Delocalized Correlations in Twin Light Beams with Orbital Angular Momentum

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We generate intensity-difference-squeezed Laguerre-Gauss twin beams of light carrying orbital angular momentum by using four-wave mixing in a hot atomic vapor. The conservation of orbital angular momentum in the four-wave mixing process is studied as well as the spatial distribution of the quantum correlations obtained with different configurations of orbital angular momentum. Intensity-difference squeezing of up to −6.7 dB is demonstrated with beams carrying orbital angular momentum. Delocalized spatial correlations between the twin beams are observed.

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The orbital angular momentum of light is a property that has recently been recognized as potentially useful for the manipulation of small objects [1], the encoding of information [2], or the transfer of orbital angular momentum to atoms [3]. The study of orbital angular momentum has centered on the family of Laguerre-Gauss (LG) beams, each of which has a well-defined value of orbital angular momentum (OAM) in the paraxial approximation. Considerable progress has been made in generating and analyzing nonclassical states of light carrying OAM at the few photon level [4]. Here, we explore the production of nonclassical states of light carrying OAM in the bright beam regime. We have demonstrated a four-wave mixing (4WM) amplifier [5,6] with the ability to generate intensity-difference or "twin beam" squeezing. This amplifier, operating without a cavity, is able to amplify a probe beam with a complicated spatial mode and produce a twin conjugate beam, also with a complicated spatial mode. We exploit this capability to generate bright twin LG beams and demonstrate more than −6 dB of intensity-difference squeezing between the probe and conjugate beams. We use these bright beams to demonstrate, in the continuous-variable regime, the conservation of orbital angular momentum in the 4WM process as well as delocalized spatial correlations.

The Laguerre-Gauss "twin beams" that we generate are not identical "twins," inasmuch as they are not only at slightly different frequencies but, perhaps surprisingly, they do not even have to be in identical OAM states. We find that the OAM of the beams produced in our 4WM configuration can be understood by invoking a simple "conservation of OAM" argument involving the light alone (no OAM transferred to the medium). The conservation of OAM in this simple sense has been investigated previously in various nonlinear wave-mixing systems, and the applicability depends on the experimental conditions [7]. By detecting coincident photons, Mair *et al.* [8] established the conservation of OAM in spontaneous parametric downconversion (PDC) clarifying what had previously been a point of confusion on the issue. OAM conservation in stimulated PDC (i.e., optical parametric amplification) has been examined by Huguenin *et al.*, [9] (for type 2 PDC) and by Devaux *et al.* [10] (for type 1 PDC). Huguenin *et al.* [9] went on to show that, although the nonlinear process itself conserves OAM, when the crystal is placed in a cavity to form an optical parametric oscillator, OAM is no longer necessarily conserved (by the light beams alone). Jiang *et al.* [11] have examined OAM conservation in 4WM at the classical level, and Torres *et al.* [12] have discussed limitations on simple OAM conservation rules. Recently, the role of the experimental geometry on the conservation of OAM has been clarified by the calculations in Ref. [13].

Altman *et al.* [14] examined the spatial correlations between signal and idler photons produced in spontaneous PDC from a pump beam carrying OAM. Because of phase matching conditions, only a portion of an LG beam was generated. Here, working with bright beams and a different nonlinear system, we generate simple LG output modes and are able to investigate the way in which spatial correlations between probe (signal) and conjugate (idler) depend on the OAM of the beams.

The 4WM amplifier has been described in Refs. [5,6] and is sketched in Fig. 1. A strong pump beam (420 mW)

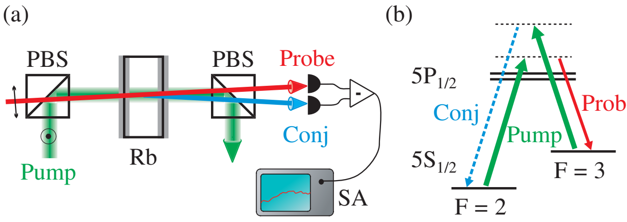

FIG. 1 (color online). (a) Setup geometry. PBS = polarizing beam splitter, SA = spectrum analyzer. (b) 4WM level scheme.

tuned ≈800 MHz to the blue of the ^{85}Rb $D1$ $5S_{1/2}, F = 2 \rightarrow 5P_{1/2}$ transition at 795 nm is sent through a 12 mm-long ^{85}Rb cell held at ≈110 °C. A weak probe beam, red-detuned by the ground state hyperfine splitting (≈3 GHz), intersects this beam at a small angle (<1 degree) and is amplified in the 4WM process, generating a conjugate beam 3 GHz to the blue of the pump. The pump has a 550 μm waist ($1/e^2$ intensity radius), and the beams overlap over the full length of the cell. The pump and the probe are resonant with a 2-photon Raman transition, as indicated in Fig. 1, between the two electronic ground state hyperfine levels $F = 2$ and $F = 3$. The noise power on the intensity difference between the probe and the conjugate is recorded with an amplified balanced photodetector and analyzed with a radio frequency (rf) spectrum analyzer. The total detection efficiency is 0.90, and the noise measurements are corrected only for the electronic noise. The gain of the optical amplifier is approximately 5.

Four-wave mixing is a parametric process, such that the initial and final states of the atomic system are the same. Thus, to the extent that 4WM is the only process taking place in the vapor, it is expected to add the same number of photons to the conjugate as it adds to the probe beam [6]. The noise on the probe-conjugate intensity difference is compared to the standard quantum limit (SQL), determined by measuring the intensity noise on a balanced pair of beams produced from a beam splitter. The measured probe-conjugate intensity-difference quantum noise reduction can be more than 8 dB below the SQL (shot noise) at 1 MHz [6], and squeezing is observed at detection frequencies from <4 kHz up to 20 MHz. The estimated 1 standard deviation systematic uncertainty on our noise measurements is ±0.2 dB.

We denote the lowest-order LG function with radial quantum number 0 and with orbital angular momentum index ℓ as LG$_0^\ell$, or more simply LGℓ. We begin by pumping with an (approximate) LG0 beam ($\ell_p = 0$). This is simply a Gaussian-profile beam. We then use a blazed holographic grating to create a good approximation to an $\ell_{\rm pr} = +1$ (LG+1) beam to inject as a probe beam into the 4WM amplifier. We create the probe by splitting off a small amount of the pump light, frequency shifting it with an acousto-optic modulator, and then passing this beam through the blazed grating. A picture of the input probe is shown in the first column of Fig. 2. In addition, we verify that the beam has a 2π phase winding by splitting the beam and interfering it with itself at a small angle [15], creating the corresponding interferogram in the second row in Fig. 2.

Also shown in Fig. 2 are pictures of the amplified probe beam that exits the 4WM amplifier, as well as the generated conjugate beam, and interferograms of these beams. The interferograms demonstrate that the probe and conjugate have $\ell_{\rm pr} = +1$ and $\ell_c = -1$, respectively, thus satisfying the selection rule $\ell_{\rm pr} + \ell_c = 2\ell_p$ as expected for a copropagating geometry [13]. The measured intensity-difference noise of the pair of output beams is 6.7 dB below the SQL, with the noise measured at 1 MHz. Inasmuch as the LG beam injected as the probe is in a "pure" LG+1 state (and the pump is purely LG0), the magnitude of OAM in each of the output probe and conjugate beams is equal to $\hbar$ times the number of photons in that beam.

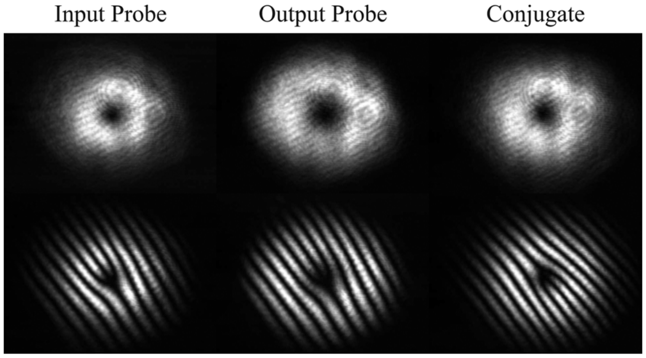

FIG. 2. Intensity distribution (upper) and phase interferogram (lower) of the probe beam at the input, the amplified probe beam at the output, and the generated conjugate beam at the output of the 4WM cell. The output probe and conjugate beams display −6.7 dB of intensity-difference squeezing. Reproduced from Ref. [16].

If a pair of beams with opposite OAM were to be generated classically, then even if each photon in each beam is in a pure state of OAM, the sum of the OAM carried by the two beams will fluctuate due to the intensity fluctuation differences between the two beams. In the present experiment, we have demonstrated both conservation of OAM in the amplified and generated light, as well as intensity correlations below the shot noise, over a band of frequencies. Thus, we conclude that if the fluctuations in the total angular momentum carried by the two beams were directly monitored, they would be found to be below the limit imposed on classically generated beams.

In order to examine the spatial distribution of the intensity correlations, we performed intensity-difference noise measurements, at a fixed rf frequency, while attenuating the beams (equally) in several different ways. In each case, we compare the noise in the intensity difference to the SQL for beams of that intensity. In the spirit of the Mandel Q parameter, we plot, as a function of the fractional transmitted intensity, the quantity $Q = $ (intensity-difference noise)/SQL $- 1$. A value of $Q < 0$ indicates quantum noise suppression, while $Q > 0$ indicates excess noise (above shot noise). The −6.7 dB of intensity-difference squeezing for unattenuated beams corresponds to a Q value of −0.79.

If the two beams are attenuated equally using neutral density (ND) filters, the magnitude of Q is reduced linearly to 0 as the mean intensity is reduced. This is shown in Fig. 3 in curve (a). Curve (b) indicates the behavior as the two beams are attenuated instead by clipping them with razor blades, cutting symmetrically with respect to the

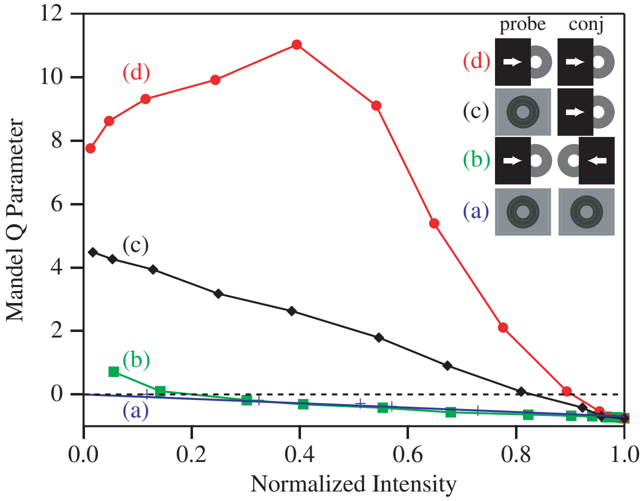

FIG. 3 (color online). Mandel Q parameter for the intensity difference as a function of the fractional transmitted intensity as the two beams are attenuated equally. The two beams are attenuated (a) with neutral density filters, (b) with razor blades moved symmetrically with respect to the pump, (c) one with a razor blade and the other with a neutral density filter, and (d) with razor blades moved antisymmetrically.

pump (from the outside edges, furthest from the pump beam). The behavior seen in the figure indicates that clipping the beams in this way has almost the same effect as attenuating with ND filters; the noise is even a small amount lower until the beam intensities are reduced by a factor of about 2. Curve (c) shows the behavior when one beam is clipped with a razor blade while the other is attenuated with a ND filter. Finally, curve (d) shows the results of clipping the beams asymmetrically, that is, from the same side of the beams. In this case, the Q parameter increases rapidly, going above 0 with only about 10% attenuation of the beams.

These measurements demonstrate that the output probe and conjugate beams should be considered multi-spatial-mode beams. Cutting out positively correlated areas from the two beams [as in case (b)] maintains the correlation statistics between the beams at about the same level as simple attenuation by ND filters [16]. On the other hand, cutting out uncorrelated areas from the beams, as for curve (d), rapidly degrades the correlations between the remaining portions of the beams. That Q goes above 10 shows that the individual amplified beams have intensity variances that are much larger than Poissonian shot noise. Curve (c) rises less rapidly since light removed from one beam with a razor blade remains correlated with an area in the other beam that is only partially attenuated with the ND filter, resulting in smaller excess fluctuations.

These observations show that a point in the probe beam is most strongly correlated to a limited area of the conjugate beam. This area is limited by the pump size (the point is reflected through each point in the pump, weighted nonlinearly by the pump intensity [17]) as well as by diffraction; the diffraction-limited size of the pump spot will be a limit to how small the correlation area can be. While the correlation area (or coherence area) is not directly measured here, it is clear that we create multi-spatial-mode beams.

In a second set of experiments, we used a blazed grating to generate a strong LG+1 beam as the pump, and injected an LG0 beam as the probe seed. Figure 4 shows pictures of the output probe and conjugate beams, as well as the pump mode. The probe and conjugate beams display -4.4 dB of intensity-difference squeezing in this case. In addition, the interferograms for these beams indicate that, at least in the paraxial approximation, orbital angular momentum is again conserved in the 4WM process. The probe photon injects no OAM into the system in this case; however, the two pump photons involved in the 4WM process each inject $+1\hbar$ of OAM into the atomic system, and this needs to be taken out by the conjugate photon to return the atomic system to its original state. Thus, for an LG+1 pump, the conjugate beam to an LG0 probe appears as a LG+2 beam.

The asymmetry in the LG modes in Fig. 4 indicates some OAM impurity, but the interferograms show that a single value predominates. The sense of the asymmetry in the conjugate is consistent with the pump asymmetry.

We again perform noise measurements under different attenuation conditions. In Fig. 5, we see that attenuating both beams with ND filters produces a linear reduction of the Q parameter from an initial value of -0.64 (-4.4 dB) to 0 at zero intensity [curve (a)]. In this case, cutting the beams with razor blades, either symmetrically with respect to the pump [curve (c)], or asymmetrically [curve (d)], very quickly destroys the correlations between the beams. Attenuating the probe with an ND filter while cutting the conjugate with a razor blade [curve (b)] destroys the correlations less quickly than either of these two methods. These results can be explained by the very delocalized

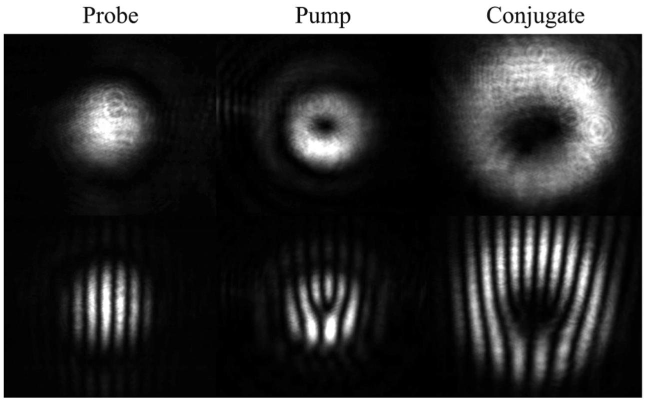

FIG. 4. Intensity distribution (upper) and phase interferogram (lower) of the amplified probe beam, the pump beam, and the generated conjugate beam at the output of the 4WM cell. The probe and conjugate beams display -4.4 dB of intensity-difference squeezing.

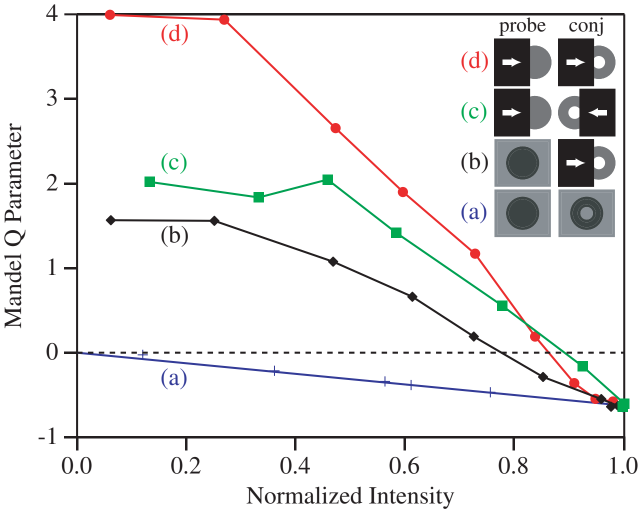

FIG. 5 (color online). Mandel Q parameter for the intensity difference as a function of the fractional transmitted intensity for equally attenuated beams. The pump is an LG+1 beam. The two beams are attenuated (a) with neutral density filters, (b) one with a razor blade and the other with a neutral density filter, (c) with razor blades moved symmetrically with respect to the pump, and (d) with razor blades moved antisymmetrically.

form of the correlations that exist between the probe and conjugate beams in this configuration. A point in the LG0 probe is now correlated to a complete ring in the LG+2 conjugate beam. Thus, there is no way of cutting into the conjugate beam that approximates removing an independent mode from that beam which is correlated to the area cut out of the probe beam. Any attempt to cut into the beam reveals an unbalanced mode with excess intensity noise.

The spatial quantum correlation properties of light beams with OAM were investigated using parametric down conversion (3-wave mixing) in Ref. [14]. Unlike PDC, the conditions we have for 4WM allow us to see the entire "quantum image" of the correlated photons. Altman *et al.* [14] showed that with an LG+4 pump for PDC, they could observe that the correlation area corresponding to a point or small area in one beam splits into two spots. They show that this results from the overlap of the phase-matched PDC ring with an annular LG conjugate beam containing the correlated photons [18]. In the present experiments, it is straightforward to see and understand how this happens, as the phase matching conditions for our 4WM process are not as restrictive and the entire correlated LG beam (LG+2 here) is generated as a visible, bright beam. Operating in this regime makes this splitting of the correlation region less mysterious. In addition, the signal-to-noise ratio is much improved in the present case.

A number of authors have discussed the possibility of using OAM beams for quantum computing or communications applications [2,4], with some advantage being obtained from having a compact multistate qudit formed in this way. Here, we have demonstrated the ability to make quantum correlated "twin beams" with OAM. In recent work, we demonstrated that these beams are quantum-entangled states [19] as well. These capabilities should enable further progress in the direction of continuous-variable optical information processing with OAM beams.

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