Propagation of a squeezed optical field in a medium with superluminal group velocity

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Received November 6, 2013; revised January 6, 2014; accepted January 10, 2014; posted January 14, 2014 (Doc. ID 200846); published February 14, 2014

We investigated the propagation of a squeezed optical field, generated via the polarization self-rotation effect, with a sinusoidally modulated degree of squeezing through an atomic medium with anomalous dispersion. We observed the advancement of the signal propagating through a resonant Rb vapor compared to the reference signal, propagating in air. The measured advancement time grew linearly with atomic density, reaching a maximum of 11 ± 1 μs, which corresponded to a negative group velocity of $v_g \approx -7,000$ m/s. We also confirmed that the increasing advancement was accompanied by a reduction of output squeezing levels due to optical losses, in good agreement with theoretical predictions.

OCIS codes: (270.0270) Quantum optics; (270.6570) Squeezed states; (270.1670) Coherent optical effects; (270.5530) Pulse propagation and temporal solitons.

http://dx.doi.org/10.1364/OL.39.001093

Manipulations of the group velocity v_g of light using coherent interactions with resonant atoms and atom-like structures have received much attention due to their numerous applications in quantum information, radar steering, all-optical delay lines, etc [1,2]. Numerous experiments have demonstrated that in a "slow light" medium (with group index $n_g = c/v_g > 1$) both coherent optical pulses and nonclassical optical fields are similarly delayed. In particular, single-photon waveforms [3] and pulses of a squeezed vacuum [4,5] have been delayed via interactions with Rb atoms in electromagnetically induced transparency conditions. However, the propagation of a quantum optical field in a "fast light" medium ($n_g < 1$) raises some interesting fundamental questions, such as the speed of the information transfer via a superluminal quantum field [6–8]. Theoretical analysis has predicted that increasing signal advancements must be accompanied by an unavoidable decrease in the SNR, thus preventing superluminal information transfer.

Here we study the propagation of a squeezed optical field through a ^{87}Rb vapor cell under fast light conditions due to a nonlinear magneto-optical interaction [9]. In these experiments, we let the sinusoidally modulated minimum noise quadrature of a squeezed optical field interact with the Rb vapor and then compare it with the identically modulated quantum field propagating in free space. An example of the measurement is shown in Fig. 1. Our measurements clearly demonstrate the advancement of the quantum noise modulation due to the interaction with the nonlinear medium. We observed an increasing time shift for both the front and back of the modulation envelope with increased atomic density, accompanied by higher incurred losses for the vacuum field in Rb vapor.

The modulated squeezed vacuum is produced in the first Rb vapor cell (squeezing cell) via the polarization self-rotation (PSR) effect [10,11]. This method can be qualitatively described using a simplified four-wave mixing process [12], as shown in Fig. 2. Due to the difference in the transition matrix elements, the strong linearly polarized pump field Ω_{ω_0} couples the two hyperfine excited states ($|c\rangle$ and $|d\rangle$) with two orthogonal quantum superpositions of the ground-state Zeeman sublevels ($|+\rangle$ and $|-\rangle$). The four-wave mixing process, enhanced by the long-lived ground-state Zeeman coherence, induces correlations between the originally independent quantum fluctuations of the orthogonally polarized vacuum field $\alpha_{\omega_0 \pm \omega}$, resulting in quadrature squeezing at the detection

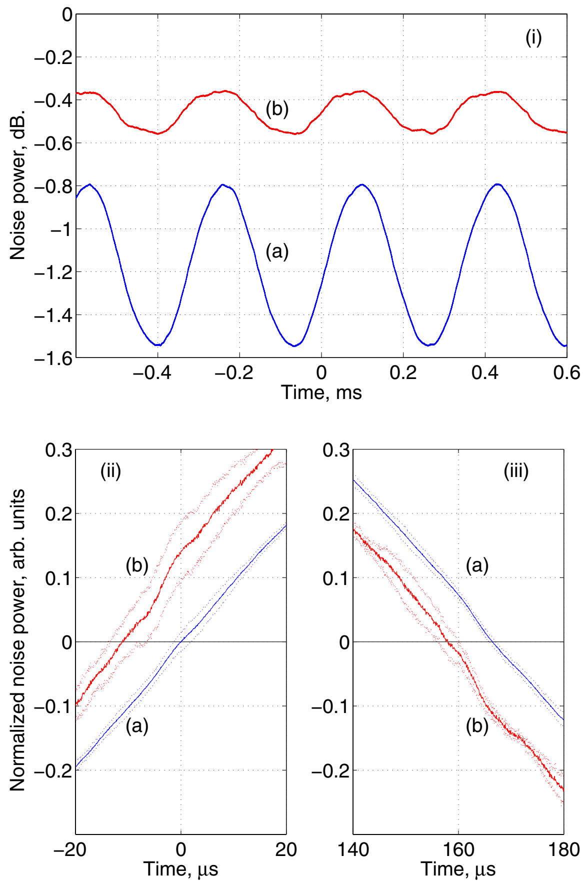

Fig. 1. (i) Example of the modulated squeezed vacuum noise power of the bypass before (a) and after interaction with Rb atoms (b). Zero corresponds to the averaged shot noise level. (ii), (iii) The zoom-ins of the averaged and normalized squeezing traces around the modulation zero crossing.

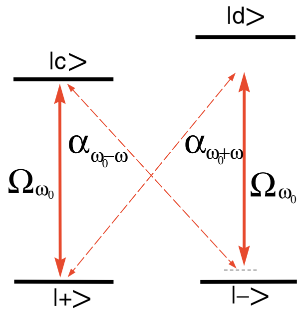

Fig. 2. Simplified interaction scheme for PSR squeezing generation. The two states $|+\rangle$ and $|-\rangle$ represent the orthogonal superpositions of the ground-state Zeeman substates that are involved in the interactions of a linearly polarized pump optical field Ω_{ω_0} with the hyperfine excited states $|c\rangle$ and $|d\rangle$. Here ω_0 is the optical frequency of the pump field. Two optical fields that close the four-wave mixing loop, $\alpha_{\omega_0\pm\omega}$, represent the quantum noise fluctuations of the orthogonally polarized vacuum field at the detection frequency ω.

frequency ω. Previous experiments have demonstrated the generation of $\lesssim 3$ dB of broadband low-frequency squeezed vacuum at several Rb optical resonance frequencies, using only a few milliwatts of pump laser power [13–15].

The degree of squeezing can be reduced by applying a longitudinal magnetic field across the Rb cell, without significantly changing the orthogonal (antisqueezed) quadrature and without rotating the noise ellipse [16]. This can be qualitatively explained using the four-wave mixing picture: the presence of the nonzero magnetic field couples the two ground-states $|+\rangle$ and $|-\rangle$. This deteriorates (or destroys) their mutual coherence and thus eliminates the correlations between the noise sidebands responsible for squeezing.

The general layout for the experiment is shown in Fig. 3. We used an external cavity diode laser tuned and locked to the ^{87}Rb $5S_{1/2}F = 2 \rightarrow 5P_{1/2}F' = 1$ transition frequency using saturation absorption spectroscopy. We ensured the high quality of the spatial mode of the input laser beam by passing it through a single-mode optical fiber; its linear polarization was controlled using a high-quality Glan polarizer (GP). The input laser power was 10 mW. Both "squeezing" and "interaction" vapor cells used in the experiments were 7.5 cm cylindrical Pyrex cells of identical geometry, mounted inside three-layer magnetic shielding. The squeezing cell contained only isotopically enriched ^{87}Rb vapor. The interaction cell, in addition to ^{87}Rb, contained a small amount of Ne buffer gas (2.5 Torr).

The laser beam was focused inside the squeezing cell using a 30 cm lens (L1) to a minimum beam diameter of 100 μm and then recollimated after the cell with the second lens L2 (focal length 40 cm) to a diameter of 1.9 mm. The temperature of the squeezing cell was maintained at (66 ± 0.1)°C. To measure the noise quadratures of the output optical field, we employed a detection scheme [15] that used the strong orthogonally polarized pump field as a local oscillator without separating it from the squeezed vacuum field. The relative phase of the polarizations was controlled by tilting a phase retardation plate (PRP)—a quarter-wave plate with its ordinary axis aligned along the pump field orientation. Then, the polarizations of both optical fields were rotated by 45° using a half-wave plate ($\lambda/2$) and evenly split for two inputs of the balanced photodetector (BPD) using a polarizing beam splitter (PBS), with common noise rejection better than 30 dB. We then used a spectrum analyzer to measure the noise of the BPD output and observed around 1.6 dB noise suppression below the shot noise in the range of detection frequencies from 200 kHz to 2 MHz. To experimentally determine the shot noise level, we used another PBS immediately after the squeezing cell, aligned to transmit the pump field and to reject the orthogonally polarized squeezed vacuum, replacing it with a coherent vacuum.

To measure the group delay, we followed an approach similar to previous experiments [17–19]; however, instead of monitoring the propagation time of a weak coherent optical probe field, we modulated the degree of squeezing by applying a time-varying magnetic field in the squeezing cell and then compared the relative shift of the sinusoidal variation at 3 kHz in the quantum noise propagating through the Rb vapor (in the interaction cell) and in free space (bypass), as shown in Fig. 3. The modulation amplitude (between 0.8 and 1.5 dB below the shot noise) was chosen so that the noise level of the squeezed vacuum field stayed below shot noise at all times. The rotation of the pump polarization due to the nonlinear Faraday effect did not exceed 2.5 mrad. To detect the time dependence on the squeezed quadrature noise power, we utilized a spectrum analyzer as a narrowband filter around the detection frequency of 500 kHz (with a resolution bandwidth of 30 kHz), then monitored the video output of the spectrum analyzer on a digital oscilloscope. A sample noise measurement is shown in Fig. 1, with each trace consisting of 10^6 averages.

The collimated output of the squeezing cell, containing both a strong pump field and squeezed vacuum in two orthogonal polarizations, was directed through the interaction cell. No squeezing occurred in this cell due to its lower atomic density (temperature) and much lower average laser intensity in the unfocussed beam. At the same time, a larger beam size and the presence of the buffer gas increased the time-of-flight of atoms through the laser beam. We can gain some information about the dispersion properties in the interaction cell by measuring its nonlinear magneto-optical rotation (NMOR) signal [9], since the polarization rotation angle ϕ of the linearly polarized optical field is proportional to the magnetically induced circular birefringence of the atomic medium:

$$\phi = \frac{L}{2c}\omega_0[n_+(B) - n_-(B)] \simeq \frac{L}{c}\omega_0\left(\frac{\partial n_\pm}{\partial \omega}\right)_{B=0} g\mu_B B, \quad (1)$$

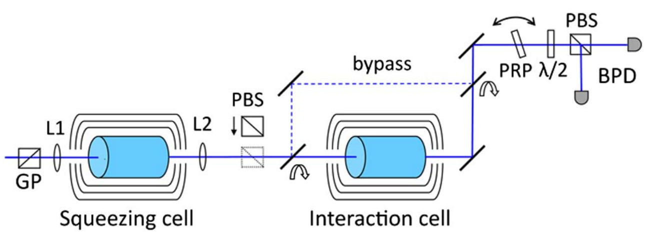

Fig. 3. Experimental setup.

where $\partial n_{\pm}/\partial\omega|_{B=0}$ is the dispersion for the two circular components for zero magnetic field B, L is the length of the atomic medium, μ_B is the Bohr magneton, and g is the gyromagnetic ratio. In the presence of velocity-changing, coherence-preserving collisions with a buffer gas, a typical NMOR rotation spectrum, shown in Fig. 4, clearly indicates two interaction time scales. The broader rotation slope (characteristic width of approximately 2 MHz) is due to the transient interaction of light with one optical transition, connected to the slow light propagation [17]. The narrower feature is due to the atomic diffusion and velocity-changing collisions, resulting in the repeated coherent interactions of light with the atoms via both Doppler-broadened excited state hyperfine components, $F' = 1$ and $F' = 2$ [20]. Such interaction gives rise to the polarization rotation in the opposite direction (compared to the transient effect), indicating an anomalous dispersion with expected superluminal signal propagation. Indeed, the negative dispersion $(\partial n_\alpha/\partial\omega) < 0$ results in the advancement time Δt_a for a weak probe field propagation:

$$\Delta t_a = \frac{L}{c} - \frac{L}{v_g} \approx \frac{L}{c}\left|\omega_0 \frac{\partial n_\alpha}{\partial\omega}\right|. \tag{2}$$

To accurately calculate the dispersion for the broadband quantum noise, one has to consider an interaction system similar to that in Fig. 2, which is beyond the scope of this work. Yet, we can use the NMOR spectrum to qualitatively explain the observed advancement for the modulated quantum noise propagation.

The typical averaged quantum noise signals before and after interaction with Rb vapor are shown in Fig. 1. While the quantum noise modulation after the interaction cell is degraded due to inevitable optical loss, it always stays squeezed, and its shape is well preserved. The data shown corresponds to the maximum measured advancement of $\Delta t_a = 11 \pm 1$ μs for an interaction cell temperature of (50.0 ± 0.1) °C (corresponding to an atomic density of 1.05×10^{11} cm^{-3} [21]). However, it is hard to directly observe the time difference between the two traces, due to the small value of the fractional delay (limited by the slow modulation period of >300 μs), as well as the difference in the squeezing level caused by absorption. To demonstrate the relative advancement more clearly, Figs. 1(ii) and 1(iii) show the normalized modulation signals. The solid curves are the averages of four independent measurements, and the dotted curves represent two standard deviation boundaries. It is easy to see that the advancement is present on both the leading and trailing fronts of one modulation period for the light traveling through the interaction cell as compared with the bypass. We also observed that the detected time difference was not very sensitive to small variations in the local oscillator phase.

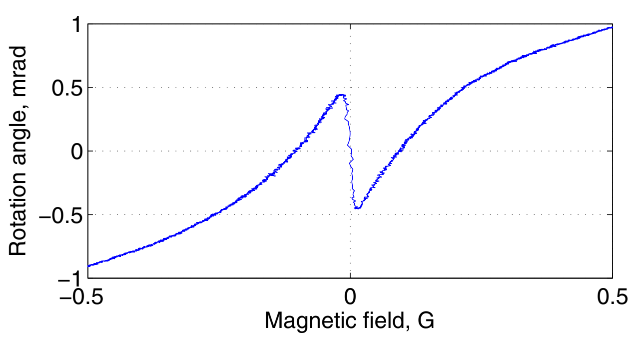

Fig. 4. Example polarization rotation signal as a function of longitudinal magnetic field B in the interaction cell. Only the central part of the wide rotation feature is visible (as an overall positive trend), and the region near zero magnetic field is characterized by a negative slope due to the narrower rotation feature. The laser power is 9.5 mW at the entrance of the interaction cell.

To verify that the observed advancement of the modulated quantum noise was due to the interaction with atoms, we repeated the measurements, varying the temperature of the interaction cell. For each temperature, we collected several traces to average over day-to-day environmental drifts. Figure 5 clearly shows that the observed pulse advancement increases roughly linearly with the atomic density (the dashed line represents a linear fit). However, as expected, the squeezing transmitted through the interaction Rb cell deteriorated at a higher cell temperature due to increased optical losses.

Boyd *et al.* [8] calculated a simple relationship between the pulse advance Δt_a and the noise figure F, which is defined as a change in the SNRs before and after the interaction cell, for a simple absorptive resonance of the width γ as

$$F = e^{2\gamma\Delta t_a}. \tag{3}$$

Figure 6 shows this predicted average noise figure as a function of atomic density given our measured advancements (Δt_a) and the approximate resonance width of $\gamma \approx 2\pi \times 5$ kHz (from Fig. 4). We compare this to the measured noise figure $F = 1/T$, as defined in Ref. [8]. Here, T is the transmission coefficient for the squeezed vacuum through the interaction cell, estimated from the experimental data using a beam splitter model, namely,

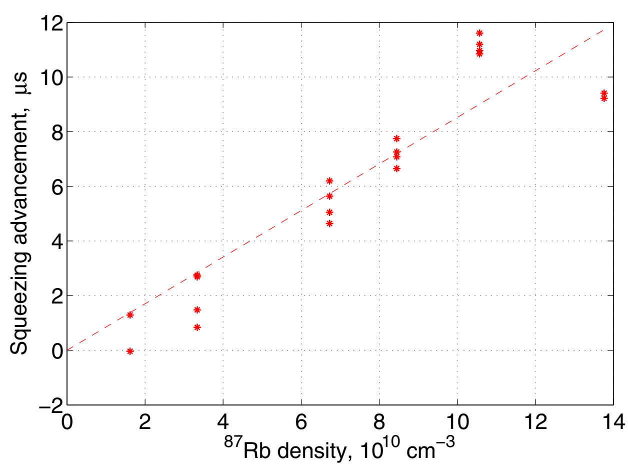

Fig. 5. Measured advancement Δt_a of the modulated squeezed vacuum as a function of the atomic density. The pump laser power before the squeezing cell is 10 mW. Each point represents a time difference extracted from fitting the input and output signals with the sine function. The uncertainties of the individual fits are too small to see.

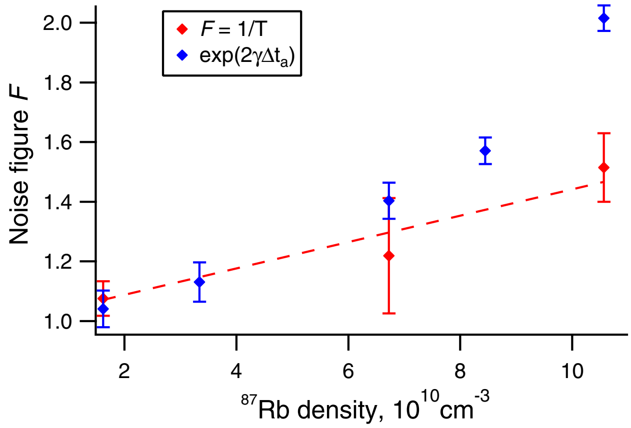

Fig. 6. Noise figure F, based on the estimated transmission of the squeezed vacuum through the interaction Rb cell, and also estimated using Eq. (3) from the measured average group delay, shown in Fig. 5.

$$\hat{a}_{\mathrm{out}} = \sqrt{T}\hat{a}_{\mathrm{in}} + \sqrt{1 - T^2}\hat{u}, \tag{4}$$

where the operators $\hat{a}_{\mathrm{in}}$ and $\hat{a}_{\mathrm{out}}$ represent the input and output optical signal fields and $\hat{u}$ corresponds to the coherent vacuum mode. This equation fits the experimentally measured squeezed noise quadratures for input and output reasonably well. Two points are excluded from Fig. 6 due to some uncertainty in the local oscillator phase, which affected the detected levels of squeezing (but not the detected time difference). Even with the limited number of experimental points, it is clear that the increasing advancement in the modulated quantum noise is followed by an increasing noise figure, and the simple model in [8] is in reasonably good qualitative agreement with the experimental data.

In conclusion, we have successfully demonstrated the transmission of a squeezed vacuum through a resonant Rb vapor, in which negative dispersion was produced by inducing a long-lived Zeeman coherence. We observed that the modulated quantum noise exits the cell earlier than for the analogous signal traveling in free space, indicating superluminal propagation. The amount of advancement increased linearly with the density of the atoms. The largest measured advancement (11 ± 1 μs) corresponds to a negative group velocity of $\approx -7{,}000$ m/s. The increased advancement was accompanied by the deterioration of squeezing due to optical losses, and the measured increase in the noise figure was in good qualitative agreement with the theoretical predictions of Ref. [8] and recent experiments with bright two-mode squeezed twin beams in a "fast light" atomic medium [22,23].

This research was supported by AFOSR grant FA9550-13-1-0098.

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