

# Generating squeezed vacuum field with nonzero orbital angular momentum with atomic ensembles

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We demonstrated that by using a pump field with nonzero orbital angular momentum (OAM) in the polarization self-rotation squeezing process it is possible to generate a squeezed vacuum optical field with the matching OAM. We found a similar level of maximum quantum noise reduction for a first-order Laguerre–Gaussian pump beam and a regular Gaussian pump beam, even though the optimal operational conditions differed in these two cases. Also, we investigated the effect of self-defocusing on the level of the vacuum squeezing by simultaneously monitoring the minimum quantum noise level and the output beam transverse profile at various pump laser powers and atomic densities and found no direct correlations between the increased beam size and the degree of measured squeezing. © 2013 Optical Society of America

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Light beams that carry an orbital angular momentum (OAM) have recently gained popularity for many optical applications [1–3]. For example, OAM provides an additional degree of freedom for an optical field (in addition to traditional frequency and polarization) that can be used to increase the information capacity of an optical network [4]. It also allows generation of entanglement between a pair of single photons [3,5–7] or between continuous optical fields [8–10] for spatial multimode quantum information systems and imaging. Moreover, a hyperentanglement between spin and OAM states of a photon [11,12] has been demonstrated to increase the dimensionality and capacity of quantum channels.

Here we demonstrate a simple way to generate an optical squeezed vacuum field with a nonzero OAM via interaction of a linearly polarized Laguerre–Gaussian pump field with a resonant atomic vapor under the polarization self-rotation (PSR) conditions [13–15]. Previous experiments in PSR squeezing have demonstrated quadrature noise suppression in the vacuum field in the orthogonal polarization up to 3 dB below the shot-noise limit [16,17]. In our experiments we used a spiral phase mask to convert the pump field into a first-order Laguerre–Gaussian beam before the interaction with Rb atoms, then analyzed the quantum noise in the orthogonal polarization after the vapor cell using the same pump field as a local oscillator (LO). In this case, we detected up to  $1.7 \pm 0.2$  dB of quantum noise suppression in the matching spatial mode. This value is comparable to the  $1.8 \pm 0.2$  dB of squeezing measured in the same vapor cell using a pump field with a regular Gaussian distribution. It is worth mentioning that a similar strategy of using an OAM pump beam was used previously for the generation of photon pairs with OAM via parametric down conversion [5,7], and more recently in demonstration of intensity-squeezed bright twin beams with nonzero OAM [9] via a nondegenerate four-wave mixing process.

The schematic of the experiment is shown in Fig. 1. The output of a cw Ti:Sapphire laser was tuned near the  $5^2S_{1/2}F=2 \rightarrow 5^2P_{1/2}$ ,  $F'=2$  transition of the  $^{87}\text{Rb}$  ( $\lambda \simeq 795$  nm). We used a single-mode optical fiber

followed by a Glan-laser polarizer (GP) to prepare a high quality linearly polarized pump beam with the Gaussian transverse profile, which then was focussed inside a cylindrical Pyrex cell (10 mm in length and 25 mm in diameter) containing isotopically enriched  $^{87}\text{Rb}$  vapor. The focal lengths of the lenses before and after the cell were correspondingly 40 and 50 cm. The size of the minimum focal spot inside the cell was  $0.13 \pm 0.01$  mm FWHM. The vapor cell was mounted inside a three-layer magnetic shielding, and the number density of Rb atoms was adjusted between  $3.4 \cdot 10^{11} \text{ cm}^{-3}$  and  $6.0 \cdot 10^{12} \text{ cm}^{-3}$  by adjusting the cell's temperature. The input laser power in the cell was controlled by rotating a half wave plate before the Glan polarizer, with maximum injection power 16 mW.

We analyzed the quantum noise of the vacuum field in orthogonal linear polarization (with respect to the pump field) after the Rb cell by means of a homodyne detection [16,17]. We reused the strong pump field as the LO, avoiding spatial separation of the LO and the squeezed vacuum field (SqV) to improve the stability of the detection. To achieve this we rotated the polarizations of both optical fields by  $45^\circ$  with respect to the axes of a polarizing beam splitter (PBS). The relative phase between the two polarizations was adjusted to detect minimum noise quadrature by horizontally tilting a phase-retarding plate (PhR)—a quarter-wave plate with optical axes aligned

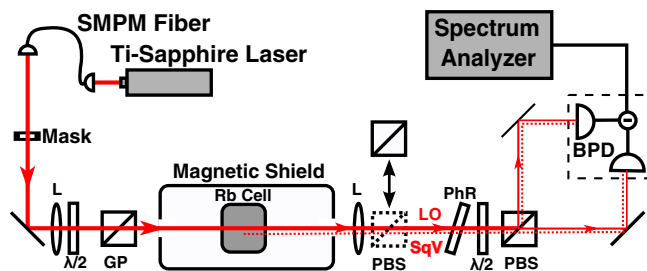


Fig. 1. Experimental setup. SMPM, single-mode polarization-maintaining fiber;  $\lambda/2$ , half-wave plate; GP, Glan-laser polarizer; PBS, polarizing beam splitter; PhR, phase-retarding wave plate; BPD, balanced photodetector.

with the LO and the vacuum field polarizations. The two outputs were then directed to a balanced photodetector (BPD) with  $1.6 \times 10^4$  V/A gain, 9 MHz 3 dB bandwidth, and dark noise level at least 10 dB below the shot noise level. The shot noise level measurements were done with a PBS placed after the Rb cell such that only the pump field was transmitted, and the modified vacuum field in the orthogonal polarization was rejected.

To modify the transverse profile of the pump beam and add a nonzero OAM, we placed a spiral phase mask in the collimated portion of the beam path before the Rb cell, as shown in Fig. 1. The azimuthal thickness variation of the mask produced a  $2\pi$  phase difference, creating a phase singularity at the center of the transmitted laser beam. As a result, its radial intensity distribution dropped to zero at the center (so-called optical vortex) [1], forming a signature “donut”-shaped transverse profile shown in Fig. 2. These images were recorded by a CCD camera placed after the Rb vapor cell. In general, the recorded intensity distributions were well described by the first-order Laguerre–Gaussian distribution, characteristic for the laser beam carrying  $1\hbar$  angular momentum:

$$I(r) = I_0 \frac{2r^2}{w^2} e^{-\frac{2r^2}{w^2}}, \quad (1)$$

where  $w$  is the waist of the vortex beam and  $\pi w^2 I_0 / 2$  is the total power. The variation in the mask’s thickness was not smooth but changed step-like through 8 discrete sectors, causing small additional features outside of the main vortex beam due to the diffraction of light on the boundaries of the phase mask sectors. Without the mask, the transverse intensity profile of the laser beam is accurately described by the regular Gaussian distribution:

$$I(r) = I_0 e^{-\frac{2r^2}{w^2}}. \quad (2)$$

Previous experiments show that PSR-based squeezing requires careful optimization of the experimental parameters, such as atomic density, laser frequency, power, and focusing characteristics inside the vapor cell [18,19]; these optimal conditions change depending on the geometry and the buffer gas composition of a Rb vapor cell. To identify these optimal conditions in the current

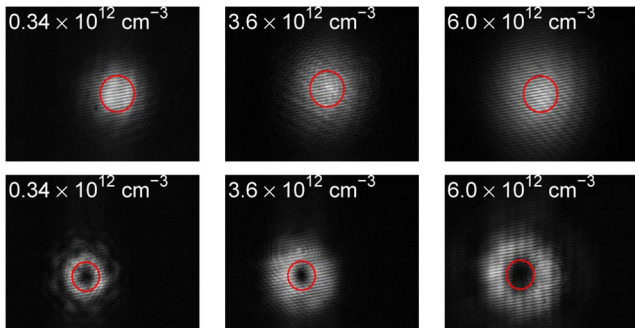


Fig. 2. Transverse profiles of a Gaussian (top) and vortex (bottom) beams after interaction with the Rb vapor cell at different atomic densities. The red (light gray) circles are shown to aid visual comparison of beam sizes in low and high atomic density cases for the Gaussian and vortex beams, correspondingly.

experimental setup, we mapped the dependence of the minimum measured quantum noise power as a function of the laser power and the atomic density. For each measurement, we optimized the laser frequency for the highest value of squeezing, within approximately 200 MHz around the center of the atomic resonance. The results of these measurements are shown in Figs. 3(a) and 3(b). For a regular pump beam with a Gaussian transverse distribution [Fig. 3(a)], the best recorded squeezing of  $1.8 \pm 0.2$  dB was observed at a pump power of 10.5 mW and the atomic density of a  $2.7 \times 10^{12} \text{ cm}^{-3}$ . The measured squeezing level was somewhat worse than previously observed values at this Rb optical transition [17], possibly due to higher cell temperature (to compensate for shorter cell length). Similar to the previous observation, the maximum squeezing occurred is a small “island” of the pump power/atomic density parameter space.

We then repeated the same procedure using a Laguerre–Gaussian pump beam. Figure 3(b) shows the minimum quadrature noise power at different values of the laser power and atomic density. The minimum quantum noise level, detected with the optical vortex pump beam, was  $1.7 \pm 0.2$  dB below the shot noise. Since the same OAM pump beam was used as the LO in the homodyne detection, we conclude that the squeezed vacuum optical field also was carrying the same OAM  $1\hbar$ . This observation is consistent with the conservation of the angular momentum. Previous experiments have demonstrated that the OAM is conserved in four-wave mixing processes [9,20]. The generation of the PSR squeezing can be described as a degenerate four-wave mixing [18], in which two photons of one linear polarization are absorbed from the pump field, and a pair of photons are emitted in the correlated noise sidebands of the orthogonal polarization. As each of the four photons involved in the process can carry the same angular momentum  $1\hbar$ , the total angular momentum is conserved.

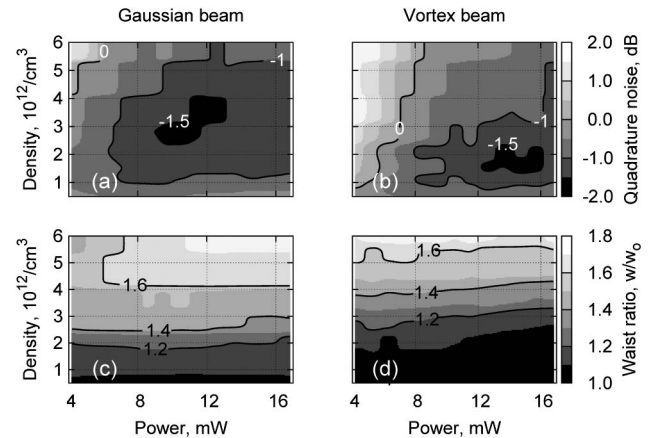


Fig. 3. Measured minimum quadrature noise power (top row) and the relative beam expansion (bottom row) for the pump beam with the Gaussian (left column) and Laguerre–Gaussian (right column) distributions as functions of the pump power and the atomic density. The beam expansion was measured as the ratio of the measured waist ( $w$ ) [from fits (1) and (2)] to its value at low temperature ( $w_0$ ), where self-defocusing was negligible. For quantum noise measurements, zero corresponds to the shot noise level. Spectrum analyzer detection frequency was 1 MHz.

The optimized value of measured squeezing with OAM pump beam matched the value obtained using a regular pump beam within the experimental uncertainty. At the same time, the optimal experimental conditions differed in these two cases. For the vortex pump beam, the best squeezing of  $1.7 \pm 0.2$  dB occurred at a higher optical pump power of 14.7 mW and a lower atomic density of  $(1.8 \pm 0.3) \times 10^{12} \text{ cm}^{-3}$ . (Under identical conditions, the squeezing obtained with a regular pump beam was only  $1.1 \pm 0.2$  dB.) Such changes in optimal experimental parameters was not surprising, since the details of the pump beam propagation inside the atomic ensemble were known to have a strong effect on the output squeezed vacuum. For example, Fig. 4 shows the variations in the measured squeezing as the magnetic shield, containing the vapor cell, was shifted back and forth along the focused Gaussian pump beam path. Considering the depth of focus of approximately 4.8 cm, it is easy to see that the best value of squeezing was obtained with the lowest pump power when the cell was positioned around the focal point. Any displacement of the cell away from the focus in either direction resulted in achieving similar value of squeezing at higher value of the pump power. Since the peak intensity of the first-order Laguerre–Gaussian beam is less than half of the peak intensity of a regular Gaussian beam with the same waist parameter, we expect to see a higher laser power to produce optimal squeezing for the vortex pump beam.

Our experimental arrangement also allowed us to investigate the effect of self-defocusing of the optical beams in Rb vapor at higher atomic density. Self-defocusing/self-focusing is a well-known nonlinear effect [21,22] where a strong optical field propagating through a resonant optical medium induces an intensity-dependent variation in its refraction index; thus, a transverse intensity distribution of an optical field, “mapped” into a spatial variation of the refraction index, creates an effective atomic lens that changes the size and divergence of the output optical beam. Figure 2 clearly shows that we observed a strong defocusing effect for both regular and vortex pump beams, which was more

pronounced at higher densities of Rb atoms. Previous work showed (both experimentally and theoretically) that such beam distortion can limit the generation of squeezed vacuum in the four-wave-mixing process [23].

To search for correlations between the beam size variation and observed squeezing level, we recorded the images of the output pump beam intensity distributions for different values of laser power and atomic density matching the experimental parameters of the squeezing level measurements depicted in Figs. 3(a) and 3(b). Since the intensity distributions of all beams were well-fitted by either Eq. (1) (with phase mask inserted) or Eq. (2) (with no phase mask), the measurements of the waist parameter  $w$  were sufficient to accurately describe beam modifications at various experimental parameters. The results of these measurements are shown in Figs. 3(c) and 3(d) for both Gaussian and Laguerre–Gaussian pump beams.

In our detection scheme, we used the output pump field as a LO, substantially reducing the sensitivity to the beam distortions (compared to an independent LO beam in [23]) as long as both the squeezed vacuum and the pump field were spatially mode-matched. A simple comparison of the data in Figs. 3(a) and 3(c) reveals that the observed maximum squeezing occurred at the region of moderate ( $\approx 50\%$ ) beam expansion for the Gaussian beam. The same is true for the OAM pump beam [Figs. 3(b) and 3(d)]. For a fixed atomic density there is very little variation in the beam diameter with respect to the laser power. Simultaneously, the measured values of squeezing showed much stronger intensity dependence, with squeezing reaching a local maximum at some intermediate power, and then decreasing at higher powers. These observations somewhat contradict the detailed theoretical calculations [18] that the value of squeezing must continuously grow with laser power. At the same time, it cannot be explained by the self-defocusing effect either, since the size of the laser beam does not change at the higher intensities compared to the optimal intensity at fixed atomic density. Thus, based solely on these measurements we cannot completely rule out the self-focusing effect, since both beam expansion and squeezing deterioration become more pronounced at high atomic densities. It is possible that as atomic density increases, the spatial modes for squeezed vacuum and the pump field may experience different defocusing, resulting in the reduction in the measured squeezing due to the mode-mismatch at the detection stage. To unambiguously distinguish such differential self-defocusing effect from other nonlinear interactions, such as spontaneous Raman generation and four-wave mixing [20,24], we need to conduct the experiment using a spatially configurable LO and thus directly mapping the output spatial mode of the squeezed vacuum.

In conclusion, we demonstrated that it is possible to generate a squeezed vacuum with nonzero angular momentum via PSR squeezing by manipulating the transverse profile of the pump beam before the vapor cell using a phase mask. We reported  $1.7 \pm 0.2$  dB of squeezing in the first-order Laguerre–Gaussian spatial mode, which was comparable to the  $1.8 \pm 0.2$  dB squeezing value observed in the same setup with a regular laser pump field. Thus, the change in the pump intensity distribution

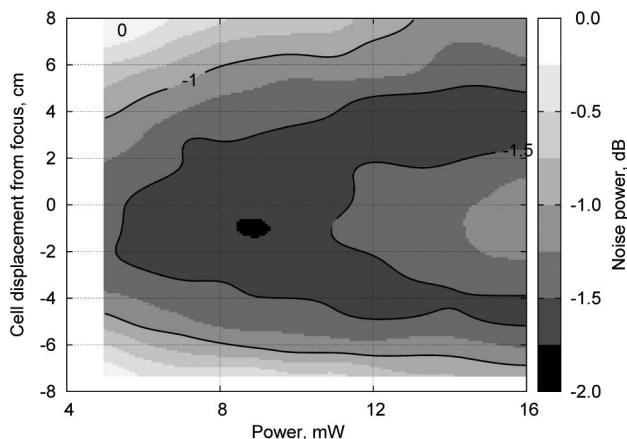


Fig. 4. Measured minimum quadrature noise power as a function of position of the focal point and the pump power. Zero displacement corresponds to the Gaussian pump laser focused at the center of the vapor cell. For quantum noise measurements, zero corresponds to the shot noise level. Spectrum analyzer detection frequency was 1 MHz.

did not change the maximum achieved value of squeezing, but only the experimental conditions (atomic density and pump laser intensity) at which squeezing occurred, so it might be possible to imprint spatial information into the squeezed vacuum optical field by controlling the profile of the pump field using, for example, a liquid crystal spatial light modulator. We also investigated the effect of self-defocusing that led to beam expansion after interaction with Rb atoms at higher cell temperature. While the sizes of both Gaussian and Laguerre–Gaussian beams increased as the atomic density increased, the overall shape was well preserved in the range of explored experimental parameters. In general, we found no clear correlation between self-defocusing effect and generation or preservation of squeezed states, although additional investigations are required.

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