Electromagnetically Induced Transparency with Squeezed Vacuum

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The squeezed vacuum resonant on the ^{87}Rb D_1 line (probe light) was injected into an optically dense rubidium gas cell with a coherent light (control light). The output probe light maintained its quadrature squeezing within the transparency window caused by the electromagnetically induced transparency (EIT). The results reported here are the first realization of EIT in the full quantum regime.

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Electromagnetically induced transparency (EIT) is a technique for turning an opaque medium into a transparent one as a result of quantum interference between two excitation processes from independent ground states [1]. The transparent width caused by EIT can be narrower than the natural linewidth, which is why EIT has spawned many applications such as giant nonlinear response [2], ultraslow propagation [3,4], and storage of light [5–7]. While the full quantum treatment of EIT was presented [8], experiments have only been carried out with the coherent lights. In such cases, semiclassical theory adequately explains the phenomenon and one can describe the atom-light system during EIT as a product between the light state (coherent state) and the atomic one (coherent spin state). However, the situation dramatically changes when squeezed vacuum is utilized as a light source because the atom-light system during EIT is no longer in a product state but is in an entangled one. Cutting off the control light makes the entanglement between photons and atoms become that between only atoms [9](squeezed spin state [10]), which could be considered storage of quantum information of light.

Here, we report on an EIT experiment with squeezed vacuum. We injected the squeezed vacuum into an optically dense atomic medium with a coherent light. Squeezing of the output light was maintained only when two-photon detuning was narrower than the natural linewidth, which is a clear sign of EIT. In this Letter, we first describe the detailed experiment results and then give a quantitative explanation based on a two-mode squeeze model.

We generated a cw-squeezed vacuum resonant on the ^{87}Rb D_1 line (795 nm) by using two independent quasi-phase-matched MgO:LiNbO$_3$ waveguides (LN1,2 in Fig. 1) [11]. We employed ridge waveguides, 5.0 μm wide $\times$ 3.0 μm thick $\times$ 8.5 mm long. They are fabricated so that quasi-phase-matching is obtained at room temperature. We coupled 269 mW of linearly polarized light from a Ti:sapphire laser into LN1 with 40% efficiency and generated 54 mW of second harmonic light. We separated the second harmonic light from the fundamental light by using a Pellin Broca prism and a dichroic mirror (DM1). Only the second harmonic light was injected into LN2 with 40% coupling efficiency, by which the squeezed vacuum was generated through the degenerate parametric process. The squeezed vacuum was separated from the second harmonic light by using DM2 and LN2. The power and spectral width of the squeezed vacuum were about 400 nW and 14 nm, respectively. In order to avoid any loss of the squeezed vacuum, we removed Glan laser prisms (GL1,2), $\lambda/4$ plates, and an ^{87}Rb glass cell and directly overlapped the squeezed vacuum with a local oscillator (5 mW) by a beam splitter. We measured quadrature noise of the squeezed vacuum by a balanced homodyne detector (PD1,2) and a spectrum analyzer. The observed squeezing level (-0.9 dB) was independent of the spectrum analyzer center frequency up to 100 MHz because our system has no cavity, unlike the standard optical parametric oscillator. The bandwidth of the squeezing was limited by that of the preamplifier in the homodyne detector. As far as we know, this is the first time wideband squeezed vacuum has been generated in cw mode using MgO:LiNbO$_3$ waveguides.

We employed a pure ^{87}Rb vapor cell filled with 5 torr of ^{4}He buffer gas as the EIT medium. The 10-cm-long, 30-mm-diameter cell was magnetically shielded by threefold permalloy. The temperature was actively stabilized to 48 °C, which corresponds to an atomic density of 1.2×10^{11} cm^{-3}. We employed the D_1 line $5\,^2S_{1/2}$, $F = 2 \rightarrow 5\,^2P_{1/2}$, $F = 2$ transition for control and probe fields. Two circularly polarized lights (control σ^+ and probe σ^-) coupled pairs of Zeeman sublevels of electronic ground state atoms, with magnetic quantum numbers differing by two, via the excited state [Fig. 2(a)].

Before the experiment with squeezed vacuum, we performed EIT with a coherent probe light. We cut the second harmonic light incident on LN2 and injected a weak fundamental light into LN2 by removing the beam block. We employed the 2.3 mW/cm^2 output beam (diameter 1 mm) from LN2 as the probe light. (Because the input power was so weak, one can neglect the effect of second harmonic generation.) The control and probe lights polarized orthogonally to each other were overlapped using GL1 and were converted to σ^+ and σ^- circularly

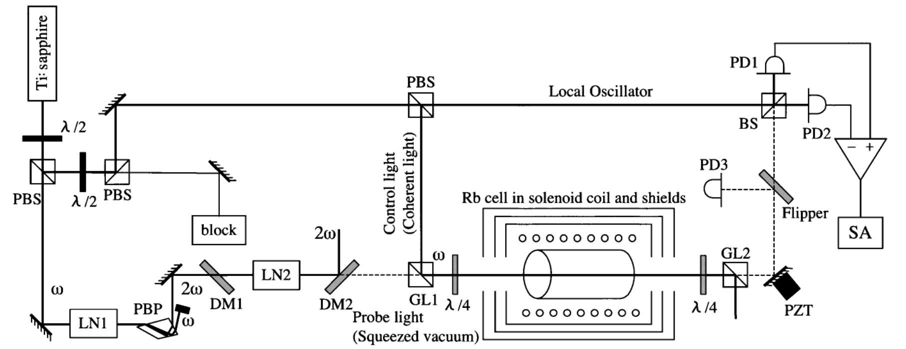

FIG. 1. Schematic explanation of the experiment setup. PBS, polarizing beam splitter; LN, quasi-phase-matched MgO:LiNbO$_3$ waveguide; PBP, Pellin Broca prism; GL, Glan laser prism; BS, beam splitter; PZT, piezoelectric transducer; DM, dichroic mirror; PD, photodetector. SA: spectrum analyzer.

polarized lights by a $\lambda/4$ plate in front of the cell. The intensity of the input control light was 830 mW/cm^2. After passing through the cell, the probe light was separated from the control light by using a $\lambda/4$ plate and GL2. A flipper and a photodetector (PD3) were used to monitor the transmitted intensity of the probe light. When a homogeneous magnetic field is applied to the cell along the light axis using a solenoid coil, energy of $|F = 2, m_z = 2\rangle$ state varies due to the Zeeman effect.

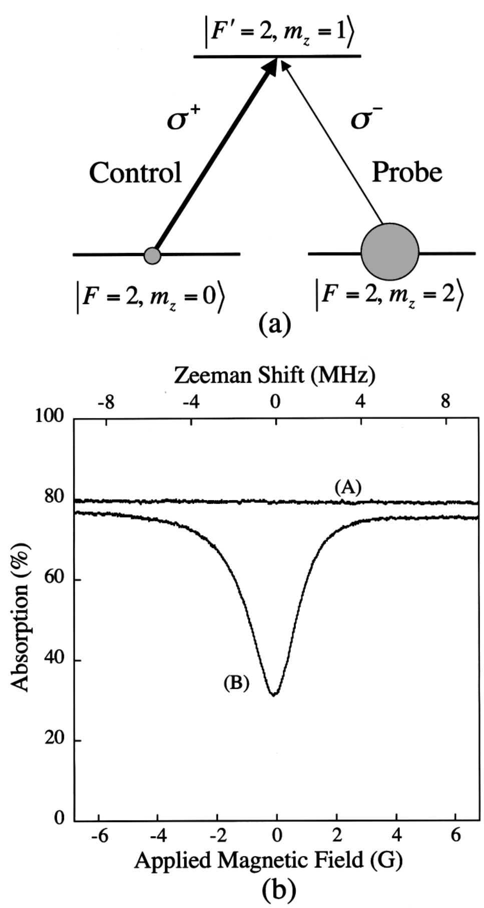

FIG. 2. (a) Λ-type configuration of ^{87}Rb atomic states resonantly coupled to a control field and a probe field. (b) Dependence of absorption of the probe light in the coherent state on the magnetic field applied to the ^{87}Rb cell. (A) Without the control light, (B) with the control light.

Thus one can change the effective two-photon detuning. Figure 2(b) illustrates a typical absorption spectrum for the probe light obtained by scanning the magnetic field. When the control light was cut off, 79% of the probe light was absorbed, independent of the magnetic field [(A) in Fig. 2(b)]. In contrast, when using the control light, the absorption was reduced up to 31% at the zero-magnetic field and the width of the transparency window was 2.6 MHz, which is narrower than the natural line width of ^{87}Rb (6 MHz) [(B) in Fig. 2(b)] [12].

Next, we performed an EIT experiment with the squeezed vacuum. We again blocked the weak fundamental light and injected the second harmonic light into the LN2. The generated squeezed vacuum (10 μW/cm^2) was used as the probe light and injected into the cell with the control light. We measured the quadrature noise of the probe light passing through the cell using the balanced homodyne detector. Figure 3 depicts the results of the balanced homodyne detection with and without the control light, where no magnetic field was applied to the cell and the quadrature noise level was normalized by the shot noise (-69.9 dBm) indicated as a dashed line. The noise was measured with the spectrum analyzer operated in the zero span at a center frequency of 400 kHz, a resolution bandwidth of 100 kHz, and a video bandwidth of 3 Hz. When the control light was cut off, the squeezing of the transmitted probe light was dramatically suppressed [Fig. 3(a)]. Squeezing was restored to -0.18 ± 0.03 dB with the control light, which indicates that the opaque atomic medium became transparent for the squeezed vacuum due to the existence of the control light [13].

One might consider that the experimental results obtained above were due to hyperfine pumping; i.e., the control light pumped almost all atoms in the $F = 2$ ground state to $F = 1$ state and the atomic medium became transparent for squeezed vacuum. In order to check this, we measured the dependence of the squeezing level of the output probe beam on the applied magnetic field [Fig. 4(a)]. Solid circles with error bars represent experimentally obtained squeezing levels for various magnetic fields. The maximum noise reduction was obtained at a zero-magnetic field, where maximum transparency was obtained in the semiclassical experiment [see (B) in Fig. 2(b)]. We also measured the dependence

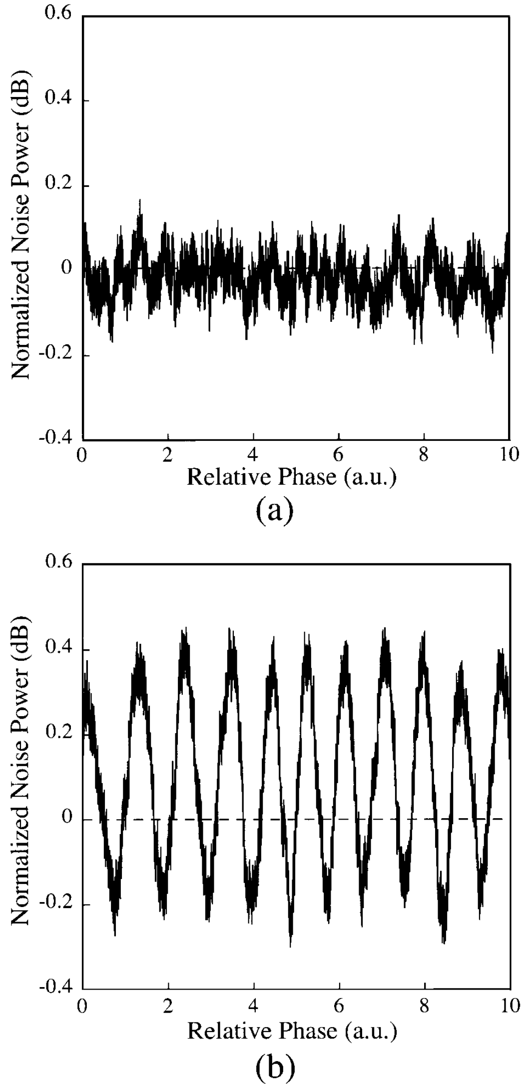

FIG. 3. Balanced homodyne signals of the probe light passed through the Rb cell (a) without the control light and (b) with the control light, where squeezed vacuum was used for the probe light. We normalized the quadrature noise levels by the shot noise ($-$ 69.9 dBm) shown in dashed lines. Relative phase between the probe field and the local oscillator was scanned using a piezoelectric transducer.

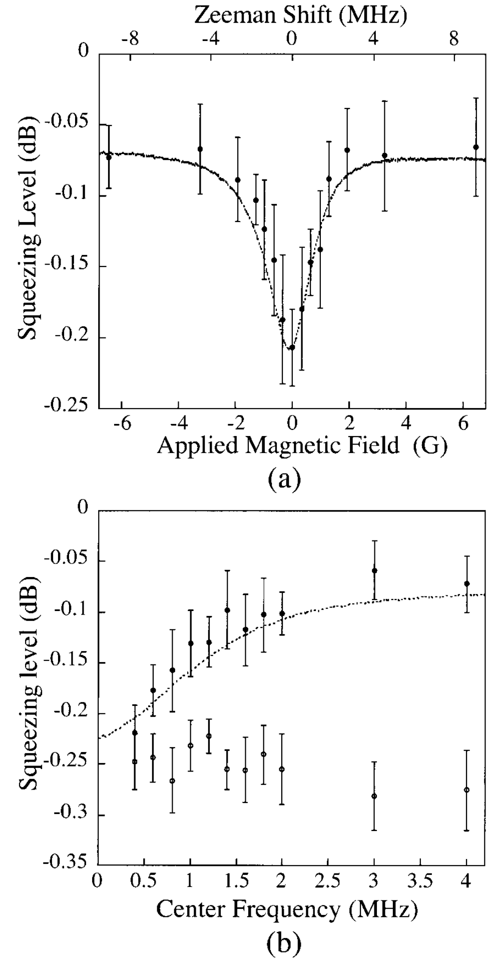

FIG. 4. (a) Measured squeezing level of probe light passing through the cell as a function of the applied magnetic field. (b) Same as (a) but as a function of the center frequency of the spectrum analyzer. The solid circles correspond to the squeezing levels when the laser was resonance (cell temperature 48 °C) and open circles correspond to that when the laser was far off resonance (cell temperature 25 °C). Each error bar represents $\pm$ standard deviation. The curved dotted lines represent numerical results of the squeezing level based on Eq. (2) and the plots (B) in Fig. 2(b).

of the squeezing level of the transmitted probe light on the center frequency of the spectrum analyzer instead of varying the magnetic field [Fig. 4(b)]. Solid circles with error bars represent the squeezing level of the probe light passing through the ^{87}Rb cell under the EIT condition. The squeezing level decreased as the center frequency of the spectrum analyzer increased, which also corresponds to the semiclassical result [(B) in Fig. 2(b)]. Open circles with error bars are data when the cell was cooled to room temperature and the laser was detuned far from the atomic resonance. The squeezing level was independent of the center frequency of the spectrum analyzer [14].

Now we will discuss the results shown in Figs. 4(a) and 4(b). We evaluated the squeezing level of the probe light from spectrum analyzer signals at the center angular frequency of ε. This means we detected not a single-mode but a two-mode squeezed state consisting of two angular frequency components differing by $\pm\varepsilon$ from the local oscillator angular frequency of ω. Therefore in order to estimate the quadrature noise, we introduce a two-mode quadrature operator represented by

$$\hat{\chi}(\varepsilon) \equiv \frac{1}{2}\{\hat{a}(\omega + \varepsilon) + \hat{a}^{\dagger}(\omega - \varepsilon)\}, \tag{1}$$

where $\hat{a}(\omega)$ is an annihilation operator of the probe mode with angular frequency of ω [15]. In order to understand the relation between squeezing level and absorption loss, one has to evaluate the loss of each mode. When $\hat{a}(\omega \pm \varepsilon)$ pass through the absorptive medium with transmittances of $T_{\pm}$, the quadrature noise of the probe light is given by

$$\langle\psi||\Delta\hat{\chi}(\varepsilon)|^2|\psi\rangle = \frac{1}{4}\left\{\left(\frac{T_+ + T_-}{2}\right)\cosh 2r - \sqrt{T_+T_-}\cos\varphi\sinh 2r + \left(1 - \frac{T_+ + T_-}{2}\right)\right\}, \qquad (2)$$

where $|\psi\rangle$ represents the state of the probe light, r the squeezing parameter, and φ the relative phase between the probe light and the local oscillator [16]. We can obtain the values of transmittances T_+ and T_- directly from the experiment results in (B) of Fig. 2(b). The curved lines in Figs. 4(a) and 4(b) represent numerical results of the squeezing level based on Eq. (2) and the plots (B) in Fig. 2(b). The experimental results agree well with the numerical ones, which indicates the transparency in our experiment was caused by EIT not by simple hyperfine pumping from $F = 2$ to $F = 1$.

In summary, we demonstrated EIT with squeezed vacuum. Squeezing was maintained only when the control light was injected into the atomic medium and the obtained transparency window was narrower than the atomic natural linewidth. EIT is a key phenomenon for storing and retrieving quantum information of light. We believe our results obtained here to be a milestone for realizing an atomic quantum memory.

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[9] When a probe light in coherent state $|\alpha\rangle_{\text{light}}$ propagates in a three-level atomic medium as illustrated in Fig. 2(a), the atom-light system during EIT is given by $|\psi\rangle = \exp\{(\alpha\hat{a}^\dagger - \alpha^*\hat{a})\cos\theta)\}|0\rangle_{\text{light}} \otimes \exp\{-\sqrt{N}(\alpha\hat{\sigma}_{ab} - \alpha^*\hat{\sigma}_{ba})\sin\theta\}|b_1\cdots b_N\rangle_{\text{atom}}$, where $|b_1\cdots b_N\rangle_{\text{atom}}$ means N atoms are in spin state $|b\rangle$. $\hat{a}$ is an annihilation operator of the probe field, and $\hat{\sigma}_{ab}$ is the spin flip operator between $|a\rangle$ and $|b\rangle$. θ is a mixing angle and is given by $\tan\theta = g\sqrt{N}/\Omega$, where g is the coupling constant between the atoms and the probe mode, N the number of atoms involved, and Ω the Rabi frequency of a classical control light. In contrast, when a squeezed vacuum $|\xi, 0\rangle_{\text{light}} = \exp\{\frac{1}{2}(\xi^*\hat{a}^2 - \xi\hat{a}^{\dagger 2})\}|0\rangle_{\text{light}}$ propagates in an atomic medium, the atom-light system is given by the following equation: $|\psi\rangle = \exp[\frac{1}{2}\{(\xi^*\hat{a}^2 - \xi\hat{a}^{\dagger 2}) \times \cos^2\theta + (\xi^*\hat{\sigma}_{ba}^2 - \xi\hat{\sigma}_{ab}^2)N\sin^2\theta + (\xi\hat{a}^\dagger\hat{\sigma}_{ab} - \xi^*\hat{a}\hat{\sigma}_{ba})\times \sqrt{N}\sin 2\theta\}]|0\rangle_{\text{light}}|b_1\cdots b_N\rangle_{\text{atom}}$. Cutting off the control light, the system becomes purely atomic state, i.e., two-axis squeezed spin state, $|\psi\rangle = \exp\{\frac{1}{2}(\xi^*\hat{\sigma}_{ba}^2 - \xi\hat{\sigma}_{ab}^2)N\}|0\rangle_{\text{light}}|b_1\cdots b_N\rangle_{\text{atom}}$.
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[12] In this experiment, the probe and control lights were derived from the same laser. Therefore the resolution when measuring the EIT transparency width is not limited by the laser spectral width (less than 50 kHz).
[13] We believe the reduction of the squeezing from -0.9 to -0.18 dB was caused by the following reasons: An absorption loss in EIT at the center frequency of the spectrum analyzer is estimated to be 36% by classical experimental results [(B) in Fig. 2(b)]. Reflection losses at the end facets of the cell and the Glan laser prism are 16% and 7%, respectively. Thus total optical loss is 54%, which corresponds to 0.51 dB reduction of squeezing [see Eq. (2)]. The rest 0.21 dB will be explained by the reduction in homodyne detection efficiency due to the distortion of the spatial profile of the squeezed vacuum which was caused by imperfect overlapping between control light and squeezed vacuum.
[14] In order to perform this experiment, the bandwidth of the squeezed vacuum should be much larger than the transparency width of the EIT (2.6 MHz), i.e., the wideband squeezing is required.
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[16] We model the absorption loss of the squeezed vacuum as a reflection by a beam splitter. The annihilation operator of the electromagnetic field which passed through the beam splitter can be described by $\hat{a}_T(\omega \pm \varepsilon) = \sqrt{T_\pm}\hat{a}(\omega \pm \varepsilon) + i\sqrt{1 - T_\pm}\hat{b}$, where $\hat{b}$ is the annihilation operator for the other incident port of the beam splitter. The fluctuation of the quadrature phase amplitude $\hat{\chi}_T(\varepsilon)$ is given by $\langle\psi||\Delta\hat{\chi}_T(\varepsilon)|^2|\psi\rangle = \langle(\hat{\chi}_T - \langle\hat{\chi}_T\rangle)(\hat{\chi}_T^\dagger - \langle\hat{\chi}_T^\dagger\rangle)\rangle_{\text{Sym}} = \frac{1}{2}\langle\hat{\chi}_T\hat{\chi}_T^\dagger + \hat{\chi}_T^\dagger\hat{\chi}_T\rangle - \langle\hat{\chi}_T\rangle\langle\hat{\chi}_T^\dagger\rangle$, where $\langle\hat{A}\hat{B}\rangle_{\text{Sym}} = \langle\hat{A}\hat{B} + \hat{B}\hat{A}\rangle/2$. Bogoliubov transformation for the squeezing operation is $\hat{a}(\omega \pm \varepsilon) \rightarrow \hat{a}(\omega \pm \varepsilon)\cosh r - \hat{a}^\dagger(\omega \mp \varepsilon)e^{i\varphi}\sinh r$. From these equations, Eq. (2) can be derived.