Propagation of quantum optical fields under the conditions of multi-photon resonances in a coherent atomic vapor

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ABSTRACT

We experimentally investigate a weak optical probe pulse propagation under the EIT conditions through a hot Rb vapor cell, and analyze the quantum noise modification resulting from interaction with atoms. We focus on understanding the sources of excess noise, observed after the EIT vapor cell in the case of both squeezed vacuum and coherent optical probe fields. We show that a small non-zero average amplitude of the probe field (due to imperfect polarization filtering) gives rise to a phase-sensitive excess quantum noise that grows with atomic density.

Keywords: quantum noise, electromagnetically induced transparency, squeezed vacuum

1. INTRODUCTION

In recent years, an increasing number of applications have improved their performance by harnessing the quantum mechanical properties of light. Quantum cryptography protocols rely on absolute security of data transmission encoded in quantum states of light.[1,2] Realization of long-distance quantum networks requires development of tools for manipulation and storage of quantum states.[3–5] Further, measurements with sensitivity beyond the standard quantum limit are possible[6–8] by replacing a standard laser probe with an optical field possessing modified quadrature noise, such as squeezed light .[9] Additionally, quantum sensors may surpass their classical counterparts by using new measurement protocols based on quantum mechanical operators.[10]

Many of the proposed and demonstrated realizations of these techniques require fundamental understanding of the interaction of quantum light with a resonant coherent atomic medium, in particular Rb vapor under the conditions of electromagnetically induced transparency (EIT).[11–13] Under ideal EIT conditions, a strong control field is used to modify the coupling of a resonant signal field to a long-lived collective spin state (spin wave), resulting in lossless propagation of the signal. EIT-based quantum memory[14] (and some of the alternative memory protocols[15]) are based on reversible mapping between an optical signal and an atomic spin wave by means of dynamic variation of the control field intensity. In practice, however, there are many factors – both fundamental and practical – that degrade ideal EIT performance.

The transmission of continuous-wave (cw) squeezed light under EIT conditions,[16–18] and slow[19] and stored light [20–22] for squeezed pulses has been successfully demonstrated; however, in all cases, some deterioration of output signal is reported. Residual optical loss due to imperfect EIT is only one of the factors contributing to reduced squeezing after interaction with atoms. Spontaneous emission due to imperfect ground state preparation, nonlinear wave-mixing, and other contributing processes may also cause excess noise in the squeezing channel.[18,23] This excess noise can noticeably deteriorate and even destroy any non-classical correlations in the probe beam, although some exceptions have been reported.[24] Thus, a better understanding of the properties leading to atom-induced noise is an important experimental task, since the complete theoretical quantum description is challenging.[25]

Efficient coupling of light via coherent atomic resonances requires that the spectral bandwidth of non-classical fluctuations falls within a sub-MHz width of a typical EIT resonance. A quadrature-squeezed light based on polarization self-rotation in Rb vapor is an excellent source of such low-frequency squeezing.[26,27] This method relies on strong cross-phase modulation between two circularly polarized fields co-propagating in a resonant atomic medium and leads to classical polarization rotation of elliptically polarized light.[28,29] If the incoming

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field is linearly polarized, the same nonlinear interaction modifies the quantum fluctuations of a vacuum field with orthogonal polarization, which becomes squeezed.[30–33] Our group has recently demonstrated up to 2.5 dB of low-frequency (< 10 kHz) broadband vacuum squeezing at optical frequencies of the ^{87}Rb D1 line.[8,30]

Here we experimentally investigate propagation of a squeezed vacuum or coherent vacuum optical probe through a hyperfine EIT Rb vapor. Our results suggest that non-zero average intensity in a probe "vacuum" field results in additional phase-dependent noise at the output, that seems to be proportional to the leaked field intensity and atomic density.

2. EXPERIMENTAL ARRANGEMENTS

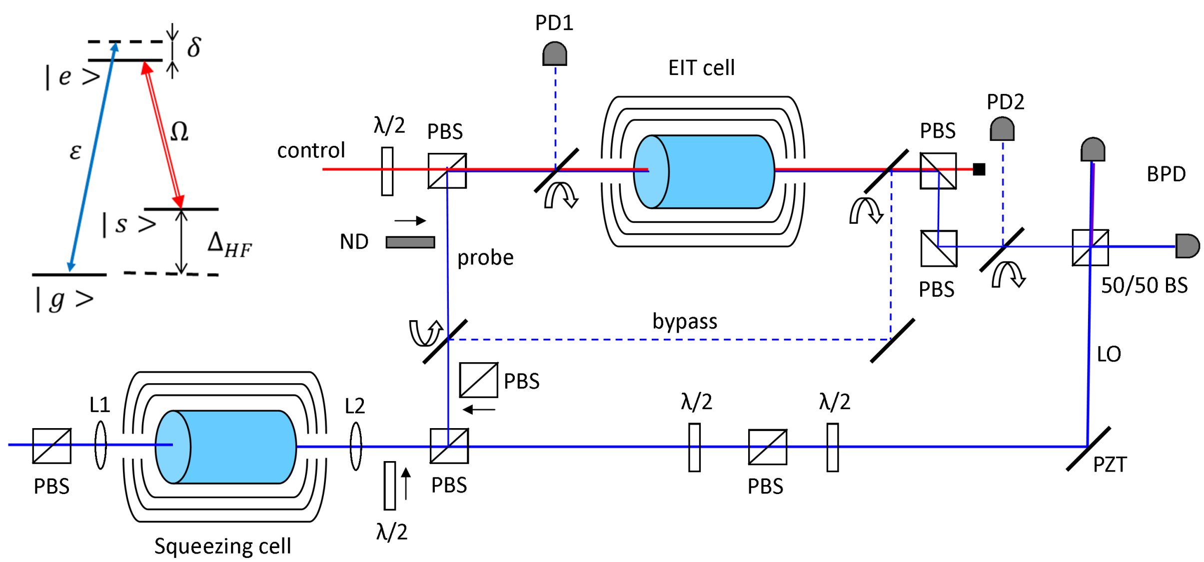

Figure 1. Experimental setup

The experimental setup for squeezed vacuum generation and quantum noise studies is shown in Figure 1. We used a TOptica DL100 external cavity diode laser as a pump laser for squeezing generation, as well as the local oscillator for the homodyne detection. For the reported measurements the laser was locked at $F = 1 \to F' = 1$ transition using saturation absorption spectroscopy technique.

2.1 Squeezing generation

A part of the original laser beam was used to pump the squeezing cell and sent through a single mode fiber to ensure good spatial mode quality. A high quality Glan-Thompson polarizer, with the transmission axis oriented horizontally, was used to clean up the polarization. A 40 cm lens (L1) focused the beam inside a Pyrex cylindrical cell (length 7.5 cm and the diameter 2.2 mm) filled with isotopically enriched ^{87}Rb vapor; the second 30 cm lens (L2) placed after the cell was used to recollimate the beam. The cell was placed inside a 3-layer heated magnetic shield to eliminate any effects of stray laboratory magnetic fields. During the experiment the temperature of the innermost layer of the shield was maintained at $(74.4 \pm 0.5)^o$C. A polarizing beam splitter (PBS in Figure 1), placed after the cell, separated the orthogonally polarized squeezed vacuum field and the pump beam.

In these conditions and using a 14 mW pump beam we observed approximately 1 dB of squeezing in the range of detection frequencies from 500 kHz to 1.5 MHz. As in the previous experiments[31] the other noise quadrature contained 10 dB of excess noise.

To calibrate the shot noise and to compare the output quantum noise for squeezed and coherent optical fields, we had an option to suppress squeezing in the probe channel by placing an additional vertically-polarized polarizing beam splitter in this channel, producing a coherent vacuum traveling along the squeezing path. When more coherent power was needed (i.e., for alignment purposes), we used a removable half-wave plate placed before the first PBS to slightly rotate the pump beam polarization sending a small fraction of its power into the squeezing channel.

2.2 Realization of the control field for EIT measurements

The generated squeezed vacuum field or a weak coherent field was then directed into the second vapor cell ("EIT cell") as a probe optical field. The hyperfine configuration, used in the experiment, thus required an additional strong coherent optical control field, frequency up-shifted by the ground-state hyperfine splitting of ^{87}Rb (6.834 GHz), as shown in the inset on Fig. 1. Since high-quality EIT requires good phase coherence between probe and control fields, we used an injection-locking arrangement to derive the control field with sufficient power from the original laser. A part of the original beam generated by the master laser was sent trough an EOM modulator driven at 6.754 GHz. This produced two sidebands separated from the carrier by the modulation frequency. We then double-passed the beam trough a temperature-controlled etalon with FSR = 20 GHz, temperature-tuned to transmit only the one modulation sideband, and reflect the carrier field and the other sideband. The selected sideband was then injected through an optical isolator into a slave laser (JDSU SDL-5431-G1 laser diode in a Thorlabs temperature-stabilized laser mount). The output of the slave laser was taken from the reflective port of the optical isolator and sent through an AOM modulator driven at 80 MHz. The AOM was tuned to maximum efficiency for the sideband separated from the carrier by 6.835 GHz, which is the required frequency to produce EIT. Such a double-modulation arrangement vs. direct modulation of the EOM at 6.835 GHz was chosen to minimize the interference between any leaking carrier field and the probe beam, since there was a lot less power of the original carrier after the AOM. After that, the beam was also sent through a single-mode optical fiber to clean its spatial profile. It is colored in red and labeled as control in the Fig. 1.

2.3 EIT characterization

The EIT cell, geometrically identical to the squeezing cell, contained isotopically enriched ^{87}Rb and 2.5 Torr of Ne buffer gas. It also was placed inside a heated 3-layer magnetic shield with accurate temperature control. Before the EIT cell, the probe (squeezed or coherent) with diameter $\approx 200\ \mu$m, and control beam with diameter ≈ 5 mm, were combined on a polarizing beam splitter; similarly, after the cell they were separated using a pair of polarizing beam splitters, as shown in Fig. 1.

To characterize the EIT spectrum we monitored a transmission of a weak coherent optical probe (power $< 10\ \mu$W) using two flip mirrors and a pair of identical photodetectors placed before and after the cell (labeled PD1 and PD2). An example of the observed EIT peak is shown in Fig. 6(a). The two-photon detuning between the probe and control was swept through the EIT resonance by changing the EOM modulation frequency around the ^{87}Rb hyperfine splitting 6.83467 GHz. The power of the control laser affected two important parameters: EIT linewidth and residual absorption. Lower control power resulted in narrower transmission resonances, that were desired for quantum noise filtering applications.[34,35] At the same time, larger residual absorption deteriorated squeezing and made this regime unpractical. The chosen control power of 5.4 mW was somewhat a compromise between these two conflicting issues, and resulted in the EIT linewidth of 250 kHz, as shown in Fig. 2(a).

The observed asymmetry was likely caused by two factors. First, we chose the frequency of the laser to correspond to the maximum value of squeezing, which was detuned by 100 MHz to the blue from the $F = 1 \rightarrow F' = 1$ resonance, and non-zero one-photon detunings are known to make EIT resonances less symmetric.[36] In addition, we observed noticeable four-wave mixing gain[37] in the probe field at higher atomic densities, and it is possible that it was affecting the EIT resonance even at the lower temperatures.

2.4 Quantum noise detection

To detect quantum noise we sent the probe beam onto a 50/50 non-polarizing beam splitter and combined it with the local oscillator. The resulting beams were detected by a balanced photo-detector (BPD). By using the BPD in a homodyne detection scheme, classical amplitudes of the beams were subtracted, leaving only the amplified

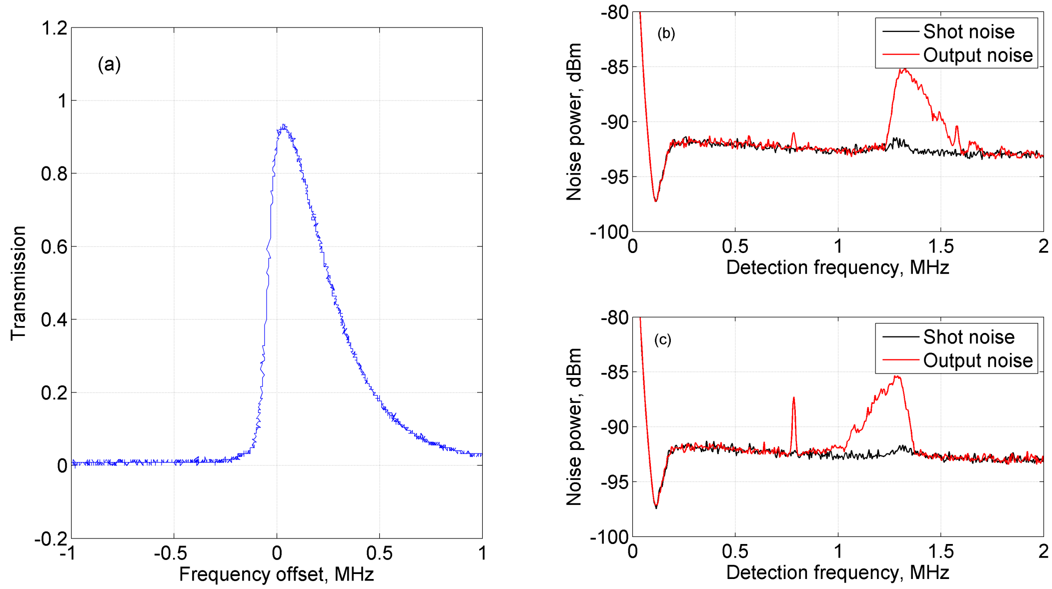

Figure 2. (a) EIT lineshape recorded using a 10 μW coherent probe; (b,c) EIT lineshape recorded using quantum noise measurements, detuning was ± 1.3 MHz.

vacuum fluctuations. The signal was then sent to either a spectrum analyzer or a digital oscilloscope with the FFT function. When using the spectrum analyzer we were able to scan the squeeze angle by tuning the voltage on the PZT mirror in the local oscillator path. Another option was to lock the angle to the desired quadrature using a noise locking technique.[38] Often it was preferable to continuously scan the angle because the noise lock resulted in less detected squeezing.

3. QUANTUM NOISE MANIPULATIONS USING EIT RESONANCES

One of the important motivations for our research is to use EIT or other coherent resonances for quantum noise manipulations, such as spectral filtering.[34,35] Figures 2(b,c) show one example of EIT effect on output quantum noise, which can be potentially used for noninvasive noise spectroscopy.[39,40] For these measurements we detuned the control field frequency (i.e., the EOM modulation frequency) by ± 1.3 MHz away from the two-photon resonance. In this case only the part of the noise spectrum that falls within EIT resonance is transmitted. Any photons at frequencies outside of the transparency window are absorbed, and thus quantum fluctuations for the remaining spectrum are replaced with coherent vacuum. It is easy to see that the shape of the transmitted noise accurately repeated the EIT lineshape, measured with a coherent probe for the positive noise two-photon detuning; for the negative two-photon detuning the shape is reversed, since the low-frequency noise sideband is transmitted. It is also interesting to note, that such filtered quantum noise lacked any dependence on the phase of the local oscillator. Indeed, the phase-dependence in the noise quadratures at a given frequency arises from the interference between the local oscillator with positive and negative noise sidebands, and in the case of such off-resonance EIT filtering only one sideband was transmitted.[39]

To realize a quantum noise filter that preserves the below-shot noise fluctuations within a certain spectral window, the carrier frequency of the probe field must be tuned in exact resonance with the control laser. In this case we expect that the low-frequency part of the spectrum will be transmitted through the EIT transparency with little deterioration, while the higher-frequency quantum noise will be absorbed by the atoms and reduced to the coherent vacuum level.[35] However, the observed experimental results were quite different. For example, Fig. 3(a,b) demonstrates the measured phase-dependent quantum noise at the output of the EIT cell when the probe field was the squeezed vacuum. At room temperature, atomic absorption was very small both with and

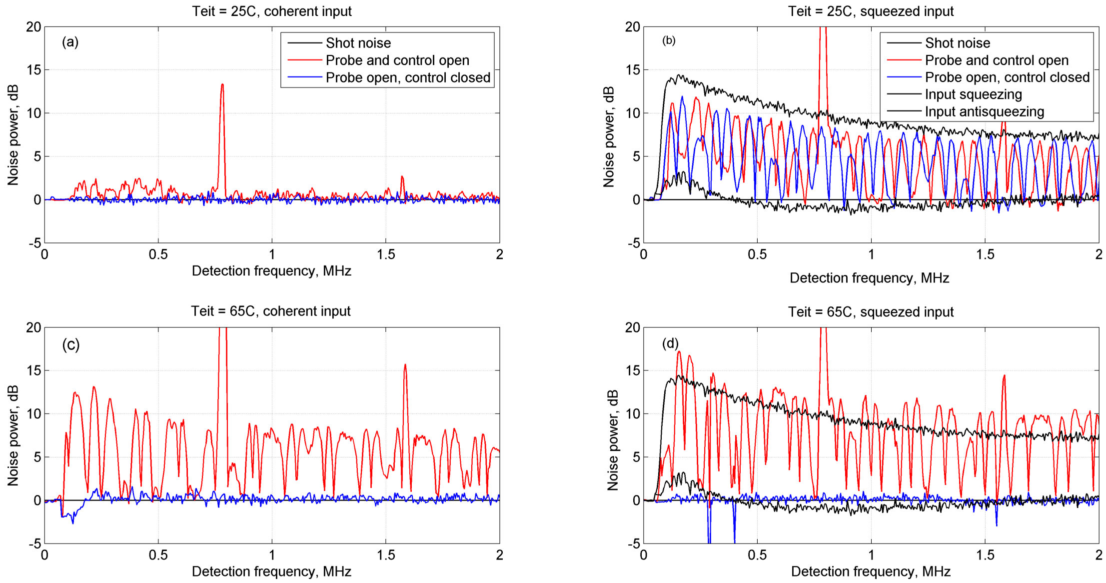

Figure 3. Detected quadrature noise powers: (a,c) coherent input; (b,d) squeezed input. Zero corresponds to the shot noise level. All traces except the input squeezing traces were taken with the squeeze angle scanned.

without EIT conditions, and the input squeezed probe was transmitted with no modifications at all detection frequencies. For high temperatures however, the quantum noise above 250 kHz [EIT resonance FWHM, see fig. 2(a)] was expected to drop to the shot noise level. Instead, we observed a strong phase-dependent noise for all detection frequencies.

The natural question arose if this noise was somehow influenced by the excess quadrature noise produced in the squeezing cell, and then modified by the atoms in the EIT cell, or was due to an independent mechanism. To answer this question, we repeated the same measurement with an additional polarizer in the squeezing channel, oriented such that it blocked the vertically polarized squeezed light, and transmitted only coherent vacuum. In this case, for low temperatures the measured noise level dropped to the shot noise limit as expected, but for higher temperatures we observed the same phase-dependent excess noise as in the case of the squeezed probe field, thus confirming that the origin of this noise was independent of the quantum state of the input field. In general, the maximum quadrature noise increased with atomic density as shown in Fig. 5.

It is also interesting to note that this noise was observed only when both probe and control field were present. Blue traces in Fig. 3 show the output probe noise with the control field blocked. In this case, for the coherent field we always measured the signal at the shot noise limit, and in the case of the squeezed probe the attenuation of the input quadrature noise was consistent with the resonant Rb absorption. We also noticed that if the probe channel is physically blocked by an opaque object, such that the input probe field was truly coherent vacuum, the measured noise also never deviated from the shot noise.

The latter observation suggested that the observed excess noise can be connected to non-zero intensity leakage of the pump field at the polarization filtering stage after the squeezing cell. In the particular experiment configuration described above, after the squeezing cell the vertically polarized pump beam was transmitted and the horizontally-polarized squeezed field was reflected to avoid residual optical losses in the transmission channel. However, in this case a small fraction of the strong pump field was also reflected into the squeezing channel, creating some non-zero average power of $\approx 0.5\ m\mathrm{W}$.

To verify the hypothesis that this leaked light was responsible for the observed noise, we repeated the output noise measurements with a polarizing beam cube in place to eliminate input squeezing, and added progressively increasing neutral density filters to even further suppress the probe power. The results are shown in Fig. 4. It

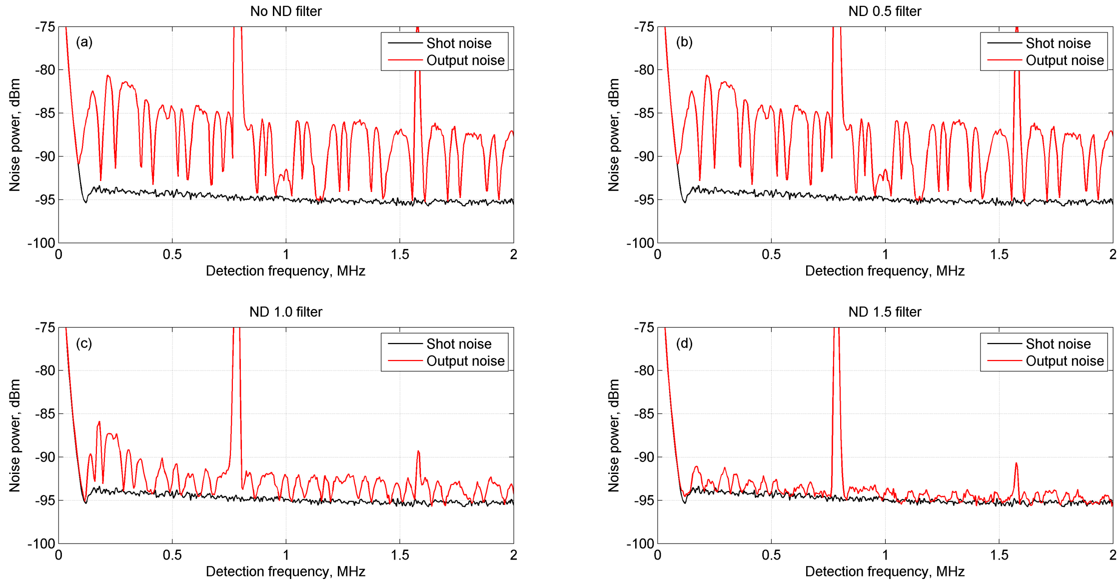

Figure 4. Excess noise power for different coherent probe input powers. Zero corresponds to the shot noise level. Maximum probe power is 0.5 μW and determined by the quality of the polarization filtering, and then further reduced by neutral density filters (ND).

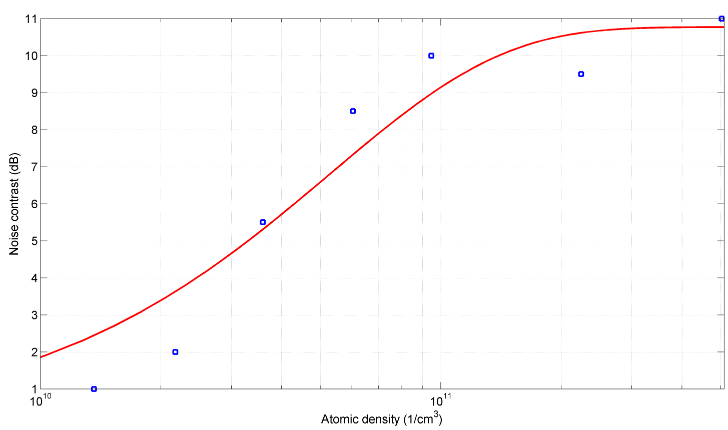

Figure 5. Maximum excess noise level, detected at 1 MHz detection frequency as a function of atomic density. The red line is to guide the eyes.

is obvious that the amplitude of the phase-dependent noise was proportional to the power of the seeded probe field.

While the exact process leading to the appearance of such noise is unknown, we speculate that a four-wave mixing may lay in its origin. This hypothesis is consistent with our experimental observations, including clear dependence of the maximum noise on the density or Rb atoms in the EIT cell. Our previous theoretical calculations[41] clearly showed that at sufficiently high optical depth the gain associated with the four-wave mixing process will result in the deterioration of squeezing, and the addition of excess noise in both probe and Stokes optical fields.

4. MODIFICATION OF THE EXPERIMENTAL SETUP

While it may be possible to suppress the four-wave mixing by carefully choosing the optical transitions and polarizations of the probe and control field, this puts too many restriction on the experimental configuration. Instead we chose to modify the experimental setup to maximally avoid the leakage of the coherent photons into the squeezed probe channel. To do that, we switched the polarization direction of the pump field in the squeezing cell, such that the squeezed field is now transmitted through a high quality output polarizer. Even though we degrade the squeezing level a little, since the transmission of this channel is only 95 %, we are now able to keep the leakage to the minimum. Also, we have have changed the transition to $F = 2 \to F' = 2$. Although this configuration leads to smaller EIT peak transmission, it seems to effectively suppress four-wave mixing.

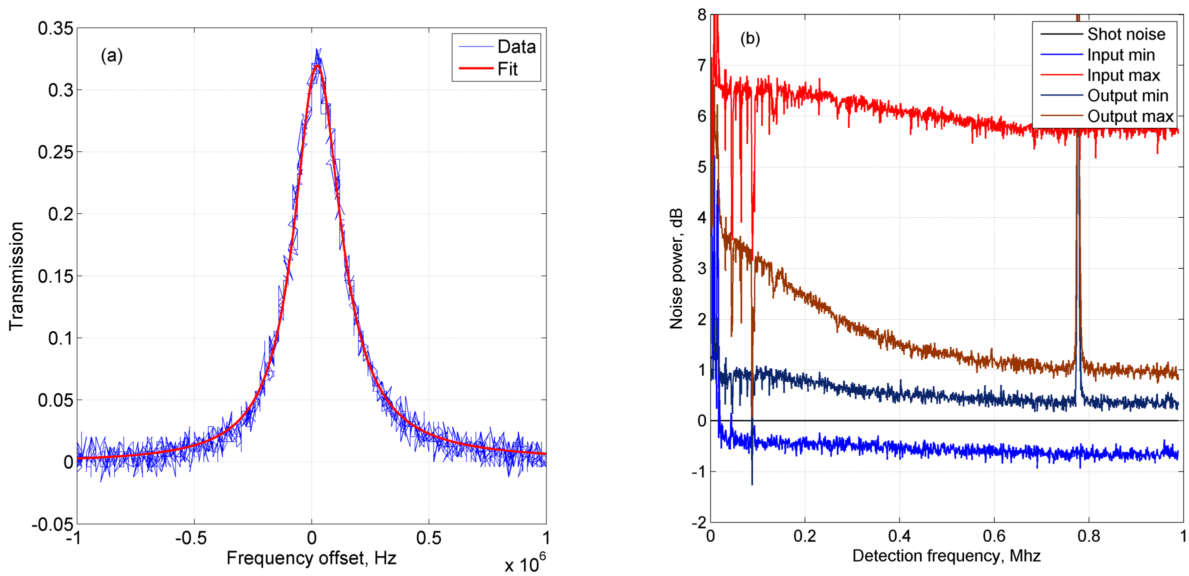

Figure 6. (a) EIT lineshape recorded using a coherent probe and control power of 2.7 mW; (b) EIT filtering of squeezed vacuum.

The output quadrature noise measured in the modified setup is shown in Fig. 6. The EIT filtering effect is much clearer, and its bandwidth loosely matches the EIT resonance linewidth. However, we were not able to transmit squeezing though the EIT cell, likely due to the low EIT transmission (50%). Also, we observe some residual excess noise above 240 kHz detection frequency (the EIT linewidth), where all incoming probe should have been absorbed by atoms. The origin of this additional noise is currently under investigation.

5. CONCLUSIONS

We have experimentally studied the modifications of quantum noise for both coherent field and squeezed vacuum field, generated via polarization self-rotation. We found that the interaction of a probe optical field with non-zero average intensity with Rb atoms under the EIT conditions gives rise to strong additional noise. This noise was observed only when both probe and control fields were present, and it grows proportionally with either the average probe intensity or atomic density. Since it is known that resonant four-wave mixing may cause excess noise dependent on the local oscillator phase, it may be responsible for the observed noise. The modifications of the experimental apparatus that reduced the amount of light leaking into the squeezed probe channel at least partially resolved this issue.

6. ACKNOWLEDGEMENTS

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