Experimental Vacuum Squeezing in Rubidium Vapor via Self-Rotation

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We report the generation of optical squeezed vacuum states by means of polarization self-rotation in rubidium vapor following a proposal by Matsko et al. [Phys. Rev. A 66, 043815 (2002)]. The experimental setup, involving in essence just a diode laser and a heated rubidium gas cell, is simple and easily scalable. A squeezing of \((0.85 \pm 0.05)\) dB was achieved.

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\[\text{FIG. 1: Transformation of the phase space: a Wigner function describing the state of the probe field in the mode polarized orthogonally to the strong pump beam. Self-rotation results in a linear shear of phase space (Eqs. 3 and 4). The circular phase-space quasiprobability density describing the vacuum state is transformed into squeezed vacuum.}\]

\[\varphi = g\epsilon, \quad 1\]

with the self-rotation parameter \(g\) dependent on the incident light intensity and frequency.

Consider a monochromatic, elliptically polarized light field of frequency \(\omega\) propagating in the z-direction. The complex field amplitudes in the two linear polarization components are given by \(E_x\) and \(E_y\), with \(|E_x| \ll |E_y|\). Assuming the “pump” amplitude \(E_p\) real, we decompose the “probe” \(x\)-field into two real quadrature components in and out of phase with the pump field:
\[ \mathcal{E}_x(z) = X_x(z) + iP_y(z). \] Then the ellipticity \( \epsilon \) of the laser light is given by

\[ \epsilon \approx \frac{P_x(z)}{\mathcal{E}_y(z)}. \quad (2) \]

The resulting self-rotation by \( \varphi \ll 1 \) causes the pump field to contribute its fraction \( \varphi \mathcal{E}_y \) into the \( x \)-polarization, namely into the \( X_x(z) \) quadrature which is in phase with \( \mathcal{E}_y \):

\[ X_x(l) = X_x(0) + \varphi \mathcal{E}_y = X_x(0) + gl P_x(0) \quad (3) \]

\[ P_x(l) = P_x(0), \quad (4) \]

\( \mathcal{E}_y \) and \( \epsilon \) remain effectively unchanged.

We now assume the \( x \)-polarized light field as classical noise described by a probability distribution in the quadrature plane (Fig. 1). To describe slow fluctuations, we regard the propagation of a light field described by \( X_x(z) \), \( P_x(z) \) and \( \mathcal{E}_y \) through the medium under stationary conditions. A random quadrature component \( P_x(0) \) results in a small random ellipticity according to Eq. 2.

The propagation through the cell will displace the point \((X_x, P_x)\) in the phase space as described in Eqs. 3 and 4. The phase space probability distribution experiences a linear shear, resulting in reduction of the noise in some phase quadratures below the original level.

Although the above treatment is purely classical, it is completely identical in application to the quantum quadrature noise. Considering the Heisenberg evolution of the field-quadrature operators \( X_x(z) \) and \( P_x(z) \) we notice that the evolution described by Eqs. 3 and 4 can be associated with the interaction Hamiltonian \( \hat{H} = \hbar gc P_x^2/2 \), \( c \) being the speed of light in the medium. Under a second order Hamiltonian, each point of the Wigner function — the quantum-mechanical analogue of the phase-space probability distribution — evolves according to the classical equations of motion [22]. The incoming symmetric Gaussian Wigner function of the vacuum is therefore transformed into an elliptical Wigner function of a minimum uncertainty squeezed vacuum state.

In a homodyne measurement such a state results in a quadrature noise depending on the local oscillator phase \( \chi \) (cf. 24):

\[ \langle \Delta E_x(\chi, l)^2 \rangle = \frac{\epsilon^2}{4} \left(1 - \alpha l \right) \left( 1 - 2gl \sin \chi \cos \chi + g^2 l^2 \cos^2 \chi \right) + \alpha l \right). \]

Here \( \epsilon^2/4 \) is the standard quantum noise limit (SQL) associated with the vacuum state, and we have taken into account absorption of a small fraction \( \alpha l \ll 1 \) of the squeezed light after passing the medium. This treatment of absorption is approximate because some of the light energy is actually lost in the atomic vapor along the propagation path. However, it permits to account for one essential feature of our experimental result: the minimum uncertainty property is lost when \( gl > 0 \) and \( \alpha l > 0 \).

\[ \psi = \frac{S_1 - S_2}{2(S_1 + S_2)} \quad (6) \]

By recording \( S_1 \) and \( S_2 \) while scanning over the rubidium \( D2 \) line for many different initial small ellipticities \( \epsilon \ll 1 \), the self-rotation parameter \( gl \) for each laser detuning was determined by polynomial fitting. Fig. 8 shows \( gl \) and the absorption coefficient \( \alpha l \) for our working temperature of 70°C. Note that a relatively high transmission on resonance is due to very high saturation of the atomic transition — in the linear small signal regime, the rubidium vapor is optically dense.

To measure the quantum field quadrature noise we employed the standard balanced homodyne detection technique. The \( y \)-polarized component of the laser beam
emerging from the cell was used as the local oscillator. To this end it was first separated from the $x$-polarized probe mode by means of a polarizing beam splitter and its polarization was rotated by 90°. It was then overlapped with the squeezed mode on a symmetric beam splitter. To achieve good mode matching, an auxiliary $\lambda/2$ plate placed directly after the cell was set to provide equal splitting into both polarization modes. The resulting Mach-Zehnder interferometer was carefully aligned for a maximum visibility of $V = 0.98 \pm 0.01$ corresponding to a mode matching efficiency of $V^2 \approx 0.96$. The auxiliary $\lambda/2$ plate was then removed.

A piezoelectric element was used to scan the local oscillator phase and thus the field quadrature whose fluctuations were measured. The intensities at the beam splitter outputs were measured with Si PIN photodiodes (Hamamatsu S3883 with a nominal quantum efficiency of 91%). The AC signals of the diodes were amplified with a low noise amplifier with a cutoff frequency of approximately 50 MHz and subtracted by a hybrid junction (H-9 from M/A-COM). The noise was measured with a spectrum analyzer operated in the zero span mode at a set of radio frequencies $\Omega_{RF}$ between 3 and 30 MHz with a resolution bandwidth of 1 MHz.

d. Results and discussion The squeezing homodyne measurements were performed at a finite radio-frequency $\Omega_{RF}$, as usual, because of the high optical and electronic noise near DC. Fig. 4 shows the phase dependent noise of the $x$-polarization mode which contains the squeezed vacuum. It is compared to the SQL which can be measured by blocking the squeezed vacuum path. The phase dependent noise minima fall below the SQL exhibiting a squeezing of $(0.85 \pm 0.05)$ dB. This corresponds to a squeezing of $(1.23 \pm 0.07)$ dB at the cell output when corrections for linear losses, inefficient photodiodes and electronic photodetector noise are made. The geometric mean noise of the squeezed mode, however, strongly exceeds the SQL so the observed ensemble is not a minimum uncertainty state. The excess noise cannot be explained by absorption alone and is presumably due to resonance fluorescence into the optical mode probed.

Fig. 3 shows the squeezing as a function of the laser detuning and the radio frequency $\Omega_{RF}$. The variation of squeezing with the laser detuning follows approximately the self-rotation curve in Fig. 3. For small $\Omega_{RF}$ the squeezing is reduced due to extra noise from resonance fluorescence which scatters light into our vacuum mode. This extra noise was measured by misaligning the mode matching until the phase dependence vanished and maximizing the spatial overlap between the pump and probe modes in the cell by maximizing the noise. Fig. 5 shows the extra noise normalized to the vacuum noise. Its spectral width approximates the natural linewidth of $\Gamma = 6$ MHz, its dependence on the laser detuning is similar to the absorption line (Fig. 3). For $\Omega_{RF} \gg \Gamma$ the excess noise becomes negligible. Maximum squeezing is achieved for $\Omega_{RF} \sim 5$ MHz to 10 MHz. The reason for the squeezing to degrade with higher $\Omega_{RF}$ might be a growing phase mismatch between the pump and the probe expected in the neighborhood of an atomic resonance.

e. Summary and outlook We reported the generation of squeezed optical vacuum states in rubidium vapor with a simple setup. A squeezing of 0.85 dB was achieved which is among the best atomic vapor squeezing results accomplished. The squeezing of 6 to 8 dB predicted in was not reached due to the degrading effects of self-focusing, phase mismatch and resonance effects of self-focusing, phase mismatch and resonance...
fluorescence. Further theoretical investigation of these effects will help us optimize the experimental parameters. The self-rotation parameter and the associated squeezing might increase by using a cell with a moderate amount of buffer gas [24]. We are optimistic that a noticeable improvement of the squeezing is possible. By splitting the laser and directing it into several rubidium cells, numerous squeezed states, which are phase locked with respect to each other, can be generated easily.

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