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Observation of optical phase-sensitive noise on a light beam transmitted through sodium vapor

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We have observed optical phase-sensitive noise in homodyne detection of a cw light beam which has propagated through sodium vapor near the D lines. Although at present the minimum noise is at or above the vacuum-state quantum limit due to zero-point fluctuations, nevertheless its phase behavior is like that of a squeezed state. Our observations are consistent both with the predictions of the quantum-mechanical theory of degenerate four-wave mixing and the theory of multiatom resonance fluorescence in the forward direction.

I. INTRODUCTION

Squeezed states of light, which exhibit phase-sensitive quantum noise, have been predicted to be generated via several processes such as degenerate four-wave mixing (DFWM),[1] resonance fluorescence,[2] and nonlinear propagation.[3] The phase sensitivity of the noise in these processes can be measured via optical homodyne detection.[4] In nearly resonant atomic systems, nonclassical squeezing of the quadrature noise below the vacuum fluctuation level is tightly constrained by loss in the medium and spontaneous emission. One may, however, generate a state of light with phase-sensitive noise above the vacuum fluctuation level. In this Rapid Communication, we report observing such squeezed classical noise via optical homodyne detection on a cw light beam which has propagated through sodium vapor near the D lines.

II. EXPERIMENT

The experimental setup is sketched in Fig. 1. The spatially filtered linearly polarized output from a ring dye laser was split to obtain a local-oscillator (LO) beam and a pump beam. The LO beam's polarization was rotated with use of a half-wave plate and a polarizer so that it had strong s and weak p components, as shown in the lower right-hand corner of Fig. 1. The LO beam was then sent through a transverse electro-optic modulator (EOM) arranged to provide an electrically controllable s-polarization phase shift. The pump-beam polarization was chosen to be s or p by means of a polarizer. In either case, a pump beam of ~ 5 W/cm^2 intensity was passed through sodium vapor near its D lines.

Two sets of homodyne measurements were made simultaneously on the transmitted pump (TP) beam, one to stabilize the Mach-Zehnder interferometer formed by the LO and pump beams and one to make quantum noise observations. The noise observations were made via homodyne detection of the s-polarized component of the TP by use of the dual-detector subtraction scheme.[5] The outputs from another set of balanced detectors observing the p-polarized light stabilized the interferometer by driving a mirror mounted on a piezoelectric transducer through feedback electronics. With this setup, the noise spectral density of the TP beam was monitored on a spectrum analyzer (SA). By setting the input-pump-beam polarization to be p or s, the noise spectrum was measured for polarizations orthogonal or parallel to the input pump, respectively. In both cases, a zero-frequency bias voltage applied to the EOM permitted the noise measurements to be made as functions of the relative phase θ between the s-polarized components of the LO and TP beams.

A typical noise spectrum is shown in Fig. 2. The lower trace is with both the LO and the TP beams blocked, whereas the upper trace is with only the TP beam blocked. Over the whole 20-MHz observation band the photodetection noise dominates the thermal noise of the detector-amplifier chain. The peaks are caused by the amplitude noise on the LO beam due to transverse mode beating in the argon-ion laser pumping the ring dye laser. However, in the 6–12-MHz band the photodetection noise is vacuum-state quantum-noise limited, as verified independently with use of an incoherent white-light source supplying the same amount of optical power as the LO beam.[6] According to quantum photodetection theory, this noise is due to interference of the LO beam at frequency ω_0 with the fluctuating vacuum field at frequencies $\omega_0 \pm \Omega$, where Ω lies in

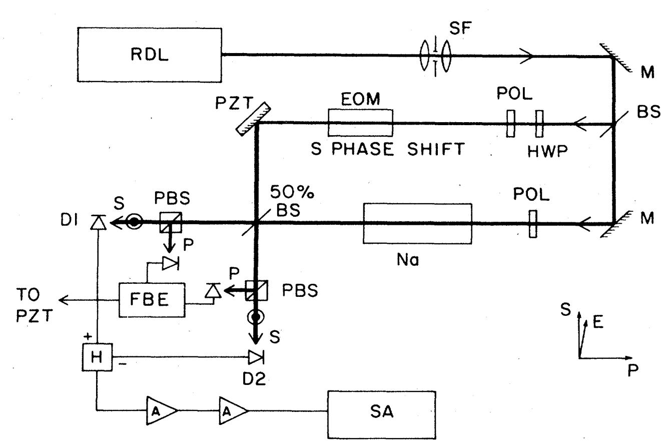

FIG. 1. Schematic of the experimental setup. The polarization state of the LO is indicated in the lower right-hand corner.

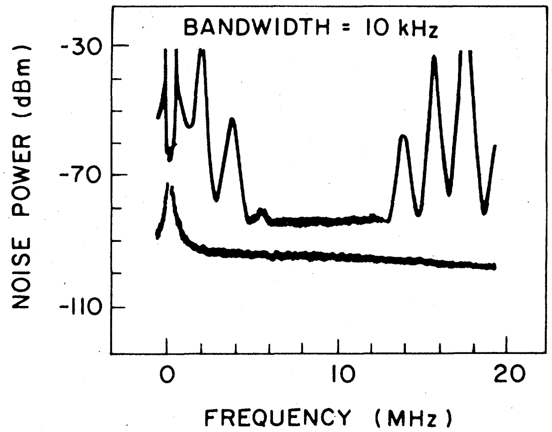

FIG. 2. Typical homodyne detection noise power spectrum as monitored by the SA of Fig. 1.

the 6–12-MHz frequency band.[7] For perfectly balanced detectors of quantum efficiency η ($\eta \sim 0.8$ in our apparatus), the noise spectra in this frequency band for p- and s-polarized pump measurements obey[8]

$$N_p \propto \eta P_{\mathrm{LO}} \langle \Delta a_\theta^2 \rangle + (1-\eta) P_{\mathrm{LO}}/4 \ , \tag{1}$$

and

$$N_s \propto \eta (P_{\mathrm{LO}} \langle \Delta a_\theta^2 \rangle + P_p/4) + (1-\eta)(P_{\mathrm{LO}} + P_p)/4 \ , \tag{2}$$

respectively, with P_{LO} and P_p being the LO and transmitted pump powers. Here the terms proportional to η are detected-light quantum-noise contributions, and the terms proportional to $1-\eta$ are subunity-quantum-efficiency detector noise.[7] The phase-dependent quadrature operator a_θ is given by

$$a_\theta = a_1 \cos\theta + a_2 \sin\theta \tag{3}$$

in terms of the canonically conjugate quadrature operators a_1 and a_2, $\langle \Delta a_\theta^2 \rangle \equiv \langle a_\theta^2 \rangle - \langle a_\theta \rangle^2$, and $\langle \ \rangle$ denotes quantum averaging.

By adjusting the feedback electronics, the Mach-Zehnder interferometer was stabilized in such a way that the p-polarized components of the LO beam and the TP beam arrived $\pi/2$ out of phase at the 50% beam splitter. Because of residual birefringence in the crystals of our EOM, zero bias voltage on the EOM did not correspond to $\theta = \pm\pi/2$. Therefore an alternate method was used to determine θ for the p-polarized pump experiment. In our setup, a stray magnetic field induced a rotation in the linearly polarized pump field near resonance. The TP beam, therefore, acquired a weak s-polarized component whose interference with the s-polarized LO beam provided the calibration for θ. When the zero-frequency signals at the noise-measurement detectors are equal, $\theta = \pm\pi/2$. In the case of the s-polarized pump, the zero-frequency signal due to interference of the LO beam with the TP beam provided such calibration.

Figure 3 shows the noise power in the 6–12-MHz quiet band as a function of θ and the EOM bias voltage V_{EOM} for (a) the p-polarized pump and (b) the s-polarized pump. In the absence of sodium, the noise in this band was phase insensitive and vacuum-state quantum-noise limited, i.e., $\langle \Delta a_\theta^2 \rangle = \langle \Delta a_1^2 \rangle = \langle \Delta a_2^2 \rangle = \frac{1}{4}$, as indicated by the dashed line in Fig. 3.

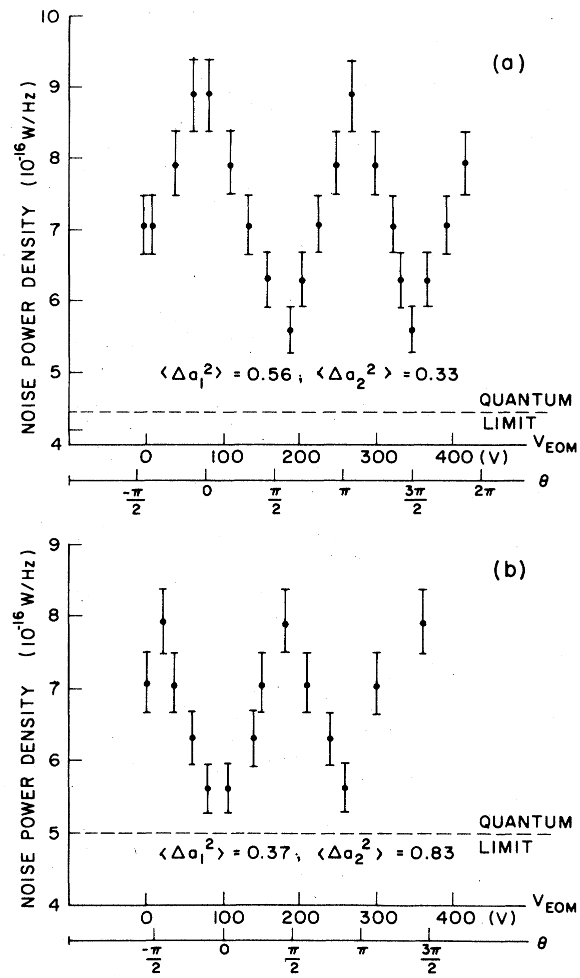

FIG. 3. Homodyne detection noise power in the 6–12-MHz band as a function of the phase θ between the LO and TP beams. (a) When the pump beam is p polarized, $P_{\mathrm{LO}} = 29$ mW, and (b) when the pump beam is s polarized, $P_{\mathrm{LO}} = 10$ mW and $P_p = 22$ mW. The dashed line in each case is the vacuum-state quantum limit determined by the LO power in (a) and by the sum of the LO and TP powers in (b). See text for the calibration of θ.

In the presence of sodium, the noise varied periodically with θ, with period π radians. For the p-polarized pump, noise maxima occurred when the pump and LO were exactly in phase ($\theta = 0$), whereas for the s-polarized pump this occurred when the pump and LO were in quadrature ($\theta = \pi/2$). For the set of data shown we measured $\langle \Delta a_1^2 \rangle = 0.56$ and $\langle \Delta a_2^2 \rangle = 0.33$ when the pump was p-polarized, and $\langle \Delta a_1^2 \rangle = 0.37$ and $\langle \Delta a_2^2 \rangle = 0.83$ when the pump was s polarized.

Figure 4 shows the saturated pump transmittance, the s-polarized quiet-band noise power for p-polarized pump, and the magnetic-field-induced zero-frequency s-polarized component as the pump laser frequency is varied across the sodium D_1 resonance line. The range of the phase-sensitive noise as θ is varied at a particular frequency is indicated by the vertical lines bounded by the dots corresponding to maximum (minimum) noise at $\theta = 0$ or π ($\pi/2$ or $3\pi/2$). The maximum-noise and greatest-phase-sensitivity range occurred on resonance, and the noise level was an increasing

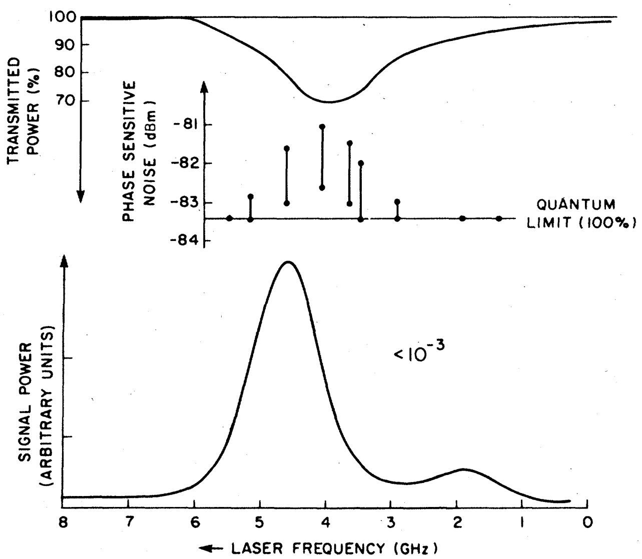

FIG. 4. Pump transmittance, s-polarized quiet band phase-sensitive noise power, and the intensity of the magnetic-field-induced zero-frequency s-polarized component as functions of the pump laser frequency varied across the D_1 resonance line. For this data the pump beam is p polarized. The quantum limit is for off-resonance pump when the transmittance is 100%. The peak intensity of the zero-frequency s-polarized component is $\simeq 10^{-3}$ times that of the pump beam.

function of pump power of up to $\sim 7\ \mathrm{W/cm^2}$. For different pump intensities and detunings, we consistently observed $\langle \Delta a_1^2 \rangle \geqslant \langle \Delta a_2^2 \rangle$ with a p-polarized pump, and $\langle \Delta a_1^2 \rangle \leqslant \langle \Delta a_2^2 \rangle$ with an s-polarized pump.

Similar noise behavior was observed in the vicinity of the D_2 resonance line.

III. COMPARISON WITH THEORY

We have considered two theoretical models, the quantum mechanical theory of DFWM by Reid and Walls[1] and multiatom resonance fluorescence in the forward direction,[9] and have shown that the phase dependence of the observed noise for an s-polarized pump is consistent with both these theories. The theory of Reid and Walls applies to a stationary two-level atomic system interacting with four spatially nondegenerate modes. In our experiment, there are three s-polarized temporally nondegenerate, spatially degenerate modes: a strong pump mode $a(\omega_0)\exp(-i\omega_0 t)$ and two weak signal modes

$$a(\omega_0-\Omega)\exp[-i(\omega_0-\Omega)t]$$

and

$$a(\omega_0+\Omega)\exp[-i(\omega_0+\Omega)t] \ .$$

Here ω_0 is the LO optical frequency and Ω is the radio frequency ($\cong 10$ MHz) at which the noise behavior is studied. When the pump field and the medium are treated classically, ideal nonclassical squeezing is predicted in modes

$$2^{1/2}a_+\cos(\Omega t)=[a(\omega_0-\Omega)\exp(i\Omega t) + a(\omega_0+\Omega)\exp(-i\Omega t)]/2^{1/2} \ ,$$

and

$$2^{1/2}a_-\sin(\Omega t)=[a(\omega_0-\Omega)\exp(i\Omega t) - a(\omega_0+\Omega)\exp(-i\Omega t)]/i2^{1/2} \ .$$

Under homodyne detection, the noise monitored by the SA at frequency Ω obeys Eqs. (1) and (2) with $\langle \Delta a_\theta^2 \rangle = 2^{-1}[\langle \Delta a_{+\theta}^2 \rangle + \langle \Delta a_{-\theta}^2 \rangle]$, where $a_{\pm\theta}$ is found from $\{a_{\pm 1}, a_{\pm 2}\}$, the quadrature operator components of a_+ and a_-, via Eq. (3). As long as Ω is less than the homogeneous linewidth, the theory of Reid and Walls is applicable to our nearly degenerate case. Also, since our experiment was performed in sodium vapor, the predominant interaction takes place with a group of atoms which are Doppler shifted into resonance with the pump beam. Therefore, in the limit of strong saturation, i.e., $z = I_{\mathrm{pump}}/I_{\mathrm{sat}} >> 1$ and zero detuning we obtain the following quadrature noise variances:

$$\langle \Delta a_{\pm 1}^2 \rangle = \tfrac{1}{4} + [\exp(2\chi L) - 1] \ , \tag{4}$$

and

$$\langle \Delta a_{\pm 2}^2 \rangle = \tfrac{1}{4} + [1-\exp(-2\chi L)](z/2+1) \ , \tag{5}$$

where L is the interaction length, $\chi \simeq \alpha_0/z$ measures the strength of the nonlinearity, and α_0 is the small-signal line-center absorption coefficient. Here $a_{\pm 1}$ ($a_{\pm 2}$) is the quadrature operator in phase ($\pi/2$ out of phase) with the pump beam. For our experimental conditions, $z >> 1$ and a saturated pump transmission of 70% implies $\chi L \cong 0.36$. Therefore, from Eqs. (4) and (5), the minimum noise occurs when the LO is in phase with the pump, in agreement with our data for the s-polarized pump. The two-state model is not applicable to our p-polarized pump data.

Squeezing has also been predicted in single-atom resonance fluorescence.[2] Nonclassical features are generally washed out in multiatom resonance fluorescence, due to the time-varying random locations of the atoms in the driving field. However, in the forward direction, the net phase of the exciting field and the scattered fields is preserved. Squeezing and phase-sensitive behavior of such forward-scattered fields from N atoms are identical to that for a single atom except for the magnitude, which is N times larger, and a $\pi/2$ phase shift, due to the collective effect of scattering.[9] Although the simple theory for independent scatterers does not include any propagation effects, the full spectrum for homodyned fluorescence can be calculated, whereas only the noise on nearly degenerate signal modes could be considered in DFWM theory. In the limit of large driving field, the noise level never falls below the vacuum fluctuation level. Nonetheless, the spectrum is strongly phase sensitive, consisting of three inelastic peaks: a central component with a $\sin^2\theta$ phase dependence, and two outlying peaks at the generalized Rabi frequency with $\cos^2\theta$ dependence. In our sodium vapor system, the outer Rabi peaks are Doppler averaged and smeared out. The behavior of the central component agrees with our observation for the case of the s-polarized pump, where the low noise occurs when the LO beam is in phase with the pump beam.

IV. CONCLUSION

We have observed optical phase-sensitive noise in homodyne detection of a polarized cw light beam which has propagated through sodium vapor. The noise minimum for parallel polarization occurs in phase with the transmitted beam, whereas for orthogonal polarization it is phase shifted by $\pi/2$. The phase behavior of the parallel polarized noise is in agreement both with the quantum theory of degenerate four-wave mixing and with the theory of multiatom resonance fluorescence in the forward direction.

Recently, other workers have also reported similar phase-sensitive noise behavior in propagation through an optical fiber.[10] Externally injected optical noise on the propagating beam was amplified or attenuated in a phase-sensitive fashion. No such noise was injected in our work and the photodetection of the input beam was quantum limited in the frequency region of interest. Slusher *et al.* have also reported observing phase-sensitive noise in their experiment.[11]

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[8]Although homodyne detection is optically phase sensitive, the spectrum analyzer is electrically phase insensitive. Thus, strictly speaking, $\langle \Delta a_\theta^2 \rangle$ in (1) and (2) should be the algebraic mean of the phase-dependent quadrature operator variances for the sine and cosine pair of frequency degenerate double-sideband modes. The simpler description is used in (1)–(3), with no appreciable loss of generality; i.e., $\langle \Delta a_\theta^2 \rangle < \frac{1}{4}$ is still nonclassical squeezing. The complete mode description is employed in Sec. III.

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