Strong low-frequency quantum correlations from a four-wave-mixing amplifier

C. F. McCormick, A. M. Marino, V. Boyer, and P. D. Lett*

Atomic Physics Division, National Institute of Standards and Technology, Gaithersburg, Maryland 20899, USA

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Using a simple scheme based on nondegenerate four-wave mixing in a hot vapor, we generate bright twin beams which display a quantum noise reduction in the intensity difference of more than 8 dB. The absence of a cavity makes the system immune to external perturbations, and strong quantum noise reduction is observed at frequencies as low as 4.5 kHz and over a large frequency range.

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Two-mode squeezed beams have become a valuable source of entanglement for quantum communications and quantum-information processing [1]. These applications introduce specific requirements on the squeezed light sources. For instance, for squeezed light to be used as a quantum-information carrier interacting with a material system, as in an atomic quantum memory, the light field must be resonant with an atomic transition and spectrally narrow to ensure an efficient coupling between light and matter. In recent years, attention has also been brought to the problem of the manipulation of cold atomic samples with nonclassical fields in order to produce nonclassical matter waves [2–4]. In this case, the slow atomic dynamics also requires squeezing at low frequencies.

The standard technique for generating nonclassical light fields is by parametric down-conversion in a crystal, with an optical parametric oscillator or an optical parametric amplifier [5,6]. While very large amounts of quantum noise reduction have been achieved in this way [7,8], controlling the frequency and the linewidth of the light remains a challenge. Only recently have sources based on periodically poled nonlinear crystals been developed at 795 nm to couple to the Rb $D1$ atomic line [9,10]. On the other hand, stimulated four-wave mixing (4WM) naturally generates narrowband light close to an atomic resonance, but its development as an efficient source of squeezed light has been hindered by fundamental limitations such as spontaneous emission. During the 1990s, nondegenerate 4WM in a double-Λ scheme [11] was identified as a possible workaround for these limitations, as described in Ref. [12]. It was not until recently that such a scheme was implemented in continuous mode in an efficient way in both the low- [13–15] and the high- [16,17] intensity regimes, where it was shown to generate twin beams where quantum correlations are not masked by competing effects.

The double-Λ scheme gives rise to complex atomic dynamics and propagation properties, such as slow-light effects [18]. In this paper, we show that 4WM in a double-Λ scheme in Rb vapor can be used to obtain over 8 dB of intensity-difference squeezing over a large frequency range. We show that, in spite of the complexity of the atomic system, the quantum properties of the scheme can be accurately described as the combination of an amplifier and a partial absorber. This model shows that the parasitic effects usually associated with atomic vapors, such as fluorescence, atomic fluctuations and other nonlinear processes, do not play a role in the intensity-difference squeezing. It allows us to improve upon our previous results [17], by more than 4 dB in the measured squeezing on the intensity difference, and to show that 4WM is a viable alternative to even the best optical parametric oscillators [7]. It also helps to identify regions of the parameter space where the system behaves like a lossless phase-insensitive amplifier, opening the way to the generation of strong continuous-variable entanglement. We demonstrate the intrinsic robustness of our scheme by extending the strong squeezing to the audio range, where technical noise usually represents a serious obstacle to the generation and the observation of quantum effects.

The double-Λ scheme [Fig. 1(a)] is a 4WM process which mixes two strong pump fields with a weak probe field in order to generate a fourth field called the conjugate. The probe and conjugate fields (the twin beams) are cross coupled and are jointly amplified, which leads to intensity correlations stronger than the standard quantum limit (SQL). These correlations are the manifestation of two-mode quadrature squeezing between opposite vacuum sidebands of the twin beams.

As in the experiments presented in [17], we use a cw Ti:sapphire ring laser, to generate a strong (≈400 mW) pump beam near the $D1$ line of Rb (795 nm). From this we derive, using an acousto-optic modulator, a weak (≈100 μW) probe beam tuned ≈3 GHz to the red of the pump. This results in very good relative phase stability of the probe with respect to the pump. The pump and probe beams are combined in a Glan-Taylor polarizer and directed (at an

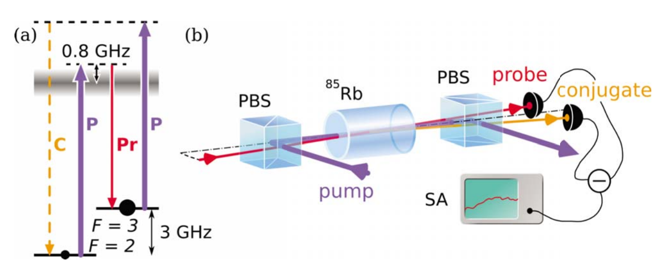

FIG. 1. (Color online) Experimental details. (a) Double-Λ scheme in ^{85}Rb, P=pump, C=conjugate, Pr=probe. The width of the excited state represents the Doppler-broadened profile. The probe and the conjugate are cross-linearly polarized with the pump. (b) Experimental setup, PBS=polarizing beam splitter, SA =spectrum analyzer.

*paul.lett@nist.gov

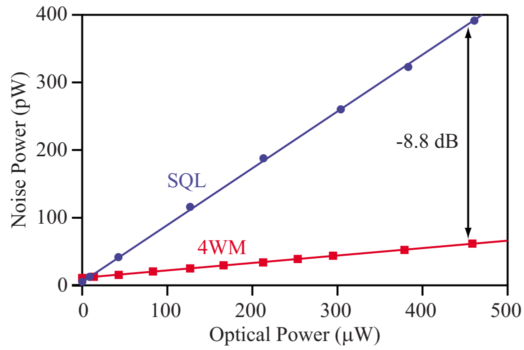

FIG. 2. (Color online) Intensity-difference noise versus total optical power at 1 MHz. Blue circles, SQL; red squares, 4WM. The ratio of the two slopes is −8.8 dB.

angle of 0.3° to each other) into a 12.5 mm long vapor cell filled with isotopically pure ^{85}Rb [see Fig. 1(b)]. The cell, with no magnetic shielding, is heated to ≈110 °C. The windows of the cell are antireflection coated on both faces, resulting in a transmission for the probe beam of 98% per window. The pump and probe are collimated with waists at the position of the cell of 650 and 350 μm ($1/e^2$ radius), respectively.

After the cell we separate the pump and probe beams using a second polarizer, with $\approx 10^5:1$ extinction ratio for the pump. With the pump at ω_0, tuned to a "one-photon detuning" of 800 MHz to the blue of the ^{85}Rb $5S_{1/2}$, $F=2 \rightarrow 5P_{1/2}$, $D1$ transition, and the probe at ω_-, detuned 3040 MHz to the red of the pump ("two-photon detuning" of 4 MHz), we measure an intensity gain on the probe of 9. This gain is accompanied by the generation of the conjugate beam at ω_+, detuned 3040 MHz to the blue of the pump, which has the same polarization as the probe, and propagates at the pump-probe angle on the other side of the pump so that it satisfies the phase-matching condition. After the second polarizer we direct the probe and conjugate beams into the two ports of a balanced, amplified photodetector. The output of this photodetector is fed into a radio frequency spectrum analyzer with a resolution bandwidth (RBW) of 30 kHz and a video bandwidth (VBW) of 300 Hz. In addition, we introduce a delay line into the conjugate beam path to compensate for the differential slow-light delay discussed in Ref. [18]. This results in a fraction of a decibel improvement in the amount of squeezing observed and increases the upper limit of the squeezing bandwidth to 20 MHz.

We measure −8.0 dB of intensity-difference squeezing at an analysis frequency of 1 MHz without compensating for any system noise or correcting for transmission or detection efficiencies. This system noise has contributions from the electronic noise of the detection system and the pump light that scatters from the atomic medium. In order to determine the effect of the system noise on the measured squeezing we vary the input probe power and we plot in Fig. 2 the intensity-difference noise of the probe and conjugate beams versus the total (probe plus conjugate) power incident on the detector. We do the same for the SQL, determined by measuring shot-noise-limited balanced beams of the same total power. The two curves fit to straight lines, with a ratio of slopes equal to 0.131=−8.8 dB. The SQL curve has a zero intercept given by −82.9 dBm, while the zero intercept of the probe-conjugate curve is higher, −79.6 dBm (due to the pump scattering). The optical path transmission and photodiode efficiencies are $(95.5\pm 2)\%$ and $(94.5\pm 2)\%$, respectively, resulting in a total detection efficiency of $\eta = (90\pm 3)\%$; all uncertainties are estimated at 1 standard deviation. The inferred squeezing value at the end of the atomic medium, corrected for detection efficiency, is better than −11 dB.

Ideally, two-mode squeezing is produced by a phase-insensitive amplifier of gain G, where the photon annihilation operators $\hat{a}$ and $\hat{b}$ for the probe and the conjugate fields transform according to

$$\hat{a} \rightarrow \hat{a}\sqrt{G} - \hat{b}^\dagger\sqrt{G-1}, \tag{1}$$

$$\hat{b}^\dagger \rightarrow \hat{b}^\dagger\sqrt{G} - \hat{a}\sqrt{G-1}. \tag{2}$$

When the probe port a is seeded with a coherent state $|\alpha\rangle$ of power P_0 and the conjugate port b is fed with the vacuum, the output powers are $P_p = GP_0$ for the probe and $P_c = (G-1)P_0$ for the conjugate, and the output intensity-difference noise is equal to the shot noise of the input state $|\alpha\rangle$. This gives a quantum noise reduction of $1/(2G-1)$ with respect to the output SQL.

In general, atomic media give rise to additional processes, such as absorption, Raman gain, two-beam coupling, etc. which may reduce the amount of intensity-difference squeezing. In our case, the probe is subject to loss by absorption since it is in the tail of the Doppler profile of an atomic resonance [19]. (Because the conjugate beam is far away from resonance, it does not suffer any appreciable loss.) To check the probe loss, we compare the powers of the input probe and the output probe and conjugate. We observe that for most operational values of the experimental parameters, the ratio of power $r = P_c/P_p$ is larger than the ideal value of $(G_{\rm eff}-1)/G_{\rm eff}$, where $G_{\rm eff}$ is the measured effective probe gain. This indicates a certain level of probe loss. In general, the 4WM gain G is different from the effective gain $G_{\rm eff}$, which also depends on the loss.

In general it is not possible to infer the quantum behavior, or noise properties, of the system from its classical description. Different quantum systems can produce the same mean intensities and have different noise properties. Since our system is able to generate a large amount of intensity-difference squeezing, we make the assumption that there is no additional source of noise other than the quantum noise associated with the probe loss. This is a rather strong assumption because atomic systems interacting with light are known to be subject to noise from fluorescence or higher-order nonlinear phenomena.

In this framework, the medium is quantum mechanically described by a simple model of distributed 4WM gain and probe loss [20,21]. Localized probe loss in the system can be modeled by a beam splitter of transmission T picking off a fraction of the probe and injecting the vacuum on the second input port (photon annihilation operator $\hat{c}$), according to

$$\hat{a} \rightarrow \hat{a}\sqrt{T} + \hat{c}\sqrt{1-T}, \tag{3}$$

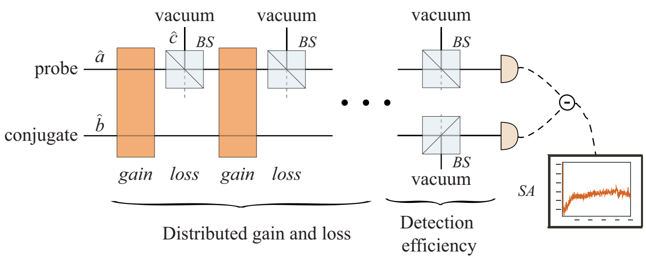

FIG. 3. (Color online) Distributed gain and loss model. The medium is modeled with a large number of interleaved gain and loss stages (see text). The loss stages affect only the probe beam, since only this beam is tuned close enough to an atomic resonance to experience absorption. The detection efficiency is modeled by a beam splitter (BS) on both beams. SA=spectrum analyzer.

$$\hat{b}^{\dagger} \rightarrow \hat{b}^{\dagger}. \tag{4}$$

Because of the vacuum noise injected into port c, such a transformation applied to the squeezed probe and conjugate is expected to degrade the squeezing. In the actual medium, gain and loss are evenly distributed. A convenient way of calculating their effect is to consider a succession of $N \gg 1$ interleaved stages of elementary gain g and N stages of elementary transmission t as shown in Fig. 3. The intrinsic gain G (probe transmission T) of the whole stack can be found by setting $t=1$ ($g=1$), respectively. Finally, the total detection efficiency η is also modeled by a beam splitter of transmission η applied to both the probe and conjugate fields. In the calculations below we set $N=200$.

As pointed out above, the experimentally accessible classical parameters are the effective (measured) probe gain G_{eff}, defined as the probe power out of the cell divided by the probe power input (corrected for window losses), and the ratio r of conjugate-to-probe output powers. The model relates both of these parameters to the intrinsic gain and loss of the probe in the medium. We numerically invert this relation to determine the values of g and t, or equivalently G and T, corresponding to a given G_{eff} and r. We perform this procedure for each observed (G_{eff}, r) pair at several one-photon detunings between 0.4 and 1.4 GHz, and use the numerically determined values of g and t to calculate the expected intensity-difference squeezing at each detuning.

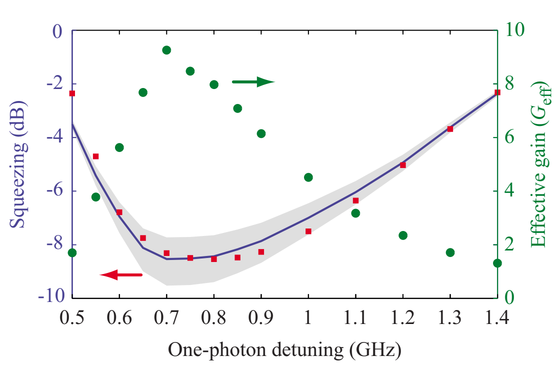

FIG. 4. (Color online) One-photon 4WM resonance. Intensity-difference noise measured at 1 MHz (red squares) and gain (green circles) versus one-photon detuning, for a two-photon detuning of 4 MHz and a cell temperature of 112 °C. The blue curve is the theoretical squeezing computed from the output power levels of the probe and the conjugate. The top and bottom of the shaded area indicate the variation of the theoretical curve for the uncertainty range of our detection efficiency.

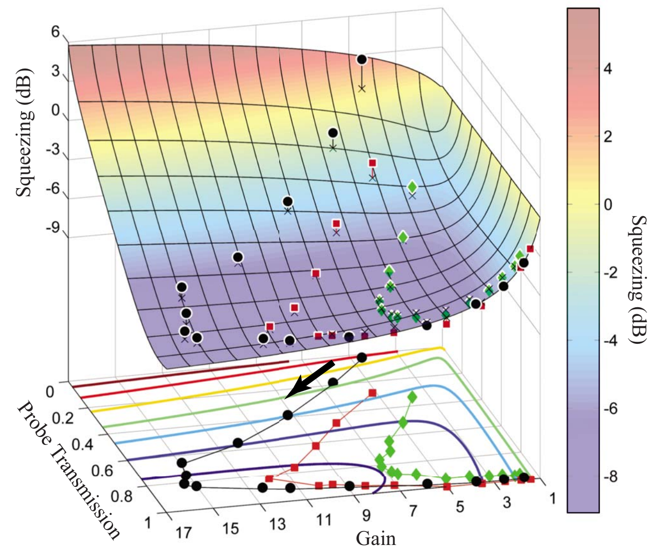

FIG. 5. (Color online) Simulated and measured intensity-difference squeezing as a function of the probe transmission T and gain of the medium G. The theory takes into account the detection efficiency (η=0.9). The squeezing (corrected for the system noise) measured at 1 MHz is shown for different cell temperatures, 109 °C (diamonds), 112 °C (squares), and 114 °C (circles), as the one-photon detuning of the pump laser is scanned. The crosses indicate the projection of the measured squeezing onto the theoretical surface while the lines connecting the points and crosses give an indication of the vertical distance between them. Most of the points are very near the surface. The projection onto the x-y plane shows contour lines of the theoretical squeezing at 2 dB intervals from +4to −8 dB, and the projections of the data points. The arrow indicates the direction of increasing one-photon detuning.

A typical curve that is obtained as the one-photon detuning is scanned is shown in Fig. 4. Here, the squares show the measured squeezing (corrected for the system noise) while the solid line shows the theoretical intensity-difference squeezing obtained from the model described above with the gray area accounting for the uncertainty in the detection efficiency. Except for the first two points, which correspond to detunings with a significant probe absorption, all the data points fall within the uncertainty and show excellent agreement with the model over a large range of one-photon detunings. In the same way, we take data at different temperatures and represent it as a function of the probe transmission T and the intrinsic gain G, as shown in Fig. 5. The experimental data points agree very well with the model, the only discrepancy occurring when the probe loss dominates the dynamics. The fact that the gain and loss description reproduces both the classical behavior of the amplifier (the intensities of the twin beams) and its quantum properties (the intensity-difference squeezing) suggests that it captures the relevant physics, and that the expected additional sources of noise, such as fluorescence or two-mode coupling, do not play a role in the intensity-difference noise measurement.

The theoretical surface of Fig. 5, calculated from the distributed gain and loss model, shows that for a given probe transmission there is an optimum gain for squeezing. At lower gain the intensity-difference squeezing is limited by the power imbalance between the probe and the conjugate, which originates from the input probe power. At higher gain the squeezing becomes limited by the amplification of the noise introduced by the loss on the probe. In the same way, for a given gain there is an optimum transmission value, smaller than 1, corresponding to this trade-off between power balancing and absorption-induced quantum noise. In order to increase the squeezing, it would be necessary to both reduce the probe absorption and increase the gain. Experimentally, the absorption and the gain both depend on the cell temperature (both increase with the atomic density) and the pump detuning, and they are not independently controllable. The best squeezing of −8.8 dB is obtained over the transmission range of 0.85-0.95, and gains of 9-15. This best value can be achieved over a range of several degrees in temperature.

An interesting feature revealed by the data in Fig. 5 is that, at large one-photon detunings, the probe transmission is unity and the intensity-difference squeezing is equal to the squeezing expected for a quantum-limited (i.e., lossless) amplifier. This hints at the possibility of operating the system in a regime described by the transformation in Eqs. (1) and (2) with a gain up to about 6, producing, in principle, a pure entangled state.

In addition to looking at the level of noise reduction obtained at a fixed frequency, we can also investigate the frequency spectrum of the noise reduction. Since there is no fundamental limitation on the low-frequency response of the system [12,18], it will be established by technical noise on the pump and probe lasers. The small number of optical components and particularly the lack of a cavity minimizes the coupling to the environment. To explore this, we record the intensity-difference noise spectrum at low analysis frequencies with the detunings fixed at 800 MHz for the one-photon detuning and 4 MHz for the two-photon detuning. The probe (conjugate) output powers are equal to 305 (290) μW, and the RBW and the VBW are reduced (see Fig. 6). The intensity-difference noise signal is 8.0 dB below the SQL and almost flat, with the exception of a few peaks, all the way down to 4.5 kHz. At this point the technical noise of the pump and probe lasers starts to dominate, resulting in the loss of the intensity-difference squeezing at frequencies below 2.5 kHz. While making these measurements we found that the frequency stabilization of the Ti:sapphire laser adds amplitude noise to the beam, which in turn prevents squeezing from being observed below 70 kHz. The data in Fig. 6 were taken with the active frequency stabilization of the laser turned off.

The low frequency limit for the intensity-difference squeezing is well below the linewidth of the laser (≈200 kHz) which is mostly limited by frequency noise. As shown in Fig. 4, the one-photon gain resonance is very broad (≈400 MHz wide). As a result, the effective gain varies slowly with the one-photon detuning (that is to say with the

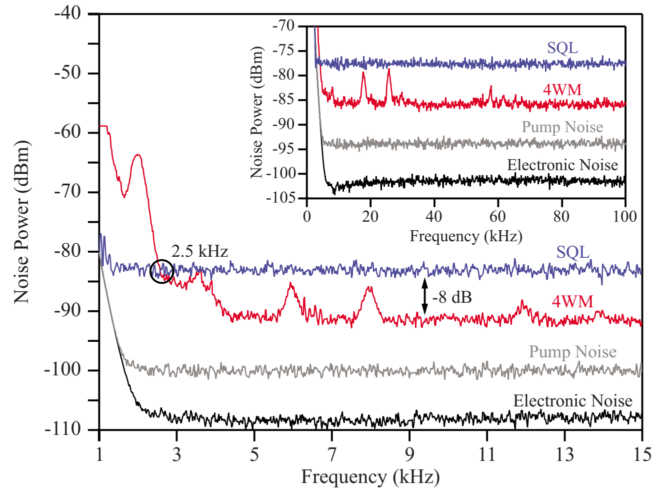

FIG. 6. (Color online) Low-frequency squeezing. Noise spectra (RBW 0.3 kHz, VBW 3 Hz) for the electronic noise, the pump scattering, the intensity difference, and the standard quantum limit. The inset shows a larger frequency span (RBW 1 kHz, VBW 10 Hz).

frequency of the laser), which avoids converting the laser frequency noise into amplitude noise. The two-photon resonance (not shown) is much narrower (≈20 MHz wide), but having the pump and the probe phase locked reduces the two-photon frequency noise to a minimum. The observation of squeezing in the kilohertz range makes our system suitable for applications such as the transfer of optical squeezing onto matter waves [2].

In addition to making the system insensitive to environmental noise, the lack of a cavity allows the system to operate as a multi-spatial-mode phase-insensitive amplifier [22], making it an ideal source for quantum imaging experiments [23]. When coupled to the low-frequency squeezing capability of our system, multimode operation could find an interesting application in photothermal spectroscopy, which measures the deflection of a beam at frequencies of the order of 1 kHz, and is currently nearly shot-noise limited [24].

An important property of twin beams is the presence of continuous-variable Einstein-Podolsky-Rosen entanglement [25]. In its current configuration, in which the probe and conjugate are 6 GHz apart in frequency, the presence of entanglement can be verified through the use of two different local oscillators, or a bichromatic local oscillator [26]. In addition, the reciprocity between the beams involved in the 4WM process should allow the pumping to occur at the two frequencies ω_+ and ω_-, in order to generate frequency degenerate twin beams at frequency ω_0 or to realize a phase-sensitive amplifier.

In conclusion, we have demonstrated a simple and robust source of intensity-difference-squeezed light based on four-wave mixing in a hot atomic vapor capable of producing a quantum noise reduction in the intensity difference of more than 8 dB over a large frequency range. The system provides a narrowband nonclassical light source near an atomic transition and is well suited for use in light-atom interaction experiments. In addition, we have shown that under certain conditions the system behaves as an ideal phase-insensitive amplifier, opening the way to the generation of pure entangled states. This realization of a high-quality source of nonclassical light may find a place in a variety of applications.

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