Observation of polarization quantum noise of laser radiation in Rb vapor cell

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We present experimental study of polarization quantum noise of laser radiation passed through optically think vapor of Rb$^7$. We observe a step-like noise spectrum. We discuss various factor which may result in such noise spectrum and prevent observation of squeezing of quantum fluctuations predicted in Matsko et al, Phys. Rev. A 63, 043814 (2001).

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The sensitivity of many experiments is ultimately limited by quantum fluctuations of electromagnetic field. This stimulates the development of various methods for generation of light with non-classical statistics (“squeezed light”). Usage of such light field in an experiment often allows measurement noise reduction below shot noise limit $^{[1]}$. Photon statistics modification often requires nonlinear optical medium; the degree of change depends on the strength of the nonlinear effects and linear losses in such medium $^{[2, 3]}$.

Recent proposals of photon statistics control based on coherent atomic vapor look quite promising from that point of view. Atomic coherence created between two hyperfine ground states of an alkali metal by a strong classical control field eliminates linear absorption and simultaneously produces strong nonlinear dispersion for a weak probe field (classical or quantized). This effect is known as electromagnetically induced transparency (EIT) $^{[4]}$. Third-order nonlinear susceptibility in an EIT medium is substantial and comparable with linear susceptibility, which enhances coupling between electromagnetic fields participating in such nonlinear processes $^{[5]}$. Ref. $^{[5]}$ demonstrated effective projection of photon quantum state on collective spin excitation of an atomic ensemble under EIT condition, long storage time, and the on-demand retrieval of quantum information.

Matsko et al. $^{[6]}$ predicted squeezing of vacuum quantum fluctuations for laser light propagating through an EIT medium with coherence between Zeeman states of the same hyperfine atomic sublevel. Theoretical calculations estimated squeezing up to 8dB under realistic experimental conditions.

The main purpose of this work was to study the polarization quantum noise of laser radiation for the $D_1$ line of Rb and to explore the possibility for squeezed vacuum observation on that transition. In particular, we studied the relation between laser intensity and the bandwidth of laser-induced quantum noise.

The mechanism of polarization quantum noise squeezing proposed in $^{[6]}$ is the following: linearly polarized laser radiation is decomposed into two circularly polarized components $\sigma^+$ and $\sigma^-$, as shown in Fig. 1(a), which form a $\Lambda$ system and create coherence between $|m_F = -1\rangle$ and $|m_F = +1\rangle$ Zeeman sublevels, producing EIT. In an ideal three-level $\Lambda$ system phase difference for two circularly polarized components does not change after interaction with atoms. However, under realistic conditions interaction of light with additional atomic levels (in particular with the other far-detuned hyperfine sublevel(s) of the excited state), Doppler effect, optical losses, etc., causes some changes in the relative phase between the $\sigma^+$ and $\sigma^-$ components. Indeed, in a dressed-state basis $^{[10]}$ the absorption spectrum of $\sigma^-$ consists of two transitions to $|+\rangle$ and $|-\rangle$ states with corresponding spectral distribution of refractive index $n(\nu)$. Emission of a spontaneous photon at a frequency $\nu_0 + (\kappa \nu)$ changes the shift $2\Omega$ between dress states $|+\rangle$ and $|-\rangle$ (as shown in Fig. 1(b)), which affects the transmission of the $\sigma^-$ field. Simultaneously, resonance refractive index changes by $\Delta n$, creating correlation between fluctuations of the photon number and the phase of the light field due to ac-Stark effect. As a result quantum noise of one laser field quadrature can be reduced at the expense of the other.

Experiments by Ries et al. $^{[6]}$ confirmed the theoretical proposal of Matsko et al. $^{[6]}$, reporting detection of squeezed vacuum at the output of a Rb vapor cell for linearly polarized light resonant with the $D_2$ transition. Observed reduction of a quadrature noise below stan-

![FIG. 1: a) $\Lambda$ system formed on Zeeman sublevels by the circularly polarized components $\sigma^+$ and $\sigma^-$ of the linearly polarized laser field. b) Same $\Lambda$ system in the dressed-state basis for stationary atoms (left part) and the atoms moving with the speed $\kappa \nu$ (right part). $\Omega$ is the Rabi frequency of the laser field, $\Omega' = \sqrt{\Omega^2 + (\kappa \nu)^2}$, $n(\nu)$ is the refractive index dispersion.](image-url)
standard quantum noise limit was −0.85 dB. It is reasonable to assume that the D₁ line is more promising for effective vacuum squeezing generation, since the D₁ line has simpler excited level structure with all sublevels participating in the coherence formation, and therefore exhibits stronger EIT and nonlinear magneto-optical effects [11].

A schematic of the experimental setup is shown in Fig. 2. Linearly polarized laser radiation propagated through a cylindrical Pyrex vapor cell containing isotopically enriched ⁸⁷Rb (cell’s length and diameter were 2.5 cm). The cell was mounted inside a three-layer magnetic shield and heated up to ∼ 95°, which corresponds to a Rb density of N = 2 × 10¹² cm⁻³. Frequency of the external cavity diode laser was close to F = 2 → F' = 1, 2 of the D₁ line of ⁸⁷Rb (wavelength λ = 795 nm). Laser power before the cell was P = 1±8 mW; laser beam diameter was D = 1 mm. To reduce asymmetry of the diode laser transverse intensity distribution we used a spatial filtering focusing the laser beam onto a 30 µm pinhole. This system provided nearly Gaussian transverse intensity distribution with ∼70% transmission. We used a traditional phase-sensitive homodyne detection scheme [11], which included a Mach-Zehnder interferometer formed by a crystal polarizer with extinction ratio of 5 × 10⁻⁸ to separate laser field E∥ and orthogonally-polarized squeezed vacuum field E⊥, mirrors, a half-wave plate to adjust the polarization of the local oscillator, and a 50:50 non-polarizing beam splitter (BS). The strong linearly polarized laser field E∥ played the role of a local oscillator.

To align the interferometer we inserted a quarter-wave plate λ/4 before the polarizer, sending the same intensity to the both interferometer channels. Best fringes visibility was ∼(96-98)%, which is evidence of a single-mode laser field.

![Image of experimental setup](image)

**FIG. 2:** Schematic of the experimental setup. E∥ marks the local oscillator channel. Orthogonally polarized radiation E⊥ propagated in the other interferometer channel. Relative phase of two interferometer channels was controlled by the mirror mounted of the piezo-drive. Polarization of the local oscillator field was rotated by 90° using a half-wave plate to observe an interference with the vacuum field.

Light at the outputs of the homodyne detection scheme was collected at two identical silicon p - i - n photodetectors D₁, D₂ with quantum efficiency of 91% (Hamamatsu S3883). The two photocurrents were amplified using a low-noise amplifiers (OPA657) and subtracted using a 180° combiner (MiniCircuits ZFSCJ-2-2) with 0.01 – 20.0 MHz. We carefully balanced the amplification in the two inputs. We modulated the laser current at ∼ 5 MHz frequency, which produced a corresponding peak in the laser spectrum. Then for equal laser intensities in the two interferometer channels we adjusted the amplification of the photodiodes such that the 5 MHz peak disappeared after the photocurrent subtraction. This procedure provided the accuracy in photocurrent subtraction better than 35 dB.

To measure a standard quantum noise level (denoted as SQL) for the homodyne detector we blocked a vacuum channel E⊥ and measured a noise spectrum of the subtracted photocurrents as a function of the laser intensity. We observed a linear dependence for a whole range of the laser intensities used in the experiment. Blocking one of the photodiode reduced the detected noise level by ∼ 1.4.

![Image of homodyne detector noise spectrum](image)

**FIG. 3:** Homodyne detector noise spectrum when the relative phase between two interferometer channels is 0° (a) and 180° (b). SQL - standard quantum limit - is the noise spectrum with the vacuum interferometer channel E⊥ blocked. Laser power is 7.4 mW. Laser frequency is blue-detuned by 150 MHz from F = 2 → F' = 1 transition. Spectrum analyzer registration bandwidth is 100 kHz, video bandwidth is 30 Hz.

We studied the quantum noise properties of the laser radiation tuned near the Doppler-broadened (HWHM ≈ 400 MHz) F = 2 → F' = 1, 2 transitions of ⁸⁷Rb D₁ line (excited state hyperfine splitting is 812 MHz). We observed enhancement of the noise both below and above the resonance frequencies. For the detuning ∼ (+150 ± 60) MHz from F = 2 → F' = 1 transition the shape of the noise spectrum looked like a step with a peak. A sample of such a spectrum is shown in Fig. 3. The position of the step was proportional to the laser intensity, and it shifted to the higher frequencies at more intense laser field (see Fig. 4). Such spectral dependence was observed only for one noise quadrature. If the relative phase between two interferometer channels changed by 180°, which corresponds to the orthogonal quadrature detection, the noise level dropped by 10 – 20 dB.
as shown in Fig. 3b). We failed to observe any vacuum squeezing in the experiment, as the the noise of the homodyne detector never dropped below the standard quantum level. The minimum excess noise occurred for the spectral frequency range close to the laser field Rabi frequency $\Omega$ (e.g., the Rabi frequency for the Fig. 3b was $\Omega \sim 26$ MHz). In the previous experiments [8] the bandwidth of the detected vacuum squeezing was close to 5 MHz while the Rabi frequency was $\sim 100$ MHz.

Discussion

Let us first point out the difference between experimental conditions in this work and the previous publications. In Refs. [6, 8] vacuum squeezing was predicted/observed for very high laser intensity comparable with hyperfine splitting of the $^{87}$Rb ground state ($\sim 6.8$ GHz). Under such conditions the influence of atomic coherence on nonlinear properties of an atomic vapor is insignificant [14]. Under such conditions the $D_1$ transition of $^{87}$Rb can be treated as a two-level system $J = 1/2 \rightarrow J' = 1/2$, where nonlinear circular birefringence occurs due to optical pumping. Resonance absorption in such a system changes faster than nonlinear dispersion, which allowed Matsko et al. to find an optimal laser detuning to observe quadrature squeezing of vacuum fluctuations. In the present experiment atomic coherence was the leading mechanism for nonlinear circular birefringence [5, 8], and the EIT parameters defined the quantum noise spectrum. For example, correlations between intensity and phase fluctuations were the most pronounced near the sharp boundary of the transparency window which occurred in optically dense EIT media. All noise components outside of the transparency window $\Gamma$ are absorbed [8, 12, 14]. EIT resonance width in an optically dense atomic vapor is proportional to the light intensity [13]:

$$\Gamma = \frac{\Omega^2}{\sqrt{\hbar c \gamma_\alpha}} \frac{1}{\sqrt{\eta \kappa L}}$$

where $\Omega$ is the laser field Rabi frequency, $\gamma_\alpha$ is the dephasing rate of the optical transition, $\gamma_{bc}$ is the ground-state decoherence rate, $\eta = 3N\lambda^3/4\pi^2$, $N$ is atomic density, and $\kappa = 2\pi/\lambda$.

Let us estimate the value of $\Gamma$. In a vapor cell $\gamma_{bc}$ is inversely proportional to the average time-of-flight of thermal Rb atoms through the laser beam, and is approximately equal to $\gamma_{bc} \approx 10^5$ Hz; the radiative decay of the excited state is $\gamma_\alpha \approx 6$ MHz. We can estimate Rabi frequency using the following expression [13]: $\Omega = \gamma \sqrt{I/8}$, where $I$ is the laser intensity in (mW/cm$^2$). Laser power $\approx 7$ mW gives a Rabi frequency $\Omega \approx 25$ MHz, and $\Gamma \sim 20$ MHz. This is relatively close to peak position in the noise spectrum shown in Fig. 3. The discrepancy is due to the inhomogeneous transverse laser intensity distribution and other factors [17].

An optically dense coherent atomic vapor is known to enhance spontaneous Raman process shown in Fig. 3, resulting in generation of new Stokes and anti-Stokes fields $S, N$ (see [13] for details).

FIG. 5: a) $^{87}$Rb $D_1$ line interacting with a strong drive field $DR$. b) Spontaneous Raman scattering, producing two new fields $S, N$ (see [13] for details).

Radiation trapping of spontaneous radiation [15], is another possible explanation why no vacuum squeezing was observed in the experiment. Reabsorption of de-phased and de-polarized spontaneous photons destroys atomic coherence. This process is particularly important in optically dense atomic vapor, where reabsorption probability is high: the negative effect of the radiation trapping on ground-state coherence lifetime begins at atomic density $\geq 10^{10}$ cm$^{-3}$. Additional decoherence due to radiation trapping grows quickly with atomic density, and for
It becomes comparable to the transient ground-state decoherence rate $\gamma_{bc}$ \[15\]. As a result the coherent EIT medium becomes more opaque, and this additional absorption reduces or destroys vacuum squeezing. Please note that this effect is stronger for the $D_2$ line due to the cycling transition $5S_{1/2}F = 2 \rightarrow 5P_{3/2}F' = 3$. Nonetheless, vacuum squeezing was detected for the $D_2$ line in \[3\], which is indirect evidence that for that experiment the effect of atomic coherence was minimal. We also note that the theory developed in \[6\] did not account for radiation trapping.

Frequency modulation to amplitude modulation (FM-AM) conversion is usually a significant noise source for experiments with diode lasers; it is particularly important in atomic frequency standards and magnetometers \[19\]. Due to the relatively low quality factor of the diode laser cavity, it has a wide phase noise spectrum which is transferred into transmitted intensity fluctuations after traversing a resonant absorbing medium. In this experiment, however, we used an extended cavity diode laser with a much lower phase noise level. Thus we believe that FM-AM conversion is not the reason for the observed quantum noise spectrum.

In conclusion, we studied the modification of the quantum noise of linearly polarized laser radiation after interaction with a Rb vapor cell. We observed a two order of magnitude enhancement of quantum noise for certain phases of homodyne detector. The spectrum on this excess noise has a step-like shape. The results presented here are useful in development of atomic magnetometers \[20\] and microwave frequency standards \[21\] based on EIT.

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