All atomic generation and manipulation of squeezed vacuum in hot Rb vapor

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We demonstrate a possibility to control the noise spectrum of squeezed vacuum by passing it through Rb vapor under EIT conditions. For this experiment, we generate low sideband frequency (1kHz-2MHz) squeezed vacuum using polarization self-rotation. As an example, we compare the quadrature noise levels to theoretical predictions and observe 'EIT filtering' of the noise due to the finite width of the EIT resonance. This work may lead to the development of a low-cost compact squeezing source for applications in gravitational wave interferometers and continuous-variable quantum memory systems. **OCIS codes: (270.0270) Quantum optics; (270.6570) Squeezed states, (270.1670).**

Quantum squeezing creates quantum-mechanical states of light with non-classical photon statistics, or alters the noise quadratures of a signal (for example amplitude or phase noise). Non-linear interactions with matter can "squeeze" the noise in one light quadrature below the standard quantum limit (SQL), while the other quadrature is stretched in compensation. Squeezed light has many promising applications. For example, it allows improved sensitivity for any interferometer-based measurements, such as gravitational wave detection experiments (LIGO) [1]. It also can be used in continuous-variable quantum information protocols and for testing fidelity of quantum memory systems [2]. Both applications rely on the ability to generate low-bandwidth (down to acoustic band) squeezed light and to manipulate its spectral characteristics to optimize performance. Such required control is possible using the interaction of squeezed light with a resonant atomic medium under the conditions of electromagnetically induced transparency (EIT). Due to its narrow-band transmission and associated controllable dispersion, an EIT medium may serve as a storage medium in quantum memory, and as a frequency-dependent noise filter for a gravitational wave interferometer.

Our experiment is the first of its type to be "all atomic", requiring no expensive or resource-demanding nonlinear crystals or fibers to generate squeezed light. We use a hot Rubidium 87 vapor as the squeezing medium and a diode laser tuned to the $F_g = 2$ to $F_e = 2$ D_1 transition of ^{87}Rb. The squeezed states are generated as a result of the nonlinear polarization self-rotation effect, where the components of elliptically polarized light propagate at different speeds acquiring a phase shift due to their interactions with the atoms [3, 4]. By sending linearly polarized light through the atoms, you can generate squeezed vacuum in the orthogonal polarization. We monitor the squeezed and antisqueezed noise quadratures by combining the vacuum with a strong local oscillator and controlling a phase shift between these fields in homodyne detection. The generated squeezed vacuum field then passes through another vapor cell of ^{87}Rb which serves as the EIT filter.

As squeezed light propagates through an atomic medium undergoing EIT, it experiences frequency dependent losses due to absorption outside of the EIT transmission window. This changes the quadrature noise levels of the signal because any losses in power degrade the squeezing and antisqueezing levels. We can calculate the expected squeezed and antisqueezed noise quadratures ($V_{\pm}$) given the known input noise and EIT transmission by the following equation derived in [1].

$$\begin{pmatrix} V_+ \\ V_- \end{pmatrix} = \begin{pmatrix} A_+^2 & A_-^2 \\ A_-^2 & A_+^2 \end{pmatrix} \begin{pmatrix} e^{+2r} \\ e^{-2r} \end{pmatrix} + \begin{pmatrix} 1-(A_+^2+A_-^2) \\ 1-(A_+^2+A_-^2) \end{pmatrix} \tag{1}$$

Here, $A_{\pm} \equiv \frac{1}{2}(T_+ \pm T_-)$ are the attenuation factors related to the light transmissions ($T_{\pm}$) at positive and negative quantum noise sideband frequencies, and $e^{\pm 2r}$ are the squeezed and antisqueezed input noise quadratures characterized by the squeezing parameter r. Ideally, for a perfectly transmissive EIT, the squeezed and antisqueezed noise levels will match the input noise at the center of the EIT window (0 Hz in our experiment) and noise frequencies outside the window will be attenuated, moving closer to shot noise due to an increased absorption of light by the atoms. By controlling the shape and the width of the EIT transmission window, one can filter the noise of the light signal so that it is squeezed (or antisqueezed) at some desirable frequencies, but not at others. This could be especially useful for gravitational wave detection.

Figure 1b shows experimental results for the minimum and maximum noise levels for squeezed vacuum propagating through EIT compared to the expected noise levels calculated from equation 1. Traces *(i)* and *(ii)* show the maximum and minimum noise levels measured after the squeezing cell but before the light enters the EIT medium. We see in Fig. 1a that the EIT transmission window is fairly wide ($FWHM = 4$ MHz) and so does not have a high contrast between the maximum and minimum transmissions in the region which we measure (0-2 MHz). Therefore, the squeezing and antisqueezing levels (*v* and *vi*) are attenuated due to a peak transmission of less than 100% , but they do not show much frequency dependent filtering in this frequency range. Note the similar attenuation of antisqueezing at all noise frequencies highlighted by the arrows in Fig. 1b. However, using a narrower and more symmetric EIT window ($FWHM = 2$ MHz) results in the noise spectrum shown in Fig. 1d, where frequency dependent attenuation is clearly visible in the squeezed and antisqueezed noise. As we move from

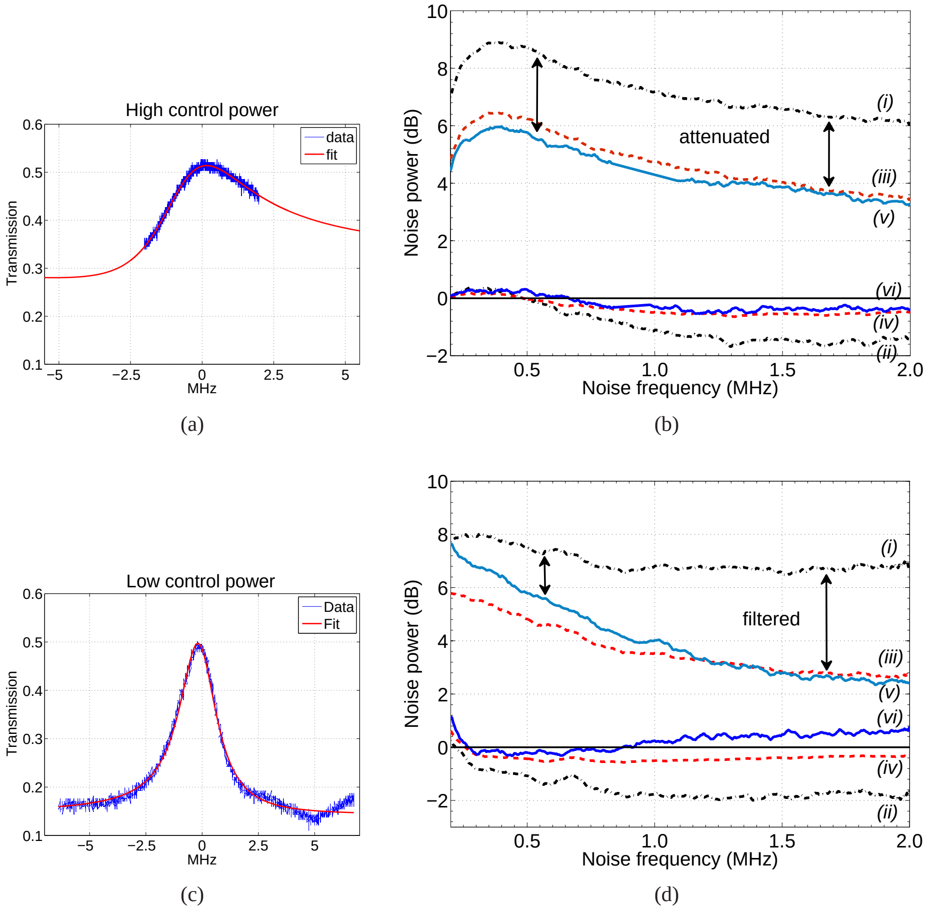

FIG. 1. (a) EIT transmission: FWHM= 4 MHz. (b) Noise spectrum: Laser power= 5 mW. (c) EIT transmission: FWHM= 2 MHz. (d) Noise spectrum: Laser power= 16 mW. *(i) input max. noise, (ii) input min. noise, (iii) expected max. noise, (iv) expected min. noise, (v) measured max. noise, (vi) measured min. noise.*

zero noise frequency, we move onto the wings of the EIT window, and so transmission is lower and squeezing/antisqueezing degrades. In each case, when the control field creating conditions of EIT in the Rb cell was blocked, we measured only shot noise with no phase-dependence because without EIT, the squeezed vacuum is absorbed by the Rb atoms. The expected noise levels (*iii* and *iv*), which are calculated from the input noise and the measured EIT parameters, compare well with the experimental data showing that we are in fact observing a predictable EIT filtering.

We have shown an example of low-pass filtering of squeezed vacuum, which can be improved or altered by changing the EIT parameters, for example peak transmission and EIT width. There are also proposals for creating other types of noise filters such as high-pass, band-pass, and S-shaped filters by using combinations of EIT and EIA (electromagnetically-induced absorption) giving further control over the noise properties of a light signal [1]. Our method has advantages over previous crystal-based experiments which have studied similar low-pass EIT filtering [2, 5] by being all-atomic using two simple vapor cells of Rb, one to produce the squeezed vacuum and one to act as an EIT filter. The main limitations of the experiment come from the less than perfect transmission and contrast of the EIT peak as well as excess noise that can couple into the system at higher laser powers. However these obstacles can be overcome in future studies by finding the best atomic transition to use for EIT and by using separate laser sources for the squeezed beam and the control beam.

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