quantum noise using spatial squeezing and entanglement based on the non-classical states of high-order transverse mode have been used for optical displacement measurements for very high precision. Treps *et al.* devised the method to obtain a factor of 1.5 precision improvement compared with the classical limit with a spatial squeezed light of 3.3 dB squeezing.[21] Our group presented and demonstrated experimentally a scheme for optical displacement measurements based on high-order Hermite–Gauss modes and balanced homodyne detection in 2014.[22] Besides, high-order modes can also provide advantages because of the complexity of quantum information protocols,[23] such as encoding information into parallel multimode, parallel transfer of quantum information and quantum key distribution in multi-channel in quantum information processing. A channel of large capacity and high rate is of importance for quantum information for high-order modes.

In this paper, we report the quadrature entanglement of TEM_{01} mode, which is generated by combining two squeezed TEM_{01} lights, which are produced in a pair of degenerate optical parametric amplifiers (DOPA) with two periodically poled KTP (PPKTP) crystals, with a beamsplitter. The value of 1.5 dB for the sum of amplitude and 1.2 dB for the difference of phase below shot noise level are measured using a Bell state detection system.

2. Setup and results

The layout of experimental setup is presented in Fig. 1. A homemade cw frequency-doubled and frequency-stabilized Nd:YVO_4-$KTiOPO_4$ laser serves for the light source, the 1-W 532-nm green laser and 80-mW 1064-nm infrared light can be exported and divided into two parts and injected into a pair of DOPAs as pump and seed beams, respectively.

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†Corresponding author. E-mail: yrg@sxu.edu.cn

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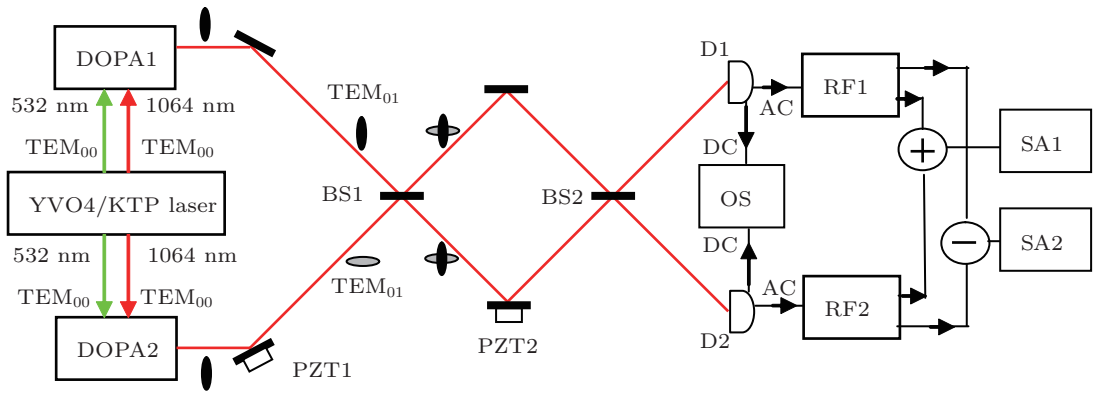


Fig. 1. (color online) The layout of experimental setup. BS1, BS2: beamsplitters, M: mirror, PZT1, PZT2: piezoelectric devices, D1, D2: detectors, SA1, SA2: spectrum analyzers, RF1, RF2: radio frequency signals, OS: oscilloscope.

A pair of DOPAs are placed symmetrically, which have the same technical parameters. The geometry lengths of both DOPAs are about 61.5 mm. Each PPKTP crystal is placed in a DOPA respectively, and the crystal dimension is 1 mm×2 mm×10 mm. The anti-reflecting-film is especially coated on both the side surfaces of the crystal to reduce the intracavity losses as much as possible. Every cavity has a standing wave configuration consisting of two concave mirrors, of which the radii of curvature are 30 mm. One of the two mirrors is an input coupler, and its transmission is 15% for pump beam, high-reflected (HR) for seed light. The other mirror is an output coupler with 15% transmission for the squeezed states, HR for pump beam, which is mounted on a piezo-electric transducer (PZT) for locking the cavity length of DOPA actively on resonance with the injected seed light at 1064 nm by Pound–Drever–Hall method. Each DOPA is seeded by a tilted TEM_{00} mode of 1064 nm and pumped by also a tilted TEM_{00} mode of 532 nm, where the weak 1064-nm field is amplified by strong 532-nm field in a parametric process. The temperature of PPKTP crystals in cavities is controlled at 32.7 °C and 33.1 °C respectively to maximize the classical gains. The classical gains of a pair of DOPAs can reach 15 and 12 for TEM_{01} seed fields, respectively. In order to obtain two bright squeezed beams with almost identical intensities, the two-seed power injected to two cavities needs to be adjusted exactly. In experiment, the relative phases between pump and seed beam for each system are locked at parametric deamplification to obtain two amplitude quadrature squeezing modes. A pair of squeezed modes of about 60 μW from two DOPAs are interfered to generate quadrature entanglement of TEM_{01} with a constant phase difference of $\pi/2$ on a 50:50 beamsplitter.

One of the EPR beams is phase shifted $\pi/2$ and then combined with another beam of the same intensity on a 50:50 beam splitter. The signals of amplitude and phase quadrature are obtained from a Bell state direct detection implemented with two photo detectors and two RF splitters. Each photocurrent directly detected from two bright beams is divided into two parts through the RF splitter. Thus we obtain the noise power for the sum of quadrature amplitude and the difference of quadrature phase simultaneously using the alternating current signals of detectors 1 and 2 with two frequency spectral analyzers. We report the value of 1.5 dB for the sum of quadrature amplitude and 1.2 dB for the difference of quadrature phase below shot noise level which are measured using a Bell state detection system. The shot noise levels are obtained with the coherent beams which have the same power as EPR beams depending on the direct current signals of detectors 1 and 2.

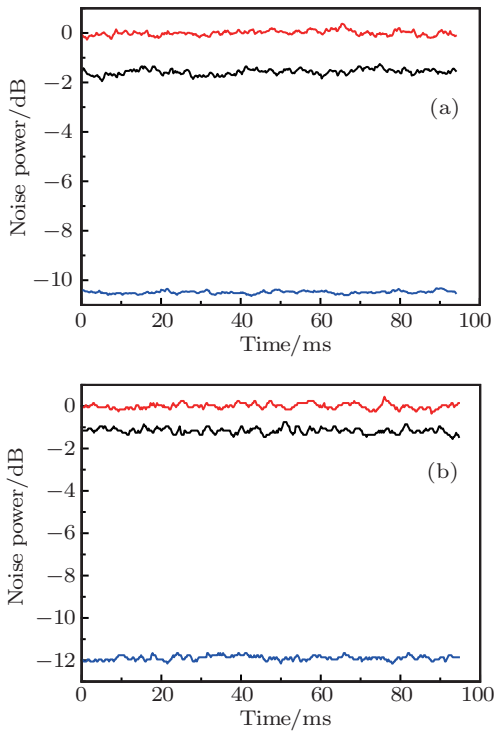


Fig. 2. (color online) Experimentally measured correlation noise power spectra for the TEM_{01} entanglement. Panels (a) and (b) correspond to the sum of quadrature amplitude and the difference of quadrature phase. The red, black, and blue curves are corresponding to the shot noise level, the sum of quadrature amplitude/the difference of quadrature phase noise, and the electronics noise, respectively. All traces are obtained under the conditions of the resolution bandwidth of 300 kHz and the video bandwidth of 300 Hz.

Realizing such a quantum noise limited amplifier in the low gain regime for TEM_{01} is a big challenge, and so does the obtaining of the exact same power of two squeezed states. The power of two squeezed modes are the same by fine controlling the power of two seed fields to compensate the different classical parametric gains (amplification factor) for two DOPAs. In our experiment, parametric gains are 15 and 12 for two TEM_{01} modes. The interference visibility on homodyne system η is 95% for TEM_{01} mode. Two cavities are locked on the TEM_{01} mode by Pound–Drever–Hall method. The two cavities have the same fineness of about 35, and they can be locked stably.

Figure 2 shows the observed noise levels for the sum of quadrature amplitude and the difference of quadrature phase of the entangled TEM_{01} mode. The analyzing frequency is 3.5 MHz with zero span. The red, black, and blue curves are corresponding to the shot noise level, the sum of quadrature amplitude/ the difference of quadrature phase noise, and the electronics noise, respectively. The observed correlation noises are 1.5±0.2 dB and 1.2±0.2 dB below the shot noise level, respectively.

3. Discussion and summary

Neither of the squeezed TEM_{01} modes are the minimum uncertainty states because of extra noises. Here, $\Delta^2 X_1 = 0.60$, $\Delta^2 Y_1 = 3.01$ and $\Delta^2 X_2 = 0.63$, $\Delta^2 Y_2 = 2.95$ for squeezed TEM_{01} modes of two DOPAs, respectively. The largest squeezing can be obtained when the power of the pump field reaches the optical parametric oscillation (OPO) threshold. The threshold power of OPO for TEM_{01} mode is higher in experiment than what we can provide, and especially for the two pump fields for two DOPAs.

The entanglement can be quantified according to the inseparability criterion[19] $V_{\text{inseparability}} = \Delta^2 X_{1+2} + \Delta^2 Y_{1-2} < 2$, the variances of $\Delta^2 X_{1+2}$ and $\Delta^2 Y_{1-2}$ correspond to the sum of quadrature amplitude and the difference of quadrature phase. Here, the inseparability coefficient $V_{\text{inseparability}}$ is 1.46. In a word, quantum entanglement indeed exists between two TEM_{01} modes. It can be used to realize spatial entanglement state and has potential applications in precision metrology, atomic force microscopy, and optical imaging in the future.

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