Low-frequency vacuum squeezing via polarization self-rotation in Rb vapor

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We observed squeezed vacuum light at 795 nm in ^{87}Rb vapor via resonant polarization self-rotation and report noise sidebands suppression of ≈1 dB below shot-noise level spanning from 30 kHz to 1.2 MHz frequencies. To our knowledge, this is the first demonstration of submegahertz quadrature vacuum squeezing in atomic systems. The spectral range of observed squeezing matches well typical bandwidths of electromagnetically induced transparency (EIT) resonances, making this simple technique for generation of optical fields with nonclassical statistics at atomic transitions wavelengths attractive for EIT-based quantum information protocols applications. © 2008 Optical Society of America

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The reliable and efficient generation of an electromagnetic field with nonclassical statistics (i.e., “squeezed” light, or “squeezed” vacuum) is important for a number of applications from precision metrology to quantum information. Many recently proposed protocols for controlling and manipulating quantum states in atomic ensembles [1,2] require sources of light with controllable quantum mechanical properties in a characteristic bandwidth that are resonant with atomic transitions. Electromagnetically induced transparency (EIT) resonances, for example, are widely used in slow light and quantum memory experiments [3,4], few photon wave-packet generation and control [5–8], etc. Their typical bandwidths range from a few tens of hertz to a few megahertz [1].

Many EIT experiments are based on the Rb D_1 line (795 nm) transitions, and the performance of traditional nonlinear crystal-based squeezers based on optical parametric oscillators [9] is limited at this wavelength owing to increased material absorption for 397 nm near-ultraviolet upconverted pump field, as well as various photothermal effects arising at higher pump power [10]. Another challenge is to produce low-frequency squeezing to match the characteristic bandwidth of EIT resonances. While the generation of squeezed light with submegahertz sideband frequencies is theoretically possible [11], in practical terms it becomes a very challenging and resource-consuming task. Nevertheless, impressive progress in generation of low-frequency squeezed vacuum at the Rb resonance wavelength has been recently reported [10]. Similar sources were used to demonstrate slow light and reversible mapping of squeezed vacuum states via EIT in Rb [12–14].

The generation of resonant squeezed vacuum based on nonlinear interaction of light with atoms offers a simpler alternative to traditional nonlinear crystal-based squeezers. Various techniques, explored recently, are reviewed in [15]. This Letter reports the successful observation of low-frequency squeezed vacuum at the Rb optical D_1 transition (795 nm) based on the nonlinear polarization self-rotation effect (PSR), recently proposed by Matsko *et al.* [16]. Ries *et al.* reported the proof-of-principle demonstration on the Rb D_2 line [17], although some later experiments failed to reproduce this result [18]. The present experiment is aimed to resolve this controversy.

The polarization self-rotation effect describes the rotation of the polarization direction of elliptically polarized light as it propagates through a medium, and it occurs in many optical substances. The effect is characterized by a self-rotation parameter g, such that $\phi_{SR}=g\varepsilon L$, where ϕ_{SR} is the polarization rotation angle of the input field with ellipticity ε after traversing an optical medium of length L. In resonant atomic vapor self-rotation occurs owing to unbalanced ac Stark shifts caused by unequal intensities of circularly polarized components of the input light field [19,20]. In the case of the linearly polarized pump field there is no macroscopic polarization rotation, but the same mechanism couples quantum noise in two initially independent circular components, and thus produces cross-phase modulation between the classical linearly polarized pump field and the vacuum field in the orthogonal polarization. As a result, quadrature squeezing of the vacuum field occurs [16]. The expected noise suppression below the standard quantum limit is proportional to $1/(gL)^2$, but is reduced by optical losses in the system. In practice, the observation of maximum squeezing requires optimization of many experimental parameters such as laser detuning and power, atomic density, etc. Spontaneous emission noise in thermal vapor may also reduce or destroy squeezing by introducing extra noise [15,18]. We also observed that squeezing generation is sensitive to the presence of an uncompensated magnetic field inside the cell.

The experimental arrangement is very simple with no need for expensive equipment, such as powerful lasers or a high-quality optical cavity, and the resulting nonclassical field is automatically generated at a near-resonant wavelength. The schematic of the experiment is shown in Fig. 1. An external cavity diode laser (≈7 mW total power) was tuned to the Rb D_1 line $5^2S_{1/2}\rightarrow 5^2P_{1/2}$ ($\lambda\simeq 795$ nm). The laser beam was focused with a pair of lenses (L) inside a cylindrical glass cell, containing isotropically enriched ^{87}Rb and

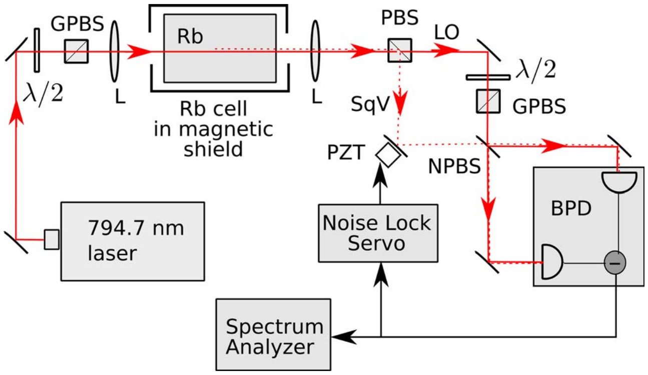

Fig. 1. (Color online) Schematic of the experimental setup. Please see text for abbreviations.

2.5 Torr of Ne buffer gas, and the estimated minimum laser beam diameter inside the cell was 0.175 ± 0.015 mm FWHM. The cell length and diameter were 75 and 22 mm, respectively, and the cell windows were tilted at ~10° to prevent backward reflections. The cell was mounted inside a three-layer magnetic shielding to minimize stray magnetic fields and maintained at 66°C. Before entering the cell the laser beam passed through a high-quality Glan polarizing beam splitter (GPBS) to purify its linear polarization. A half-wave plate ($\lambda/2$) placed in front allowed for smooth adjustments of the pump field intensity.

After the cell the electromagnetic field in orthogonal polarization [squeezed vacuum field (SqV)] was separated on a polarization beam splitter (PBS), and its noise properties were analyzed using a homodyne detection. The original pump field played the role of a local oscillator (LO) that was attenuated and brought to the same polarization as the vacuum field using another GPBS and a half-wave-plate combo. Phase differences between the local oscillator and the vacuum field was controlled by a mirror placed on a piezoceramic transducer (PZT). We then mixed these two fields at a 50/50 nonpolarizing beam splitter (NPBS), and directed two beams to a homemade balance photodetector (BPD) with a gain of 10^4 V/A, 1 MHz 3 dB bandwidth, and an electronic noise floor at 6 dB below shot noise at low frequencies. For our measurement we locked the relative phase in the BPD detection scheme to the minimum value of quadrature noise in SqV channel by using a noise-locking technique [21].

Figures 2(I) and 2(II) show the self-rotation and absorption of the pump field when a small ellipticity $\varepsilon=4°$ was introduced by a quarter-wave plate placed before the cell (we define ε as an angle between $\lambda/4$ plate fast axis and pump field polarization direction). Maximum self-rotation was observed near both $F_g=2\rightarrow F_e=1,2$ transitions of ^{87}Rb, although the polar-ization ellipse rotated in opposite directions. Increasing the laser power resulted in increased transparency of the atomic vapor owing to more effective optical pumping of atoms into noninteracting combination of Zeeman sublevels of $F_g=2$ state as well as to off-resonant $F_g=1$ state. The second mechanism was most likely also responsible for some reduction in the self-rotation.

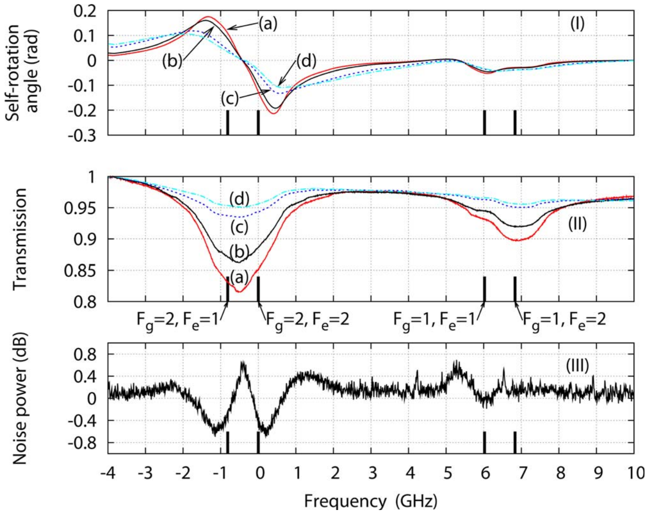

Fig. 2. (Color online) (I) Polarization self-rotation angle (ϕ_{SR}) and (II) transmission in the ^{87}Rb cell for the light field with $\varepsilon=4°$ ellipticity. Laser powers are (a) 1.04, (b) 1.54, (c) 4.15, and (d) 6.37 mW. (III) Minimum quadrature noise in orthogonal polarization at 1200 MHz central frequency, for linearly polarized pump field with power 6.58 mW. Zero laser detuning corresponds to $F_g=2\rightarrow F_e=2$ ^{87}Rb transition.

Figure 2(III) shows a sample spectrum of minimum (squeezed) quadrature of the optical field of orthogonal polarization in case of linearly polarized pump field (i.e., no measurable polarization self-rotation occurs). The positions of squeezing peaks correspond roughly to those of self-rotation. A maximum squeezing of 0.6 dB was detected at detunings of ~100 MHz to the red from $F_g=2\rightarrow F_e=1$ as well as ~100 MHz to the blue from $F_g=2\rightarrow F_e=2$, and excess noise was observed in the region between two transitions. We also observed minute amount of squeezing near $F_g=1\rightarrow F_e=1$ transition. Vacuum squeezing showed similar dependence of the optical frequency for different pump powers.

At the same time the squeezed quantum noise frequency spectrum showed rather strong variation with the pump field power, as Fig. 3 demonstrates. The detected squeezing was uniformly low at low laser powers >1 mW. As the pump power increased, we first observed maximum squeezing in the low-frequency part of the quantum noise spectrum. Then broadband squeezing kept increasing at the expense of low-frequency components and reached its maximum at ~4 mW. Further power increases began slowly degrading observed squeezing, which is consistent with a reduction of the self-rotation parameter shown in Fig. 2(I), caused by the depopulation of the $F_g=2$ level owing to optical pumping.

To investigate the low-frequency part of the squeezing spectrum in more detail we studied the case of 1.54 mW pump power more carefully. The inset in Fig. 3 demonstrates that broadband low-frequency squeezing was generated at sideband frequencies as low as 30 kHz. A few extra noise peaks at 40 and 70 kHz were most likely owing to backscattering of the pump field into the system.

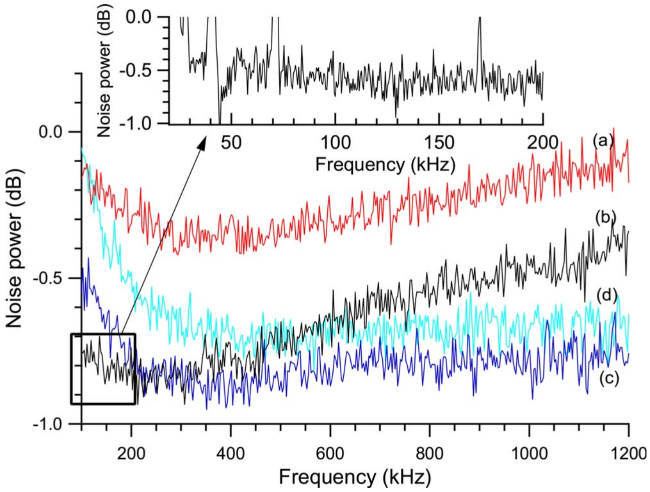

Fig. 3. (Color online) Squeezed quadrature noise versus sideband frequency for different laser power settings. Laser powers are (a) 1.04, (b) 1.54, (c) 4.15, and (d) 6.58 mW. Inset, low-frequency component of squeezed quadrature noise spectrum (b). Shot noise corresponds to 0 dB. The laser is tuned to the maximum squeezing near 100 MHz detuning.

Further improvements in PSR-induced squeezing will require detailed experimental and theoretical analysis of two competing processes affecting the detected fluctuations of electromagnetic field in a squeezing channel: polarization self-rotation itself, and excess spontaneous noise [17,18,22]. Successful observation of squeezing depends on finding the range of experimental conditions when the excess noise is low enough not to overwhelm the squeezing completely. Both theory [15,18] and experiments [22] indicate strong dependence of the spontaneous noise power and spectral composition on the parameters of the experiment, such as Zeeman level structure of the chosen atomic transition, laser intensity, optical depth, presence of a buffer gas, etc. In the present experiment squeezing was observed in the regime of low laser powers and low sideband frequencies not explored in experiments of Hsu *et al.* [18]. Also, the numerical simulations in [15] predict a possibility of a low-frequency squeezing combined with a high-frequency excess noise, although a different interaction scheme was considered. Recently reported measurements of a strong low-frequency relative intensity squeezing by four-wave mixing [23] also indirectly indicate the possibility to overcome the spontaneous noise in Rb vapor.

In conclusion, we successfully demonstrated generation of low-noise broadband squeezing via self-rotation effect in ^{87}Rb at 795 nm, independently confirming the previous proof-of-principle experiments of Ries *et al.* [17]. The maximal measured squeezing value is 0.87 ± 0.02 dB at 400 kHz, and the squeezing was detected in the range of sideband frequencies from 30 kHz to 1.2 MHz. To the best of our knowledge, this is the first demonstration of a submegahertz quadrature-squeezed vacuum in atomic systems. Further improvements are possible with optimization of the system. Such a low-cost method for the generation of low-frequency nonclassical fields near atomic optical resonances may be useful and attractive for various quantum memory tests and applications.

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