Self-interfering technique for observing intensity squeezing in four-wave mixing in a pure two-level system

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We report on the observation of intensity squeezing based in four-wave mixing (FWM) on a pure two-level system. We employ a two-mode probe beam, where the two probe modes play a double role, either for generating the forward-FWM beams as well as a reference interfering beam. The technique relies on the phase conjugation property associated with the generated forward-FWM. Using a cold ensemble of cesium atoms and a pump beam red-detuned by 30 MHz from resonance of the closed transition $6S_{1/2}, F = 4, m_F = 4 \rightarrow 6P_{3/2}, F' = 5, m_{F'} = 5$, we have demonstrated directly the production of of light intensity squeezing. Possible extension of the present technique is also discussed for FWM processes involving more complex atomic-level schemes.

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I. INTRODUCTION

About four decades ago, The first experimental demonstration of squeezed light generation by Slusher *et al.* [1] initiated a new era in the quantum optics research field, leading to the phenomenal development of new platforms for quantum information processing based on continuous variables (CVs) [2–6]. In addition to applications in quantum metrology [7,8], the generation of squeezed light can lead directly to the production of CV entanglement of light, which is an essential resource in any quantum information processing protocol [9]. Several other quantum protocols based on discrete variables (DVs) have also been proposed and demonstrated [9], all of them being probabilistic protocols. For instance, the well-known DV probabilistic quantum Duan-Lukin-Cirac-Zoller (DLCZ) protocol [10] is one of the most investigated and employed to generate light-atom entanglement. On the other hand, CV quantum protocols allow deterministic generation and manipulation of entangled light [2,11], which might represent some advantages with respect to DV protocols. For instance, CV entanglement has been demonstrated between two macroscopic atomic ensembles [12], as well as quantum light to matter teleportation [13].

The observation of quantum phenomena in atomic systems, however, suffers from the deleterious effect of spontaneous emission, which tends to mask the quantum nature of the light-atom interaction. A seminal proposal for the observation of squeezing and entanglement in CV systems using atomic ensembles via four-wave mixing (FWM) was presented as a theoretical proposal in Refs. [14,15]. These previous schemes use three-level atoms in a Λ configuration thus allowing one to achieve high values of the third-order nonlinear susceptibility $\chi^{(3)}$, determining the efficiency of the FWM process, together with negligible absorption of the incident and generated light fields due to the creation of a dark state involving the two ground state levels of the Λ system, which mitigates the effect of spontaneous emission. Different groups have used this mentioned scheme to demonstrate a very high degree of squeezing in thermal atomic vapors [16–20]. However, in a cold ensemble of pure two-level atoms, i.e., a closed two-level system, excited by nonresonant high-intensity light, one can also achieve high values of the third-order nonlinearity with negligible absorption and a reduced effect of spontaneous emission. Indeed, it was demonstrated theoretically [21] that spontaneous FWM in a pure two-level system can lead to biphoton generation presenting quantum correlations. The clear experimental observation of this quantum correlation in a pure two-level system of cold rubidium atoms was recently demonstrated [22,23]. In these previous works, the quantum correlations are observed by measuring the second-order correlation function $g^{(2)}(\tau)$, which correspond to the DV domain. Our main goal in this work is to investigate quantum correlations in FWM in two-level atoms in the CV domain. It is worth mentioning that classical correlations have been recently observed in forward-FWM (FFWM) using cold two-level rubidium atoms [24]. As we have suggested in Ref. [25], FFWM associated with a two-mode incident probe beam could be used as a simpler experimental configuration to demonstrate light squeezing. Although we have to mention that previous works have also proposed [26] and demonstrated [27] the use of a dual probe beam in a phase-sensitive amplifier to enhance the degree of observed squeezing via the nondegenerate FFWM process in a three-level Doppler-broadened system, here we use the two-mode probe interfering technique to demonstrate intensity squeezing via FFWM in a two-level system of cold atoms, by which we observe squeezing under such an experimental configuration. Furthermore, we demonstrate that this self-interfering technique can work even in situations of very small FFWM reflectivity and gain, where the generated FFWM signal intensity is below the electronic noise level of the balanced detector. We have to mention that our proposed experimental configuration is different from the one used in Ref. [28] to

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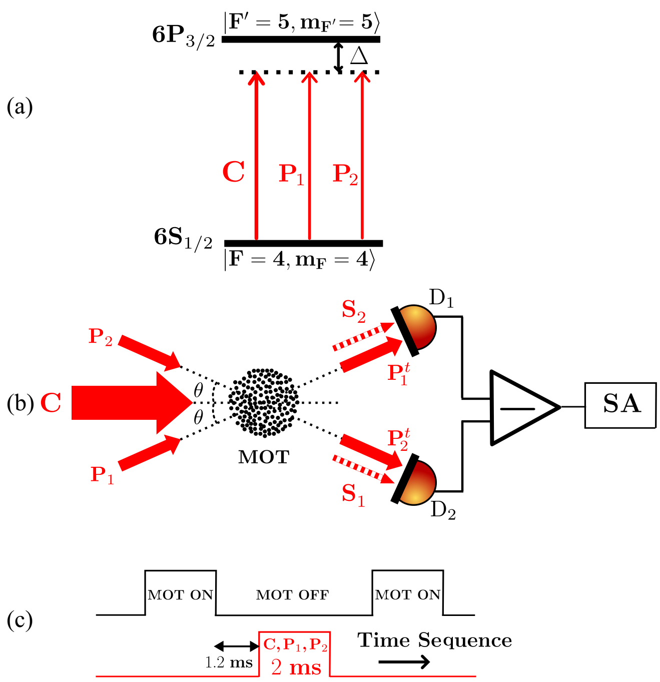

FIG. 1. (a) Pure two-level system associated with the cesium transition $6S_{1/2}(F=4, m=4) \leftrightarrow 6P_{3/2}(F'=5, m'=5)$, interacting with the incident pumping beam (C) and the two-mode probe beams (P_1 and P_2). (b) Experimental beam configuration to observe double FFWM associated with the two-mode probe. For small angle θ, each generated FFWM beam is nearly collinear with the other transmitted probe beam mode. (c) The time sequence: the beams C, P_1, and P_2 are turned on 1.2 ms after the MOT is turned off.

observe squeezing using a truncated SU(1, 1)-based FWM interferometer.

II. EXPERIMENTAL SCHEME

In this work, we use a pure two-level system of cold cesium atoms, produced by optical pumping, to demonstrate light intensity squeezing via FFWM. As indicated in Fig. 1(a), in the experiment we use the closed two-level system $6S_{1/2}(F=4, m_F=4) \leftrightarrow 6P_{3/2}(F'=5, m_{F'}=5)$ of cold cesium atoms obtained from a magneto-optical trap (MOT). The preparation of the atomic system was previously described in Refs. [29,30]. In Fig. 1(b) we show the incident configuration for the pumping C and the two-mode probe beams P_1 and P_2 and in Fig. 1(c) the time sequence for the measurements, while the MOT beams and the quadrupole magnetic field are switched off. We also use a microwave spectroscopy technique to cancel the local magnetic field [29]. All the beams are circularly polarized with the same helicity and each probe mode makes a small angle $\theta \approx 2^\circ$ with the pumping beam. All the beams have the same frequency which can be scanned around the resonance frequency of the two-level system by an acousto-optic modulator (AOM) not shown in the figure.

As we have demonstrated in Ref. [25], when the two modes P_1 and P_2 are present, each detector measures the coherent superposition of the incident probe mode with the FFWM-generated phase-conjugated beam associated with the other probe mode. The phase conjugation property of the FFWM signal leads to the same interference condition in each arm of the balanced detector, so the total intensity measured by each photodetector is always the same. As we will describe next, this is essential to directly measure the intensity squeezing in a balanced detector.

In order to analyze mathematically our technique, we calculate the instantaneous photocurrent in each arm of the balanced detector, which contains two optical field modes: the corresponding transmitted probe mode component and the FFWM phase conjugate field associated with the other probe mode component. If we represent the transmitted probe field component and the FFWM conjugate field component, respectively, by E_{P_1} and $E_{S_1} = \beta E^*_{P_2}$ and E_{P_2} and $E_{S_2} = \beta E^*_{P_1}$, the total field reaching each photodetector can be written as

$$E_1 = E_{P_1} + \beta E^*_{P_2}, \tag{1}$$

$$E_2 = E_{P_2} + \beta E^*_{P_1}, \tag{2}$$

where $\beta = \alpha \chi^{(3)} E_C^2$, with $\chi^{(3)}$ the effective third-order nonlinear susceptibility, E_C is the amplitude of the classical pumping field, and α a dimensional constant. Now we consider the probe and conjugate fields as quantum fields and replace the classical amplitudes defined above by field operators given by [28] $\hat{E}_{P_1} = [E_{P1} + \delta\hat{X}_{P_1}(\beta) + i\delta\hat{Y}_{P_1}(\beta)]e^{i\phi_{P_1}}$ and $\hat{E}_{P_2} = [E_{P2} + \delta\hat{X}_{P_2}(\beta) + i\delta\hat{Y}_{P_2}(\beta)]e^{i\phi_{P_2}}$, with $E_{P_1} = \langle\hat{E}_{P_1}\rangle$, $E_{P_2} = \langle\hat{E}_{P_2}\rangle$, and ϕ_{P_1} and ϕ_{P_2} being the corresponding optical phase. The quantum noise quadratures $\delta\hat{X}_{P_j}$ and $\delta\hat{Y}_{P_j}$ ($j = 1, 2$) are assumed to depend on β, i.e., on the nonlinear process. The photocurrents produced in each photodetector are given by $\hat{I}_1 = |\hat{E}_1|^2$ and $\hat{I}_2 = |\hat{E}_2|^2$, therefore, if we subtract the two photocurrent and neglect terms quadratic in the field quadrature noise operators, and assume the averaged field amplitudes are approximately equal ($\langle\hat{E}_{P_1}\rangle \approx \langle\hat{E}_{P_2}\rangle$), we obtain the instantaneous photocurrent difference,

$$\hat{I}_- = \hat{I}_1 - \hat{I}_2 = 2E_{P_1}[\delta\hat{X}_{P_1}(\beta) - \delta\hat{X}_{P_2}(\beta)](1 - |\beta|^2). \tag{3}$$

This simple result shows that the photocurrent difference gives directly the difference in the fluctuations associated with the same quadrature of the two field modes. The noise power variance, defined by $\langle\Delta I_-^2\rangle = \langle I_-^2\rangle - \langle I_-\rangle^2$, is given by

$$\langle\Delta I_-^2\rangle \propto \langle[\delta\hat{X}_{P_1}(\beta) - \delta\hat{X}_{P_2}(\beta)]^2\rangle(1 - |\beta|^2)^2. \tag{4}$$

It is worth noting from Eq. (4) that the measured variance does not depend on the relative phase of the two-mode probe and that just a single balanced detector is enough to measure directly light intensity squeezing. Moreover, by just switching off the MOT, our employed scheme also allows to measure directly the shot-noise level associated with the incident probe mode intensity. For beams with the same circular polarization, the atoms are pumped into the highest magnetic Zeeman ground state level, forming a pure two-level system. We first detected separately each FFWM signal, associated with each probe mode, using two removable mirrors, which send the corresponding signal to two independent fast photodetectors, not shown in the figure.

III. EXPERIMENTAL RESULTS AND DISCUSSIONS

In Fig. 2 we show the generated FFWM signal spectrum associated with one of the mode component of the incident

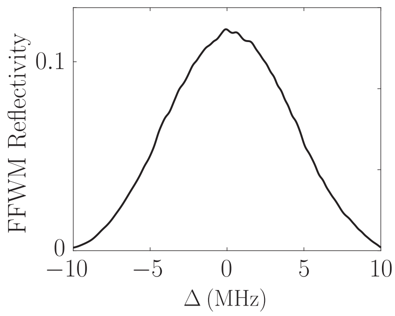

FIG. 2. FFWM spectrum associated with the probe mode P_1. The FFWM spectrum associated with probe mode P_2 is similar. Each spectrum is measured separately in the absence of the other probe beam mode. The reflectivity is measured with relation to the intensity of the corresponding probe mode.

probe beam (P_1) as a function of the common frequency detuning Δ from the atomic resonance. The scanning range is limited by the AOM efficiency. However, as the frequency is scanned around the atomic resonance, to record this spectrum, we have reduced the pumping and probe beam intensities to approximately 1.6 $\mathrm{mW/cm^2}$ and 0.02 $\mathrm{mW/cm^2}$, in order to avoid the strong pushing of the cold sample. The FFWM signal associated with the other probe mode is nearly identical to the one shown in Fig. 2 and the reflectivity of both signals, measured in relation to the corresponding intensity of the incident probe mode component, is of the order of 10%. As can be seen, the FFWM signal linewidth is of the order of 10 MHz and corresponds to the power-broadened linewidth of the two-level transition with a natural linewidth $\Gamma/2\pi = 5.2$ MHz.

To measure the quantum fluctuations associated with the double FFWM processes, we fixed the pumping and probe beams' common detuning at 30 MHz ($\approx 6\Gamma$) below the atomic resonance and increased the pumping and probe beam intensities, respectively, to 50 and 0.9 $\mathrm{mW/cm^2}$. This detuning was chosen in order to minimize the losses due to absorption which was measured to be approximately equal to 4%. It is difficult to measure directly the gain or the reflectivity of the FFWM process under this exact experimental condition, since the FFWM signal associated with the two-level system is masked by the FFWM signal associated with the recoil-induced resonance (RIR), which presents a higher reflectivity under the same experimental conditions, as we have reported in Ref. [25]. However, we can roughly estimate the FFWM reflectivity and gain in our squeezing measurement from the FFWM spectrum shown in Fig. 2, which gives a reflectivity of about 10% measured on resonance for a pump intensity about 3% of the intensity used in the squeezing measurement. Considering that the FFWM intensity scales as $Ip^2/[1 + (\delta/\Gamma)^2]^3$, where Ip is the pump intensity and $\delta/\Gamma = 6$ for a detuning of 30 MHz, we estimate a FFWM reflectivity of about $R = 0.18\%$. Thus, the corresponding gain associated with the FFWM process scales as $(1 + 2\sqrt{R})$ and leads to an estimated gain of the order of $G = 1.08$.

For this probe intensity level, the detected signal is above the electronic noise of the balanced photodetectors (ThorLabs: PDB465A-AC), which only allows high-frequency measurements for the photocurrent difference associated with the two photodetectors. We then used this amplified balanced detector shown in Fig. 1(b) to detect the intensity difference associated with the two interfering probe modes and the nearly collinear generated FFWM. The RF output signal of the balanced detector is then fed into a radio-frequency spectrum analyzer set at 10 MHz with zero span, with a resolution bandwidth of RBW = 1 MHz, and a video bandwidth of VBW = 1 MHz, and a sweep time of 20 ms. The spectrum analyzer is triggered by the incident probe pulse shown in the time sequence of Fig. 1(c). The 10 MHz chosen for the analysis frequency is within the bandwidth of the FFWM signal and gives the maximum squeezing, although we have also observed squeezing at 5 MHz. It is worth mentioning that at these analyzed frequencies, we completely eliminate the contribution of the FFWM signal associated with RIR, which has a bandwidth of about 20 KHz.

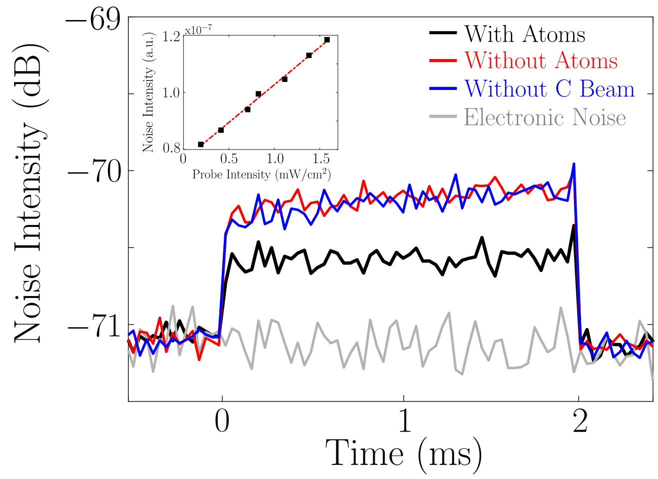

FIG. 3. Black curve: measured difference intensity noise in the presence of the FFWM beams generated by each probe mode. Blue curve: measured intensity noise, when the pumping beam is blocked. Red curve: measured intensity noise for the case where the cold atoms are removed. Under this situation, the measured noise level corresponds to the shot-noise level associated with the corresponding incident probe intensity. The gray curve corresponds to the electronic noise level. Inset: shot-noise level as a function of the incident probe intensity.

Our main results are presented in Fig. 3, where the black curve shows the averaged measured noise power in the presence of the cold atomic ensemble and the two generated FFWM signals. As can be seen in the figure, this noise power level is clearly below the measured noise power level when either the cold atomic sample (red curve) or the pumping beam C (blue curve) are removed. Our experimental beam configuration also allows us to directly determine the shot-noise level associated with a specific intensity of each probe mode. Since the estimated FFWM gain is small, the change in the probe intensity is negligible and the shot-noise level can be measured at the incident probe intensity. Moreover, we have previously demonstrated that for our experimental scheme, the interference condition for each total field reaching each detector is always the same and maxima and minima of interference occur simultaneously. Therefore, as the

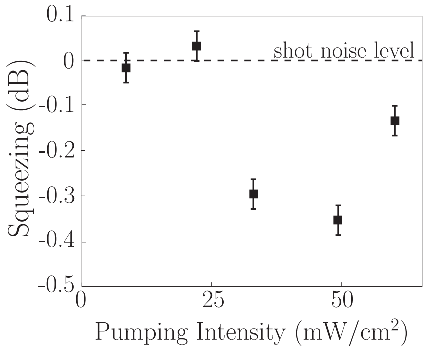

FIG. 4. Measurement of the squeezing level for different pumping beam intensities.

relative probe phases are not controlled in our experiment but vary randomly, the average intensity in each detector is equal to the incident probe intensity, even in the presence of the FFWM process. Based on this we consider the calibration for the shot-noise level at the incident probe intensity. Thus, the curve obtained in the absence of the cold atomic ensemble furnishes the corresponding shot-noise level associated with the incident probe intensity. From the data presented in Fig. 3, we estimate a difference intensity squeezing of approximately -0.35 ± 0.05 dB, compared to the level of shot noise at the used probe intensity of 0.9 $\mathrm{mW/cm^2}$. However, despite this relatively low degree of squeezing, if we subtract the electronic noise, we obtain a relative noise reduction of 64%. In the inset of Fig. 3, we show the measured noise intensity for different intensities of the probe beam, which clearly shows the expected linear dependence. It is worth noting that for the very low intensity of the generated FFWM signal, a single-seeded probe beam would not allow us to measure directly the quantum variance, since the FFWM intensity would fall below the electronic noise floor of the detector. However, with the double-seeded FFWM scheme the squeezing variance, which is coherently amplified via the self-interfering mechanism using the strong probe beams as a reference, is measured at a level that is clearly above the electronic noise (gray curve in Fig. 3).

We have also measured the level of squeezing for different intensities of the pumping beam, and the result is depicted in Fig. 4. Although the physical origin of this observed pump intensity dependence, is still under investigation. Indeed, we note that the simple linearized model [Eqs. (3) and (4)] presented here does not account for the observed dependence of squeezing on pump intensity, and that this effect is an experimental result attributed to complex, unmodeled factors such as competing reflectivity changes and atomic density variation caused by the pump beam pushing.

IV. CONCLUSIONS

In summary, we have demonstrated the observation of squeezed light via FFWM using a pure two-level system of a cold ensemble of cesium atoms. We have applied a self-interfering technique to detect intensity squeezing in which the incident two-mode probe beam also plays the role of an interfering reference beam. This technique could in principle be extended to other atomic-level schemes involving different FWM processes. For instance, in nondegenerate FFWM in a three-level atomic system, one can employ a two-mode probe having different frequencies. In particular, it will be useful in situations where the parametric gain associated with the FWM process is such that the generated optical signal intensity is below the electronic noise level of the balanced detector. As we have suggested in Ref. [25], we emphasize that the present self-interfering technique could in principle be used to measure intensity squeezing in FFWM via recoil-induced resonance if balanced detectors with low electronic noise at the kilohertz range are used.

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DATA AVAILABILITY

The data that support the findings of this article are not publicly available. The data are available from the authors upon reasonable request.

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