PHYSICAL REVIEW A **81**, 021605(R) (2010)

Quantum memory of a squeezed vacuum for arbitrary frequency sidebands

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(Received 17 May 2009; published 22 February 2010)

We have developed a quantum memory that is completely compatible with current quantum information processing for continuous variables of light, where arbitrary frequency sidebands of a squeezed vacuum can be stored and retrieved using bichromatic electromagnetic induced transparency. The 2 MHz sidebands of squeezed vacuum pulses with temporal widths of 470 ns and a squeezing level of -1.78 ± 0.02 dB were stored for 3 μs in laser-cooled ^{87}Rb atoms. Squeezing of -0.44 ± 0.02 dB, which is the highest squeezing reported for a retrieved pulse, was achieved.

DOI: 10.1103/PhysRevA.81.021605 PACS number(s): 42.50.Gy, 42.50.Dv

Quantum-information processing (QIP) for continuous variables of light has been developed using a squeezed vacuum [1–3]. To generate the squeezed vacuum, a parametric down-conversion process is used, in which a photon having a frequency of $2\omega_0$ is converted to two photons having frequencies of $\omega_0 \pm \Delta$. The resultant squeezed vacuum is an entangled state between two different frequency modes, i.e., the sidebands. The range of Δ is determined by the phase matching condition and the squeezing with the specific value of Δ can be selectively monitored using the homodyne technique, which has been critical to the development of QIP of light [4,5]. In particular, quantum teleportation was successfully demonstrated by monitoring the squeezing with megahertz-order sidebands [4], which prevented signal from being polluted by low-frequency environmental noise.

For the further development of QIP with light, quantum memory is crucial. One promising technique involves the use of electromagnetically induced transparency (EIT). Quantum memories of the squeezed vacuum have been demonstrated using EIT [6,7] and have been investigated in more detail [8–10]. However, these quantum memories operate only when the value of Δ is sufficiently small. This is because a narrow transparency window is essential in order to spatially compress the light pulse inside the atomic medium. In the present Rapid Communication, we propose a method using bichromatic control light, which realizes quantum memory for the squeezed vacuum for an arbitrary value of Δ. Previously reported EIT using bichromatic control light [11] does not provide 100% transparency and cannot be applied to the quantum memory process, whereas our method provides a perfect solution to this problem.

Let us first explain the primary mechanism of the proposed bichromatic EIT from an intuitive point of view (Fig. 1). Here, we assume the probe and control lights to be classical. The intensity of the control light beats due to the interference of the two frequency components. When a single-mode probe light is used, the probe light suffers from absorption, because the intensity of the control light, which induces the transparency, periodically disappears, while the intensity of the probe light is constant. However, using a two-mode probe light, the intensity of the probe also beats. When the phases of the beating for both the probe and control lights are coordinated, 100% transparency can be obtained for the probe light. In contrast, when the beats are out of phase, the probe light are completely absorbed by the atoms.

Next, we explicitly treat the proposed bichromatic EIT for an arbitrary quantum state of the probe field. A two-mode probe light denoted by the annihilation operators $\hat{a}(\omega_0+\Delta)$ and $\hat{a}(\omega_0-\Delta)$, which are $\pm\Delta$ from the resonant frequency, is coupled to the $|b\rangle \to |a\rangle$ transition of each of the N atoms. A bichromatic control light detuned by $\pm\Delta$, having Rabi frequencies of Ω, is coupled to the $|c\rangle \to |a\rangle$ transition. The interaction Hamiltonian of the system is described in an interaction picture by

$$\hat{V} = \hbar g \sum_{j=1}^{N} \hat{a}(\omega_0+\Delta) e^{-i\Delta t} \hat{\sigma}^j_{ab} + \hbar g \sum_{j=1}^{N} \hat{a}(\omega_0-\Delta) e^{i\Delta t} \hat{\sigma}^j_{ab} - \hbar\Omega e^{-i\Delta t} \sum_{j=1}^{N} \hat{\sigma}^j_{ac} - \hbar\Omega e^{i\Delta t} \sum_{j=1}^{N} \hat{\sigma}^j_{ac} + \text{H.c.}, \quad (1)$$

where $\hat{\sigma}^j_{\mu\nu} = |\mu\rangle_{j\,j}\langle\nu|$ is the flip operator of the jth atom between states $|\mu\rangle$ and $|\nu\rangle$, and g is the coupling constant between the atoms and the probe light. In order to clarify the characteristics of this bichromatic EIT system, we introduce the following bosonic operators:

$$\hat{a}_\pm = \frac{1}{\sqrt{2}}[\hat{a}(\omega_0+\Delta) \pm \hat{a}(\omega_0-\Delta)]. \quad (2)$$

The continuous-mode descriptions of modes $\hat{a}_\pm$ are given by

$$\hat{a}_+ = \frac{1}{\sqrt{\pi}} \int_{-\infty}^{\infty} dt\, \hat{a}(t) e^{i\omega_0 t} \cos(\Delta t),$$
$$\hat{a}_- = \frac{1}{\sqrt{\pi}} \int_{-\infty}^{\infty} dt\, \hat{a}(t) e^{i\omega_0 t} \sin(\Delta t), \quad (3)$$

where $\hat{a}(t)$ is the Fourier-transformed operator of $\hat{a}(\omega)$ defined by $\hat{a}(t) = (2\pi)^{-1/2} \int_{-\infty}^{\infty} d\omega \hat{a}(\omega) \exp(-i\omega t)$. The temporal function of $\cos(\Delta t)$ describing mode $\hat{a}_+$ is identical to the beating of the amplitude of the control light due to the interference of the two frequency components.

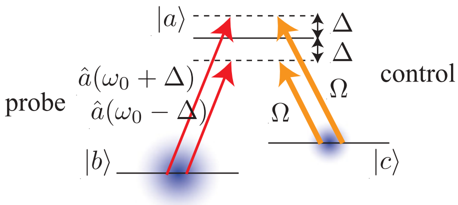

FIG. 1. (Color online) Three-level atoms coupled to two-mode probe light and bichromatic control light.

Using these bosonic operators, Eq. (1) is rewritten as

$$\hat{V} = \sqrt{2}\hbar g\cos(\Delta t)\sum_{i=1}^{N}\hat{a}_{+}\sigma_{ab}^{i} - 2\hbar\Omega\cos(\Delta t)\sum_{i=1}^{N}\sigma_{ac}^{i} + \sqrt{2}\hbar g\sin(\Delta t)\sum_{i=1}^{N}\hat{a}_{-}\sigma_{ab}^{i} + \text{H.c.} \tag{4}$$

Since the first and second terms, which indicate the interaction between the atoms and mode $\hat{a}_+$ and the interaction between the atoms and the control light, have the same time dependence of $\cos(\Delta t)$, there exist dark states for mode $\hat{a}_+$, as well as the conventional EIT with monochromatic control light [12]. In contrast, the interaction between the atoms and mode $\hat{a}_-$ has a time dependence of $\sin(\Delta t)$, and there are no dark states for mode $\hat{a}_-$. This means that the bichromatic EIT renders the medium completely transparent only for the excitation of mode $\hat{a}_+$.

In the following, we describe the relationship between the squeezed vacuum and modes $\hat{a}_\pm$. We treat the two-mode squeezed vacuum of the sideband frequency of Δ defined as

$$|\zeta\rangle = \exp[\zeta^*\hat{a}(\omega_0+\Delta)\hat{a}(\omega_0-\Delta) - \zeta\hat{a}^\dagger(\omega_0+\Delta)\hat{a}^\dagger(\omega_0-\Delta)]|0\rangle, \tag{5}$$

where ζ is the complex squeezing parameter. This can be written in terms of modes $\hat{a}_\pm$ as

$$|\zeta\rangle = \exp\left(\frac{\zeta^*\hat{a}_+^2}{2} - \frac{\zeta(\hat{a}_+^\dagger)^2}{2}\right)\exp\left(-\frac{\zeta^*\hat{a}_-^2}{2} + \frac{\zeta(\hat{a}_-^\dagger)^2}{2}\right)|0\rangle. \tag{6}$$

A two-mode squeezed vacuum is thus represented by the product of the single-mode squeezed vacua at modes $\hat{a}_\pm$. In other words, when a bichromatic control light is used, only the squeezed vacuum for mode $\hat{a}_+$ can be stored in the atoms.

In experiments involving the sidebands of the squeezed vacuum, homodyne detection with a local oscillator (LO) light, the frequency of which is identical to the frequency of the squeezed vacuum, is used and the power of the frequency component corresponding to the sideband frequency is measured. The obtained power is represented by $\langle\hat{X}_\Delta^\dagger(\theta)\hat{X}_\Delta(\theta)\rangle$, where $\hat{X}_\Delta(\theta) = [\hat{a}^\dagger(\omega_0-\Delta)e^{i\theta} + \hat{a}(\omega_0+\Delta)e^{-i\theta}]/2$ is the two-mode quadrature and θ is the relative phase between the squeezed vacuum and the LO. This power can be rewritten with the quadratures of modes $\hat{a}_\pm$, which are

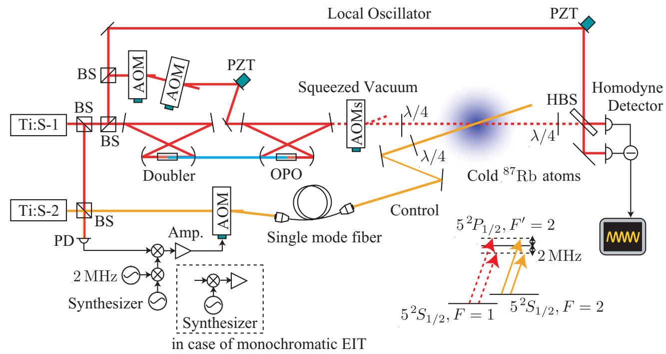

FIG. 2. (Color online) Schematic diagram of the experimental setup. BS: beam splitter, HBS: half-beam splitter, AOM: acousto-optic modulator, PD: photodetector, PZT: piezo electric transducer, Amp: RF amplifier.

defined as $\hat{X}_\pm(\theta) = (\hat{a}_\pm^\dagger e^{i\theta} + \hat{a}_\pm e^{-i\theta})/2$, i.e.,

$$\langle\hat{X}_\Delta^\dagger(\theta)\hat{X}_\Delta(\theta)\rangle = \tfrac{1}{2}\langle\hat{X}_+^2(\theta)\rangle + \tfrac{1}{2}\langle\hat{X}_-^2(\theta+\pi/2)\rangle. \tag{7}$$

Since the both the $\hat{a}_+$ and $\hat{a}_-$ modes contribute to Eq. (7), the optical loss for mode $\hat{a}_-$ degrades the observable squeezing. However, since the temporal function describing mode $\hat{a}_+$ is already known, as shown in Eq. (3), using the time domain homodyne method [13,14], we can selectively monitor the quadrature of mode $\hat{a}_+$. As mentioned above, the quantum memory of the squeezed vacuum for arbitrary sidebands can, in principal, be implemented using bichromatic EIT with no degradation.

The experimental setup is shown schematically in Fig. 2. A laser-cooled atomic ensemble of ^{87}Rb was used as the EIT medium. Here, Ti:sapphire laser 1 was used to generate and detect the squeezed vacuum, the carrier frequency of which was resonant on the $5\,^2S_{1/2}$, $F = 1 \rightarrow 5\,^2P_{1/2}$, $F' = 2$ transition, and Ti:sapphire laser 2 was diffracted by an acousto-optic modulator (AOM) and was used as the control light. The relative frequency between the probe light and the control light was stabilized using the feed-forward method [15]. By adjusting the frequency of the synthesizer, the detuning of the control light could be precisely controlled around the $5\,^2S_{1/2}$, $F = 2 \rightarrow 5\,^2P_{1/2}$, $F' = 2$ transition. When bichromatic control light is used, the synthesizer output was mixed with a sine wave at the frequency Δ, and the bichromatic control light was detuned by $\pm\Delta$. Although the diffraction angles of the AOM for the two frequency components differed slightly, they were coupled to the single-mode fiber, and thus had identical spatial modes when injected into the cold atoms. The probe and control lights were circularly polarized in the same direction and were incident on the cold atoms with a crossing angle of 2.5°. The radii of the probe and control lights were 170 μm and 790 μm, respectively. One cycle of the experiment was 10 ms. Each cycle consisted of a 9 ms preparation period to prepare the cold atoms in the $5\,^2S_{1/2}$, $F = 1$ state and a 1 ms measurement period (for details, refer to [16]). The optical depth of the atoms was approximately eight which was measured by using a single photon counting module.

We first demonstrate experimentally that EIT cannot be achieved for high-frequency sidebands for the case in which a monochromatic control light is used. During the measurement period, the squeezed vacuum was incident on the cold atoms with the control light in a coherent state and having a power of 200 μW. The squeezed vacuum passed through the cold atoms and was measured by the time-domain homodyne method. The measured homodyne signals were imported into a high-speed digital oscilloscope, which had a signal sampling rate of 5×10^7 samples/sec. We evaluated the spectrum of the quadrature noise by squaring the Fourier transform of the obtained data. The relative phase between the squeezed vacuum and the LO was set to $\theta = \pi/2$ or 0 during the preparation period using a weak coherent beam, which had a spatial mode that was identical to that of the squeezed vacuum. During the measurement period, the feedback voltages to the PZTs were kept constant, and this weak beam was turned off using the AOM.

Figure 3(a) shows the observed spectra of the quadrature noise when the frequency of the control light was resonant on the $5\,^2S_{1/2}$, $F = 2 \rightarrow 5\,^2P_{1/2}$, $F' = 2$ transition. Trace (A) indicates the shot noise, and traces (B) and (C) indicate the quadrature noise of the squeezed vacuum in the absence of cold atoms. Traces (D) and (E) indicate the quadrature noise of the squeezed vacuum that passed through the cold atoms due to EIT. Here, the relative phases were $\pi/2$ in traces (B) and (D) and were 0 in traces (C) and (E). Each trace is the average of 1000 measurements. Electromagnetically induced transparency for the squeezed vacuum was observed in the low-frequency region, where 95% transparency was obtained. When the control light is resonant on the transition, each sideband used to construct the two-mode squeezed vacuum undergoes a phase shift of the opposite sign, and thus the effect of the phase shifts is canceled [16]. Figure 3(d) shows the corresponding numerical simulation, where the atomic absorption loss and the phase shift caused by dispersion under the EIT condition were taken into account.

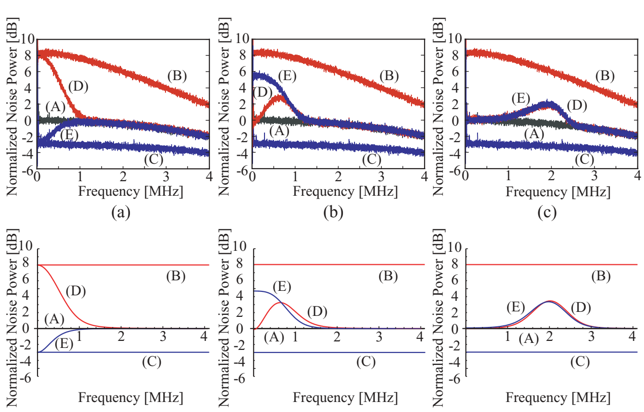

FIG. 3. (Color online) Quadrature noise spectra of the squeezed vacuum incident together with the monochromatic control light, where the frequencies of the control light were (a) resonant on the $5\,^2S_{1/2}$, $F = 2 \rightarrow 5\,^2P_{1/2}$, $F' = 2$ transition, (b) detuned by 500 kHz, and (c) detuned by 2 MHz. (d), (e), and (f) show the numerical simulations of the EIT for the squeezed vacuum shown in (a), (b), and (c), respectively. Traces A, B, C, D, and E are described in the text.

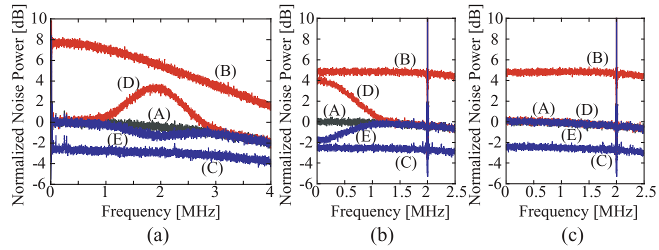

FIG. 4. (Color online) Quadrature noise spectra of the squeezed vacuum incident with bichromatic control light detuned by ± 2 MHz obtained by (a) squaring the Fourier transform of the direct homodyne signals and by (b) multiplying the 2-MHz sine waves having phases that are identical to the phase of the beating amplitude of the control light and (c) the phase that differs from the beating amplitude of the control light by $\pi/2$ before taking the Fourier transform. Traces A, B, C, D, and E are identical to those in Fig. 3.

Figures 3(b) and 3(e) show the experimental results and numerical simulations when the control light was detuned by 500 kHz. Since perfect cancellation of the dispersion effect no longer exists, the noise spectra are completely different. Upon further detuning of the control light [Fig. 3(c), where the control light was detuned by 2 MHz], only one of the sidebands used to construct the two-mode squeezed vacuum passed through the atoms, whereas the other sideband was absorbed. Therefore, the observed quadrature noise exceeded the vacuum noise and was phase insensitive. The corresponding numerical simulation is shown in Fig. 3(f). These results demonstrate that EIT cannot be achieved for the high-frequency sidebands of a squeezed vacuum by simply detuning the control light.

Next, we demonstrate EIT for a squeezed vacuum using bichromatic control light. During the measurement period, the squeezed vacuum and bichromatic control light, which were detuned by ± 2 MHz, were incident on the cold atoms. The frequency components of the control light have the same power, yielding a total power of 200 μW. Figure 4(a) shows the quadrature noise spectra evaluated by squaring the Fourier transform of the homodyne signals, as was done in Fig. 3. In contrast to Fig. 3, both antisqueezing and squeezing were observed around 2 MHz. However, as has already been discussed, absorption for mode $\hat{a}_-$ limited transmission to 50%.

In order to extract the quadrature noise of mode $\hat{a}_+$, we need information about the phase of the beating amplitude of the control light. In the experimental setup, this phase was determined by that of the 2-MHz sine wave mixed with the synthesizer output. We measured this sine wave together with the homodyne signal, which enabled us to determine the temporal function describing mode $\hat{a}_+$. The obtained data of the homodyne signal was multiplied by the 2-MHz sine wave of the temporal function, and the power spectrum was then evaluated [Fig. 4(b)]. The transparency window, which appeared around 2 MHz in Fig. 4(a), was down-converted to the low-frequency region, and the transparency was greatly enhanced (approximately 75%) compared to that of Fig. 4(a). Moreover, the environmental noise in the low-frequency region in Fig. 4(a) was up-converted to approximately 2 MHz and, in contrast with Fig. 3(a), did not appear in the transparency window. The quadrature noise of mode $\hat{a}_-$ was observed

[Fig. 4(c)] using the 2-MHz sine wave, the phase of which differed from that of the beating amplitude of the control light by $\pi/2$. As theoretically predicted, the squeezed vacuum was completely absorbed. Note that mode $\hat{a}_+$ can be monitored using the bichromatic LO [17] if the phase of the beating of the bichromatic LO is set to that of the bichromatic control light.

Finally, we demonstrated quantum memory of the squeezed vacuum with bichromatic EIT. Squeezed vacuum pulses, which were Gaussian with temporal widths of $\tau = 470$ ns, were created from the continuous-wave squeezed vacuum with three AOMs. The residual photon flux at the tail of the pulses was approximately 1%. Note that the bandwidth of the storage is limited by the frequency width of the transparency window [see trace D or E in Fig. 4(b)]. The pulsed squeezed vacuum was incident on the cold atoms together with bichromatic control light and was stored in the atoms by turning off the control light using an AOM. The squeezed vacuum was retrieved after 3 μs by turning on the control light. The homodyne signal data were acquired at a signal sampling rate of 1×10^8 samples/sec. In order to observe the squeezed vacuum pulses at mode $\hat{a}_+$, the obtained data were multiplied by a 2-MHz sine wave and then multiplied by a temporal function corresponding to the retrieved pulse. Finally, they were integrated and squared to evaluate the temporal variation of the quadrature noise of mode $\hat{a}_+$. The temporal function used here was $f(t) = H(t)\exp(-t^2/2\tau^2)$, and $H(t)$ is a step function, which was expected from the experimental results obtained for the storage and retrieval of the pulses in a coherent state. The quadrature noise of mode $\hat{a}_+$ is shown in Figs. 5(a) ($\theta = \pi/2$) and 5(c) ($\theta = 0$), and that of mode $\hat{a}_-$ is shown in Figs. 5(b) ($\theta = \pi/2$) and 5(d) ($\theta = 0$). Traces (A) indicate the shot noise, and traces (B) and (C) indicate the quadrature noise of the squeezed vacuum pulses with no cold atoms and the ultraslow propagation of squeezed vacuum pulses with EIT, respectively. Trace (D) indicates the quadrature noise when the squeezed vacuum pulses were stored and retrieved. Traces (A), (B), and (D) were averaged 900 000 times, and traces (C) were averaged 450 000 times. The observed antisqueezing and squeezing levels for the retrieved squeezed vacuum pulses were 1.80 ± 0.02 dB and -0.44 ± 0.02 dB, respectively. The margin of error was estimated by the standard deviation of the temporal variation of the shot noise due to a small amount of environmental noise.

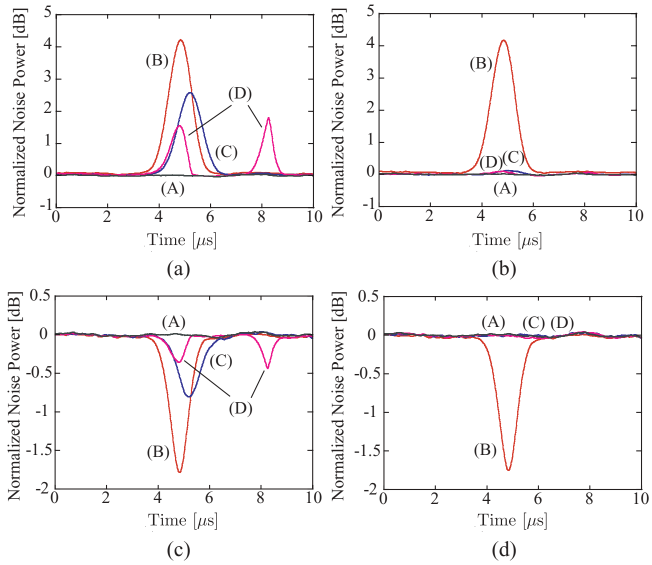

FIG. 5. (Color online) Temporal variation of the quadrature noises of mode $\hat{a}_+$ (left column) and mode $\hat{a}_-$ (right column), where the relative phases between the squeezed vacuum and the LO were set to $\pi/2$ [(a) and (b)] and 0 [(c) and (d)]. Traces A, B, C, and D are described in the text.

In conclusion, we demonstrated a novel type of quantum memory that can be applied to arbitrary sidebands of a squeezed vacuum. This method is robust against environmental noise and is compatible with the current QIP for continuous variables of light. Frequency range where the current technique is applicable will be extended by using an atomic gas cell with Doppler-broadened spectrum [7].

The authors acknowledge the support from the GCOE Program by MEXT through the Nanoscience and Quantum Physics Project of the Tokyo Institute of Technology.

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