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

Yang Rong-Guo(杨荣国),   Sun Heng-Xin(孙恒信),

Zhang Jun-Xiang(张俊香), and Gao Jiang-Rui(郜江瑞)[†]

State Key Laboratory of Quantum Optics and Quantum Optics Devices, Institute of Opto-Electronics,

Shanxi University, Taiyuan 030006, China

Spatial quantum optics and quantum information based on the high order transverse mode are of importance for the super-resolution measurement beyond the quantum noise level. We demonstrated experimentally the transverse plane TEM_{01} Hermite–Gauss quantum squeezing. The squeezed TEM_{01} mode is generated in a degenerate optical parametric amplifier with the nonlinear crystal of periodically poled $KTiOPO_4$. The level of 2.2-dB squeezing is measured using a spatial balance homodyne detection system.

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

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Entanglement state is a key quantum resource and has been applied to many important protocols in quantum information processing, such as sensing and gravitational-wave detection,[1,2] quantum key distribution,[3] quantum communication and quantum teleportation,[4,5] quantum secret sharing,[6] noiseless amplification,[7] quantum dense coding,[8] quantum logic operation.[9] Squeezed entanglement state, a key ingredient in both quantum optics and quantum information with continuous variables,[9] is consist of two quadrature squeezed states in general. It is also an important resource for quantum measurement,[10] metrology,[11] etc. Recently, Akira Furusawa group and Hannover university have produced −9-dB and −10-dB quadrature squeezed states.[12,13] The strong squeezing level state is important to achieve an excellent result. However, all the above schemes are based on the traditional TEM_{00} mode. At the same time, parallel research field into continuous variable (CV) spatial transverse quantum correlation has been investigated,[14] and concentrated on the quantum image and spatial information transmission,[15,16] which is called the spatial quantum optics field for high order transverse modes. Some proposals for more advanced applications in this field are also given, such as super-resolution measurement[17] and quan-tum holography.[18] Multiple spatial modes and high order modes can also provide advantages in regard to the complexity of quantum information protocols in continuous and discrete systems,[19] such as parallel transfer of quantum information, encoding information into parallel multimode and quantum key distribution in multi-channel in quantum information processing. The channel of large capacity and high rate is of importance for quantum information.[20,21] In addition, spatial transverse quantum correlation can be applied to the sensitive measurement of minuteness displacement and tilt beyond the standard quantum limit,[22−25] noiseless images amplification.[26,27] The key component of this field is the squeezed high order transverse mode. Lassen *et al.*[28] experimentally demonstrated squeezing in the high order transverse mode by fine-tuning the phase matching condition of the nonlinear material and the cavity resonance condition of an optical parametric amplifier in 2007. It is also an important problem to generate TEM_{01} and more high order mode squeezing state effectively and stably.

In this paper we report the quardrature squeezing of TEM_{01} mode generated in a degenerate optical parametric amplifier (DOPA) with periodically poled KTP (PPKTP). The 2.2-dB squeezed TEM_{01} mode is

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

obtained and measured using balance homodyne detection with a local beam provided by another symmetry cavity to the DOPA. The 2.8-dB squeezed TEM_{00} mode is also obtained in the same device.

As we know, the positive frequency part of a general field $E^+(\boldsymbol{r}, z)$ can be decomposed in a set of modes using the definition of the field envelope:

$$E^+(\boldsymbol{r}, z) = \mathrm{i}\sqrt{\frac{\hbar\omega_0}{2\varepsilon_0 cT}} \sum_n \hat{a}_n u_n(\boldsymbol{r}, z). \qquad (1)$$

Here T is the detect time, ω_0 is the field frequency, c is the speed of light. $\hat{a}_n$, the annihilation operators of spatial mode u_n at position $(\boldsymbol{r}, z)$, can be separated into the mean value and quantum fluctuations,

$$\hat{a}_n = \alpha_n + \delta\hat{a}_n, \qquad (2)$$

where $\langle \hat{a}_n \rangle = \alpha_n$ is the mean value of the annihilation operator $\hat{a}_n$ and $\delta\hat{a}_n$ is the corresponding quantum fluctuation operator. The quantum amplitude and phase quadratures of mode u_n are shown as

$$\hat{X}_n = \hat{a}_n^\dagger + \hat{a}_n, \quad \hat{Y}_n = \mathrm{i}(\hat{a}_n^\dagger - \hat{a}_n). \qquad (3)$$

Thus, if any one of the quantum noises termed with $\langle \Delta^2 \hat{X}_n \rangle$ or $\langle \Delta^2 \hat{Y}_n \rangle$ are below the corresponding shot noise level, the mode u_n is squeezed.

There are a group of eigen-modes for any one cavity. The $\{u_n\}$ is a set of orthogonal and complete base vectors, such as Hermite–Gauss base vectors. The mode u_n, one of $\{u_n\}$, shows transverse plane behaves of the n-th order spatial mode. Every eigen-mode has a different oscillating frequency or transverse distribution. In general, when a beam is misaligned relative to an optical cavity, the transmission of transverse modes as a function of the cavity length is composed of several peaks. Each one of them corresponds to the resonance of a particular transverse mode inside the cavity. Locking the cavity length at different position allows the generation of the corresponding mode.[29] In our experiment, we can obtain TEM_{01} mode, one of the Hermite–Gauss base vectors, by locking the cavity resonantly with this mode. The cavity works here as a mode filter. We only study the TEM_{01} mode squeezing in the DOPA.

A TEM_{01} mode amplitude is shown in Fig. 1 with the axes in waist units. The amplitude is opposite y direction in transverse plan (x–y plan). Figure 1(b) corresponds to the three-dimensional intensity representation which can be observed experimentally.
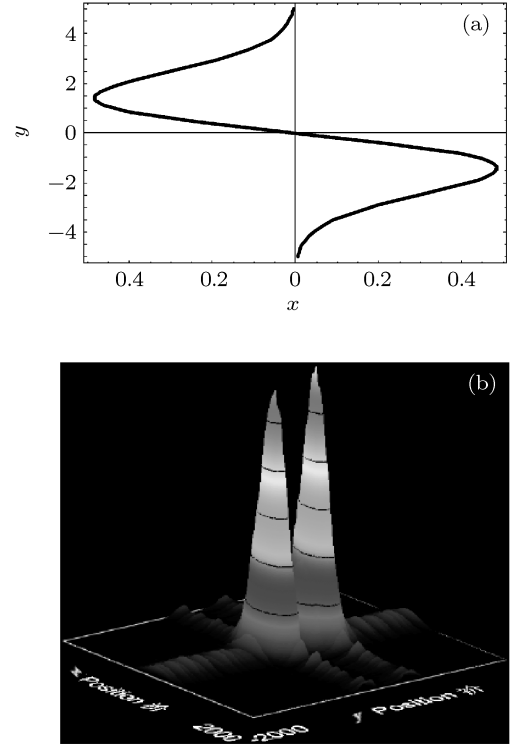
Fig. 1. Theory and experiment figures for TEM_{01} mode: (a) one-dimensional representation in the transverse plane, (b) three-dimensional representation.

The layout of experimental set-up is shown as Fig. 2. A homemade cw frequency-doubled and frequency-stabilized $Nd:YVO_4$-$KTiOPO_4$ laser serves as the light source, which can provide 1-W 532-nm green laser and 80-mW 1064-nm infrared light. TEM_{01} modes are obtained from the cavities of mode converter and a DOPA respectively.

A bright amplitude quadrature squeezed TEM_{01} mode is generated from a subthreshold DOPA. The cavity of the DOPA has a standing wave configuration consisting of two concave mirrors (radius of curvature: 30 mm). One of the two mirrors is an input coupler and its transmission is anti-reflected (AR) for pump beam, high-reflected (HR) for seed light. The other mirror is an output coupler with 15% transmission for seed light, HR for pump beam. The other cavity is used as a mode converter. Transmission of input and output coupler is respectively 6% and 15%, then we obtain about 1.7-mW local beam of TEM_{01} mode. The geometry lengths of the two cavities are 61.5 mm. Two PPKTP crystals are placed in the two cavities respectively and the crystal dimension is 1 mm×2 mm×10 mm. The PPKTP crystals are especially anti-reflecting-coated to reduce the intracavity losses as much as possible. Mode converter is injected by a specially tilted TEM_{00} mode of 1064 nm

to generate a TEM_{01} transverse mode as local beam. The DOPA is also seeded by a tilted TEM_{00} mode of 1064 nm and pumped by also a tilted TEM_{00} mode of 532 nm to produce TEM_{01} transverse mode squeezing output, where the weak 1064-nm field is amplified by strong 532-nm field in parametric process. The 1064-nm and 532-nm fields are commonly named as seed and pump light. The quantum noise of the squeezed beam can be analysed using a spatial homodyne detection system. Temperature of PPKTP crystal in DOPA is controlled at 32.7 °C in which we maximize the classical gain. Squeezed light from the DOPA is measured by a balanced homodyne detector. The relative phase between pump and seed beam is locked to deamplification and therefore to obtain amplitude squeezing. The relative phase between local beam and squeezed beam on the balanced homodyne detect system can also be locked.

In addition, it is more difficult to obtain high classical parametric gain (amplification factor) for TEM_{01} than for TEM_{00} mode because of the sensitive phase matching and cavity coupling efficiency of TEM_{01} mode. In our experiment, parametric gain is $G = 5.5$ for TEM_{01}, TEM_{00} mode corresponding to $G = 52$. The interference visibility on homodyne system is $\eta = 95\%$ for TEM_{01} mode. It is hard to gain good visibility because it embodies not only the matching of waists size and position between two beams but also the accord of two beams transverse direction. Two cavities are locked on the TEM_{01} mode by Pound–Drever–Hall method.[30] The cavities fineness is about 35 and it can be locked stably using the Pound–Drever–Hall method. The closed-loop control

system can be seen in Fig. 2.

Figure 3(a) shows the observed noise levels for the squeezed TEM_{01} HG mode with the pump powers of 410 mW. The analysing frequency is 3.5 MHz with zero span. The curve a is the shot noise level, the curve b is the noise level with the local phase locked at the squeezed quadrature, the curve c is the noise level with the local phase locked at the anti-squeezed quadrature and the curve d is a noise level with the local phase scanned. The observed TEM_{01} mode squeezing level is (2.2 ± 0.2) dB and the antisqueezing level is (4.8 ± 0.2) dB.

Using the same experiment devices, we also obtain the TEM_{00} mode squeezing. Figure 3(b) shows the observed noise levels for the squeezed TEM_{00} mode. The observed squeezing level is (2.8 ± 0.2) dB and the antisqueezing level is (7.9 ± 0.2) dB. The pump power corresponds to 160 mW.

Both the two squeezed modes are not the minimum uncertainty states, there are extra noises here. The amplitude and phase quadrature variances ($\Delta^2 X$, $\Delta^2 Y$) of the detected field can be determined from Fig. 3. We find $\Delta^2 X = 0.52$ and $\Delta^2 Y = 6.16$ for squeezed TEM_{00} mode, $\Delta^2 X = 0.60$ and $\Delta^2 Y = 3.01$ for squeezed TEM_{01} mode, respectively. Generally, the best squeezing should be obtained when OPO operates near threshold. The threshold of OPO for TEM_{01} mode is 4 times for TEM_{00} mode in experiment, so the relative pump intensity of TEM_{01} mode is weak in our experiment. In fact, the TEM_{01} mode OPO operating is far from the threshold compared with corresponding TEM_{00} mode here.
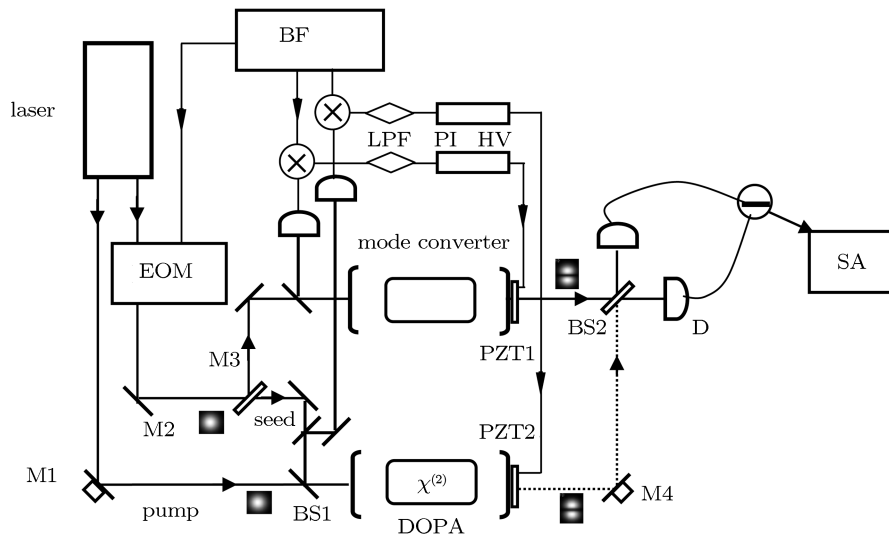
Fig. 2. Layout of experimental set-up for TEM_{01} transverse modes squeezing generation. BS: beam splitter, M: mirror, PZT: piezoelectric device, D: detector, SA: spectrum analyser, EOM: electric optic modulator, RF: RF-radio frequency signal, LPF: low pass filter, PI: proportional integral control, HV: high voltage.
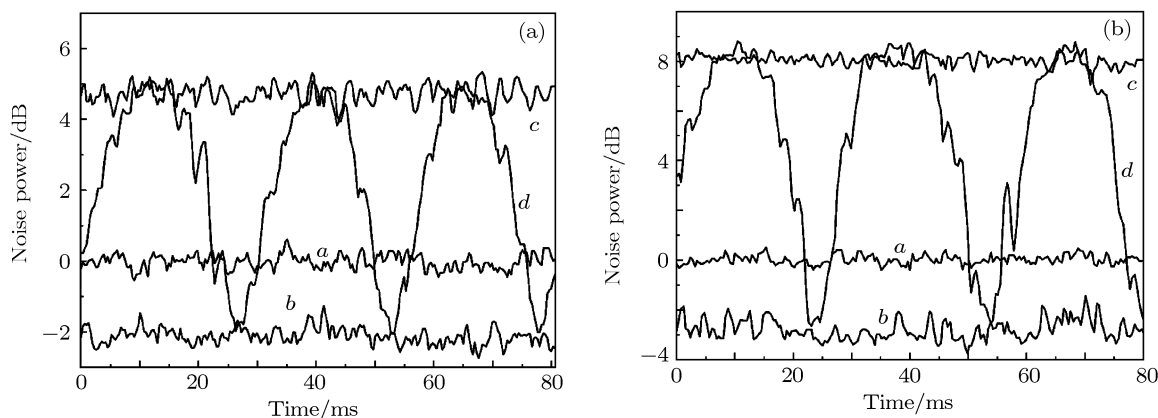
Fig. 3. Experimentally measured squeezed light noise power for the TEM$_{01}$ mode (a) and the TEM$_{00}$ mode (b). Curve a to curve d are respectively the shot noise level, squeezed quadrature noise, antisqueezed quadrature noise and a noise level when the local phase is scanned. All traces are obtained at the conditions of the resolution bandwidth of 300 kHz and the video bandwidth of 300 Hz.

In conclusion, the 2.2-dB squeezed TEM$_{01}$ and the 2.8-dB squeezed TEM$_{00}$ modes are obtained in the degenerate optical parametric amplifier with the nonlinear medium periodically poled KTP crystal in the process of parametric down conversion. The squeezed TEM$_{01}$ and the TEM$_{00}$ modes are generated and detected with the corresponding balance homodyne detection system. It can be used to realize the high order mode entanglement and spatial entanglement state in future.

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