Generation of a squeezed vacuum resonant on a rubidium D_1 line with periodically poled $KTiOPO_4$

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We report the generation of a continuous-wave squeezed vacuum resonant on the Rb D_1 line (795 nm) using periodically poled $KTiOPO_4$ (PPKTP) crystals. With a frequency doubler and an optical parametric oscillator based on PPKTP crystals, we observed a squeezing level of -2.75 ± 0.14 dB and an antisqueezing level of $+7.00\pm0.13$ dB. This system could be utilized for demonstrating storage and retrieval of the squeezed vacuum, which is important for the ultraprecise measurement of atomic spins as well as quantum information processing. © 2006 Optical Society of America

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Recently, a novel scheme for mapping the quantum state of a light field onto an atomic ensemble was proposed[1,2] in which the electromagnetically induced transparency (EIT) plays a major role. This "storage of light" technique enables us to overcome the difficulty of localizing photons, which are mainly used as carriers of quantum information. While the storage and retrieval of a single-photon state has already been realized,[3,4] it has not been demonstrated for a squeezed vacuum. It should be noted that the former experiment can be performed conditionally, whereas the latter should be demonstrated in a deterministic manner, and thus is sensitive to field loss. Mapping the squeezed state onto an atomic ensemble is a critical task not only for quantum information processing but also for ultraprecise measurement of atomic spins.

To perform such an experiment, it is necessary to generate a high-level squeezed vacuum resonant on an atomic transition. By utilizing $KNbO_3$ crystals, a squeezed vacuum has already been generated resonant on the Cs D lines (852, 894 nm), and the interaction between the atoms and the squeezed vacuum has also been intensively investigated.[5] However, there have been relatively few experiments done on the generation of a squeezed vacuum resonant on the Rb D lines (780, 795 nm), while Rb has played an important role in quantum information processing along with Cs. So far, maximum squeezing of −0.9 dB has been obtained for 795 nm with quasi-phase-matched $MgO:LiNbO_3$ waveguides.[6] Note that the $KNbO_3$ crystal, which is useful at the Cs resonance line, cannot be utilized at the Rb one.[7] In this Letter, we demonstrate −2.75 dB squeezing at 795 nm using a periodically poled $KTiOPO_4$ (PPKTP) crystal,[7,8] which, to the best of our knowledge, is the highest squeezing obtained at the Rb D_1 line.

Figure 1 shows the experimental setup. A continuous-wave Ti:sapphire laser (Coherent, MBR 110) at 795 nm was employed in this experiment. The beam from the Ti:sapphire laser was phase modulated by an electro-optic modulator (EOM). This

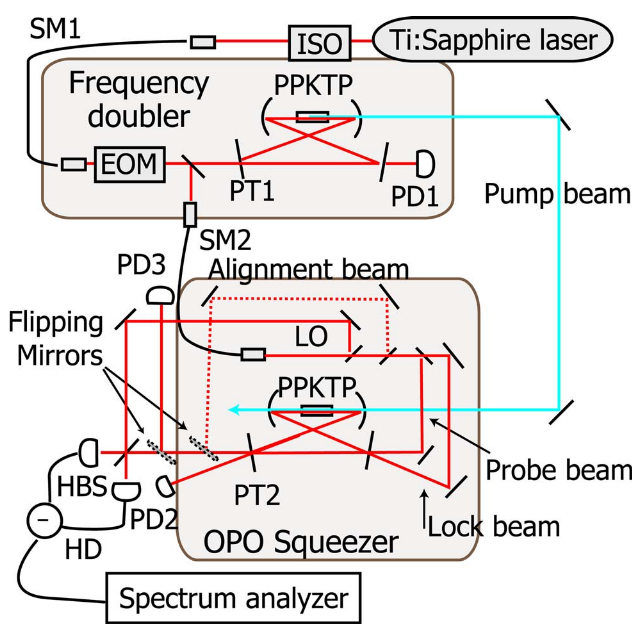

Fig. 1. (Color online) Experimental setup. ISO, optical isolator; EOM, electro-optic modulator; OPO, subthreshold degenerate optical parametric oscillator; HBS, half-beam splitter; PT, partial transmittance mirror; HD, balanced homodyne detector; PD, photodiode; SM, single-mode fiber.

modulation was utilized to lock a cavity for frequency doubling and a cavity for squeezing using the FM sideband method.[9]

The frequency doubler had a bow-tie-type ring configuration with two spherical mirrors (radius of curvature of 100 mm) and two flat mirrors. One of the flat mirrors (PT1) had a reflectivity of 90% at 795 nm, and was used as the input coupler, while the other mirrors were high-reflectivity coated. All the mirrors had reflectivities of less than 5% at 397.5 nm. The round-trip cavity length was $l=520$ mm, and a beam waist radius inside the crystal was 26 μm. A 10 mm long PPKTP crystal (Raicol Crystals) was used for second-harmonic generation. We obtained 105 mW of second-harmonic light for 285 mW of the incident fundamental light. We observed instability of the blue output power when the fundamental light exceeded approximately 300 mW, which is, we believe, due to a strong thermal lensing effect arising from the blue absorption.[10] Utilizing a longer crystal and loosening a beam focusing will lead to better performance.

The generated 397.5 nm beam pumped a degenerate optical parametric oscillator (OPO) that also had a bow-tie-type ring configuration using two spherical mirrors (radius of curvature of 50 mm) and two flat mirrors. One of the flat mirrors (PT2) had a reflectivity of 90% at 795 nm and was used as the output coupler. The round-trip cavity length was $l=600$ mm, and a beam waist radius inside the crystal was 20 μm. A 10 mm long PPKTP crystal was again used for parametric downconversion. The OPO was driven below the parametric oscillation threshold $P_{\mathrm{th}}=150$ mW, which was derived theoretically from the nonlinear efficiency of the crystal $E_{\mathrm{NL}}=0.023\ \mathrm{W}^{-1}$, the intracavity loss $L=0.0173$, and the transmittance of the input coupler $T=0.10$ using the following expression: $P_{\mathrm{th}}=(T+L)^2/(4E_{\mathrm{NL}})$.

The IR beam from the Ti:sapphire laser was split into four beams: an alignment beam, a probe beam, a lock beam, and a local oscillator beam for homodyne detection. The alignment beam was an auxiliary beam, and was used for aligning the cavity, measuring the intracavity loss, and matching the spatial mode of the pump beam with the OPO cavity. For the last application, the alignment beam was converted to a second-harmonic beam using the OPO and was used as a reference beam. This reference second-harmonic beam propagated in the opposite direction to the pump beam and represented the OPO cavity mode. This meant that by matching the spatial mode of the reference beam with that of the pump beam, the pump beam could be matched with the OPO cavity mode.

The probe beam was utilized to measure the classical parametric gain. This was done by injecting the beam into the OPO cavity through a high-reflection flat mirror, and detecting the transmitted probe beam from the output coupler with a photodiode (PD3).

The lock beam was also injected into the cavity through a high-reflection flat mirror in the counterpropagating mode to the probe beam. The transmitted lock beam from the output coupler was detected with a photodiode (PD2), and the error signal for locking the cavity length was extracted using the FM sideband method.

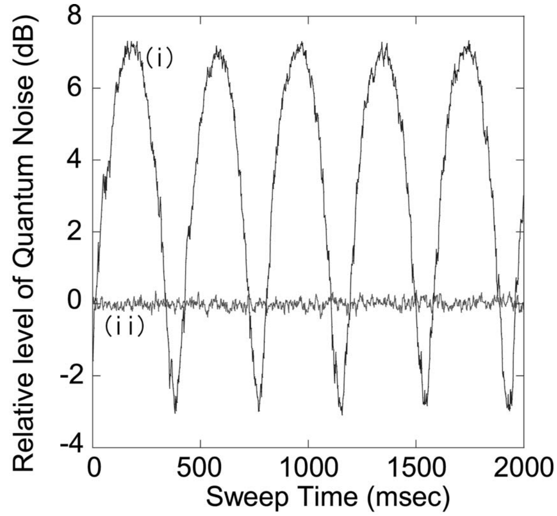

Fig. 2. Measured quantum noise levels. (i) Local oscillator beam phase was scanned. (ii) Shot-noise level. Noise levels are displayed as the relative power compared to the shot-noise level (0 dB). The settings of the spectrum analyzer were zero-span mode at 1 MHz, resolution bandwidth =100 kHz, and video bandwidth=30 Hz.

The generated squeezed light was combined with a local oscillator (LO) at a half-beam splitter (HBS) and detected by a balanced homodyne detector (HD). The HD had two photodiodes (Hamamatsu Photonics, S-3590 with antireflection coating) that had a quantum efficiency of 99%. The output of the HD was measured at the sideband component of 1 MHz using a spectrum analyzer. The circuit noise level of the homodyne detector was 14.0 dB below the shot-noise level.

Figure 2 shows the measured quantum noise levels at a pump power of 61 mW as the local oscillator phase was scanned. The noise level was measured with a spectrum analyzer in zero-span mode at 1 MHz, with a resolution bandwidth of 100 kHz and a video bandwidth of 30 Hz. The squeezing level of -2.75 ± 0.14 dB and the antisqueezing level of $+7.00\pm0.13$ dB were observed, where the standard deviation was estimated from a fitting based on Eq. (1).

The variance of the output mode S can be modeled using[5,11]

$$S=1+4\alpha\rho x\left[\frac{\cos^2\theta}{(1-x)^2+4\Omega^2}-\frac{\sin^2\theta}{(1+x)^2+4\Omega^2}\right],\quad(1)$$

where θ is the relative phase between the squeezed light and LO, and α and ρ are the detection efficiency and the OPO escape efficiency, respectively. The detection efficiency α is the product of the photodiode quantum efficiency η, and the homodyne efficiency ξ^2 (where ξ is the visibility between the output and the local oscillator mode): $\alpha=\eta\xi^2$. The OPO escape efficiency can be written as $\rho=T/(T+L)$, where T and L

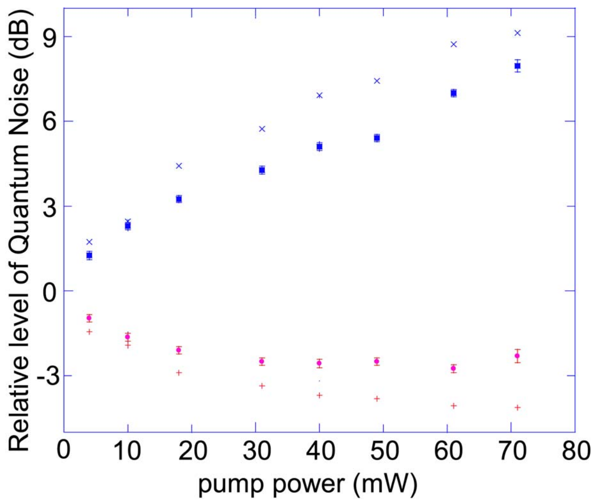

Fig. 3. (Color online) Squeezing and antisqueezing levels for several powers of the pump beam. The ○ and □ indicate measured values, while + and × indicate theoretical values, which are calculated using the parametric gains.

are the transmission of the output coupler and the intracavity loss, respectively. The pump parameter x is defined by the pump power P_{pump} and the oscillation threshold P_{th} and is expressed using the parametric gain G by $x \equiv (P_{\text{pump}}/P_{\text{th}})^{1/2} = 1 - 1/G^{1/2}$. The detuning parameter Ω is given by the ratio of the measurement frequency ω to the OPO cavity decay rate $\gamma = c(T+L)/l$, i.e., $\Omega = \omega/\gamma$, where c is the speed of light.

In our setup, $\eta = 0.99$ and $\xi = 0.91$, therefore $\alpha = 0.82$. $T = 0.10$ and $L = 0.0173$ yield $\rho = 0.85$. Note that our crystal made no measurable difference to the intracavity loss in the presence of the pump beam.[7] The detuning parameter was $\Omega = 0.107$. The classical parametric gain of $G = 5.3$ measured with a 61 mW pump light yields $x = 0.57$. With these values, Eq. (1) predicts theoretical squeezing–antisqueezing levels of −4.4 and +8.9 dB, respectively. These theoretical squeezing–antisqueezing levels become −4.1 and +8.7 dB when one accounts for the effect of the circuit noise.

We repeated the above measurement and analysis for various pump powers. The results are summarized in Fig. 3. There is a similar discrepancy from the theoretical values for both squeezing and antisqueezing data. This discrepancy cannot be explained by simply introducing unknown field loss, because squeezing is theoretically very sensitive to the field loss compared with antisqueezing. In the current setup, the spatial mode of the incident probe beam was not perfectly matched to that of the OPO cavity. Therefore the thermal lens effect caused by injection of the blue pump beam could modify the cavity mode and increase (or decrease) the transmittance of the probe beam. When we measured the parametric gain G, we set the transmittance of the probe beam without the pump beam to unity. If the thermal lens effect discussed above had occurred, the measured parametric gain should be corrected. Introducing an approximately 10% correction for the value of G and considering unknown field loss, the discrepancy between theoretical values and squeezing–antisqueezing data can be explained. The observed squeezing level became slightly degraded when the pump power reached 70 mW, which could be explained by mixing the highly antisqueezed component with the observed quadrature noise due to the temporal fluctuation in the LO phase.

In conclusion, we observed -2.75 ± 0.14 dB squeezing and $+7.00 \pm 0.13$ dB antisqueezing at 795 nm, which corresponds to the D_1 transition of Rb atoms. It should be possible to achieve a higher squeezing level by increasing the visibility of the homodyne system and reducing the phase fluctuation by actively stabilizing the setup. While electromagnetically induced transparency was observed with the squeezed vacuum in our previous work,[6] neither slow propagation nor storage could be realized due mainly to the low squeezing level. The squeezing level obtained in this study was much higher than that previously obtained with the periodically poled lithium niobate waveguide, and thus we believe that storage of the squeezed vacuum should be achievable with the current setup. Note that EIT-based quantum state transfer works in the low-frequency range. To check the performance of our OPO in the low-frequency range, we are now constructing the setup to digitally Fourier transform the differential photocurrent obtained by the balanced homodyne detector.[12]

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