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Experimental Generation of Multimode Squeezing in an Optical Parametric Amplifier *

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We experimentally demonstrate that HG_{01} (Hermit–Gauss) and HG_{10} squeezed states can be generated simultaneously in an optical parametric amplifier. The HG_{01} mode is a bright squeezed state and the HG_{10} mode is a vacuum squeezed state. The squeezing of the HG_{01} mode is −2.8 dB, and the squeezing of the HG_{10} mode is −1.6 dB. We also demonstrate that the output field is also continuous-variable entanglement with orbital angular momentum.

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Squeezed and entangled optical fields are essential resources in continuous-variable (CV) quantum optics and quantum information.[1] To date, the vast majority of continuous-variable research has focused on fields which exhibit nonclassical features of Gaussian modes. Spatial forms of entanglement have well been studied in the discrete variable (DV) regime,[2−4] and a number of papers have been published on squeezing and entanglement of spatial multimode states in a continuous-variable field, which have previously been generated in atomic vapor,[5] in an optical parametric oscillator,[6,7] and in linear interference between different single modes,[8−10] which is effectively generated by a degenerate optical parametric oscillator (DOPO). A type of squeezing and entanglement can be applied in quantum imaging and quantum metrology.[11] Recently, Lassen *et al.*[12] experimentally demonstrated generation of entanglement in the Stokes parameter of optical orbital angular momentum (OAM) modes using a type-I OPO. The same result was also independently demonstrated theoretically by Carlos *et al.*[13]

In this Letter, we demonstrate experimentally an HG_{01} and an HG_{10} squeezed state simultaneously in one type-Ⅱ optical parametric amplifier (OPA). We compensate the astigmatic effect of nonlinear crystal and make both HG_{10} and HG_{01} modes resonant simultaneously in the cavity. Both −2.8 dB bright squeezing of the HG_{01} mode state and −1.6 dB vacuum squeezing of the HG_{10} mode are obtained. We also demonstrate that the output field is continuous-variable orbital angular momentum entanglement. It can be widely applied in the field of quantum information and connected with atoms for storage of continue-variable information.[14,15]

In general, the spatial modes of a laser include two types: Hermit–Gauss (HG) modes and Laguerre–Gauss (LG) modes. LG modes are denoted as $\mathrm{LG}_p^{\pm l}$, where l and p are azimuthal and radial mode indices, and the LG_p^l and LG_p^{-l} have left-handed and right handed corkscrew-like phase fronts, respectively. HG modes are denoted as HG_{mn}, where m and n are horizontal and vertical mode indices. The HG and LG modes can be transformed into each other. For example, as shown in Fig. 1, the transformation relationship[13] between the first-order LG modes (LG_0^1, LG_0^{-1}) and the first-order HG modes ($\mathrm{HG}_{01}, HG_{10}$) is

$$\hat{a}_{\mathrm{HG01}} = \frac{1}{\sqrt{2}}(\hat{a}_{\mathrm{LG}_0^1} + \hat{a}_{\mathrm{LG}_0^{-1}}),$$
$$i\hat{a}_{\mathrm{HG10}} = \frac{1}{\sqrt{2}}(\hat{a}_{\mathrm{LG}_0^1} - \hat{a}_{\mathrm{LG}_0^{-1}}). \quad (1)$$

For the OPA process with the first-order spatial modes,[12,13] from a quantum mechanical point of view, once a pump photon with the Gaussian mode is annihilated (created) in the process, due to conservation of energy and orbital angular momentum, a pair of down-converted photons can be created (annihilated): one photon is emitted in the LG_0^1 mode and the other photon is emitted in the LG_0^{-1} mode. Then, the OPA can produce co-propagating LG modes entanglement. Due to the transformation relationship between LG and HG modes, the LG_0^1 and LG_0^{-1} modes overlap in space and appear in the form of HG modes, which are squeezed states.

The experimental setup is shown in Fig. 2. The two cavities (MC1, MC3) are mode-cleaners and used to suppress infrared and green light noise,[16] respectively, while the third one (MC2) acts as a mode converter to transform an HG_{00} mode into an HG_{01} mode. The 1080 nm HG_{01} beam is injected into the OPO cavity as the seed. The green light, the OPA pump, is the Gaussian mode beam. The OPA cavity is composed of

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two curved mirrors with 30 mm curvature radii. The input coupler (M1) is highly reflective at both 540 nm and 1080 nm, while the output coupler (M2) is antireflective at 540 nm and has transmittance of T=6.38% at 1080 nm.

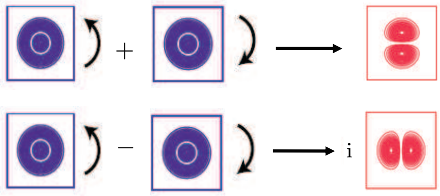

Fig. 1. The relationship between HG modes and LG modes. These modes are LG_0^1,$LG_0^{-1}$and $HG_{01}(HG_{10})$ from left to right.

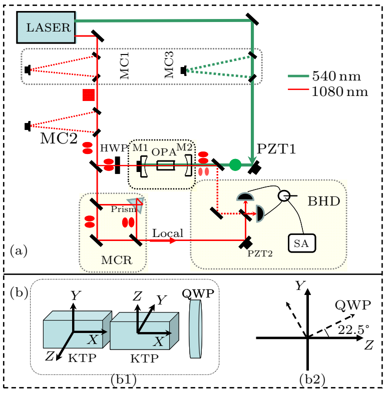

Fig. 2. (Color online) Experimental setup: (a) generation and measurement of HG-mode squeezed states with a mode cleaner (MC), a half-wave plate (HWP), a piezoelectric element for controlling phases (PZT), a mode converter for generating local light of the HG_{10} mode (MCR), a spectrum analyzer (SA), balance homodyne detectors (BHD). (b) Placement of KTP crystals in the OPA. X, Y and Z are the axes of the KTP crystal; QWP: quarter-wave plate. There is an angle of 22.5° between the crystal axes ((Y, Z), solid lines) and the quarter-wave plate axes (dashed lines).

In the general OPA cavity, the astigmatic effect ($\sigma_j \neq 0$) is inevitable because of the birefringence in nonlinear crystal. Therefore, the Gouy phase effects of the HG components (HG_{01} and HG_{10}) are different.[17] In general, HG_{01} and HG_{10} modes cannot resonate simultaneously in the cavity. In order to make the HG_{01} and HG_{10} modes degenerate, as shown in Fig. 2(b), we use a pair of α-cut type-II KTP crystals ($3\times3\times10$ mm) with their neutral axes perpendicular to each other, moreover, we insert a quarter-wave plate whose neutral axes rotate 22.5° in comparison to the crystal. The crystal and the wave plate are coated with antireflective coating at both 540 nm and 1080 nm. The temperature of the two crystals is independently controlled. When selecting proper temperatures, the optical length of the two crystals is equal and then the HG_{01} and HG_{10} modes can degenerate and resonate simultaneously.

At the pump power of 700 mW (below the threshold), the classical gains of HG_{01} and HG_{10} modes are 4 and 3, respectively. When the OPA is operated at de-amplification, we can simultaneously obtain two squeezed states, the HG_{01} squeezed state is bright due to a bright input and the HG_{10} squeezed state is dark.

In the present experiment, although we have not separated the HG_{01} and HG_{10} modes into two beams, we can measure the HG mode by selecting local light, because HG_{01} and HG_{10} modes are orthogonal to each other. The local oscillator's mode is either the HG_{01} mode or the HG_{10} mode, depending on which mode is measured in the balanced homodyne detection scheme. The HG_{01} local mode is produced by using a mode converter cavity, MC2, and the HG_{10} local mode is generated by converting the HG_{01} mode using a prism (MCR).

The results of measurement are shown in Fig. 3 at the analysis frequency of 6 MHz and the measurement parameters of the spectrum analyzer (SA) with resolution bandwidth (RBW) of 1 MHz and video bandwidth (VBW) of 300 Hz. We first calibrated the shot noise limit (SNL) (blue dashed line), and next we measured the noise traces for the HG_{01} mode and the HG_{10} mode while the phases (PZT2) of the local beams were scanned. After fitting the measured data, we can find that the HG_{01} mode has amplitude squeezing of -2.8 dB (Fig. 3(a)) and the HG_{10} mode's amplitude squeezing is about -1.6 dB (Fig. 3(b)).

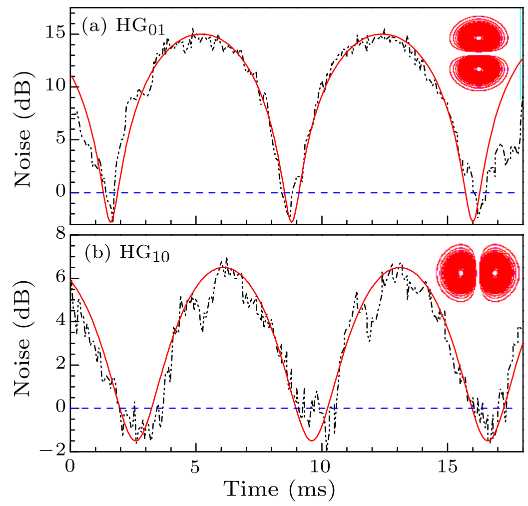

Fig. 3. (Color online) The experimental results of HG mode squeezing: (a) HG_{01} and (b) HG_{10}. The blue dashed line: shot noise limit (SNL). The red solid line: the HG mode noise.

The two output field modes HG_{01} and HG_{10} here are a pair of coupling models by two orthogonal LG_0^1 and LG_0^{-1} modes in fact. From Eq. (1), it is easy to show

$$\hat{X}_{HG01} = \frac{1}{\sqrt{2}}(\hat{X}_{LG_0^{-1}} + \hat{X}_{LG_0^1}),$$
$$\hat{X}_{HG10} = \frac{1}{\sqrt{2}}(\hat{P}_{LG_0^{-1}} - \hat{P}_{LG_0^1}), \tag{2}$$

where $\hat{X}$ and $\hat{P}$ are amplitude and phase quadrature.

From the measurement results shown in Fig. 3, we can infer that the correlation noise spectra satisfy the entanglement criterion of Duan *et al.*[18] and Simon.[19]

$$\langle \varDelta^2(\hat{X}_{\mathrm{LG}_0^{-1}} + \hat{X}_{\mathrm{LG}_0^1})\rangle + \langle \varDelta^2(\hat{P}_{\mathrm{LG}_0^{-1}} - \hat{P}_{\mathrm{LG}_0^1})\rangle = 1.2 < 2. \quad (3)$$

Thus we prove that we have generated entanglement between two co-propagating LG modes. Although we have not separated them into two independent spatial beams, it is possible.[20] We will separate them into two independent LG_0^1 and LG_0^{-1} entangled beams using an asymmetric Mach–Zehnder interferometer in our next work. Because the LG mode is also called the orbital angular momentum (OAM) mode, we experimentally generate continuous-variable OAM entanglement.

The measured values are degraded by various inefficiencies in our setup. We estimate this efficiency to be $\eta_{\mathrm{tol}} = \eta_{\mathrm{pop}}\eta_{\mathrm{det}}\eta_{\mathrm{hd}}$, where $\eta_{\mathrm{pop}} = 0.89$ is the measured propagation efficiency, $\eta_{\mathrm{det}} = 0.90$ is the measured photodiode (Epitaxx ETX500) efficiency, $\eta_{\mathrm{hd}} = 0.88$ is the measured spatial overlap efficiency in the homodyne detector for HG_{01} and HG_{10} modes, respectively, the total estimated detection efficiency for our experiment is therefore $\eta_{\mathrm{tol}} = 0.70$. From these efficiencies, we can obtain the inferred squeezing are -4.9 dB and -2.5 dB for the HG_{01} and HG_{10} modes, respectively, and the inferred entanglement criterion of the LG modes are

$$\langle \varDelta^2(\hat{X}_{\mathrm{LG}_0^{-1}} + \hat{X}_{\mathrm{LG}_0^1})\rangle + \langle \varDelta^2(\hat{P}_{\mathrm{LG}_0^{-1}} - \hat{P}_{\mathrm{LG}_0^1})\rangle = 0.88. \quad (4)$$

In summary, we have experimentally demonstrated squeezing of the HG_{01} and HG_{10} modes generated simultaneously in one OPA. The HG_{01} squeezed state is a bright field, and the HG_{10} squeezed state is a vacuum field. Considering experimental measurement efficiency, we infer that HG_{01} amplitude squeezing is -4.9 dB and HG_{10} amplitude squeezing is -2.5 dB. We also demonstrate that the output field is also continuous-variable orbital angular momentum entanglement. It is important for quantum information.

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