Strong quantum correlations in four wave mixing in ⁸⁵Rb vapor

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ABSTRACT

We study quantum intensity correlations produced using four–wave mixing in a room–temperature rubidium vapor cell. An extensive study of the effect of the various parameters allows us to observe very large amounts of non classical correlations.

1. INTRODUCTION

Quantum mechanical description of the electromagnetic field introduced 45 years ago the fundamental concepts of coherent state associated to a "standard quantum noise" that describe quantum fluctuations associated to uncertainty principle.[1] At the same time, this description clearly showed the possibility to create squeezed states in which purely quantum correlations can reduce quantum fluctuations associated to an observable while increasing the fluctuations associated to its conjugate (*e.g.* two quadratures of the field) *e.g.*[2] Beyond the beautiful observation and verification of quantum optical properties exhibited by intense beams, the experimental realization of quantum correlated beams may become of practical importance in order to increase the precision in optical measurements ("noise reduction") or as a resource for quantum information protocols. Therefore, the search for physical systems capable to generate large noise reduction stems from applications such as quantum information[3] or for the observation of very weak signals such as those expected in gravitational wave detection.[4]

Four–wave mixing (4WM) in optical media displaying $\chi^{(3)}$ nonlinearities enables the generation and amplification of so–called signal and idler beams in the presence of an intense pump beam. Because signal and idler beams are generated by parametric conversion of two pump photons, 4WM has been identified very early on as a very efficient method to generate intense, non classical correlated beams.[5] Indeed, the first demonstrations of squeezed light were made using 4WM 25 years ago.[6–8] Soon after, it was realized that parametric generation in $\chi^{(2)}$ crystalline media also provided very efficient sources for the generation of intense non–classical states[9, 10] with the advantages associated to non-absorbing optical materials. Indeed record amounts of quantum correlations[11] or of quantum noise reduction[12] were produced using optical parametric amplifiers based on $\chi^{(2)}$ media. However, recently, $\chi^{(3)}$–based experiments regained a novel interest. In fact, very large amounts of quantum correlations between intense beams have been demonstrated in an experiment based on non–degenerate 4WM in "hot" atomic vapors.[13, 14] These experiments have a significant advantage over $\chi^{(2)}$ based nonclassical beam generation: the strong nonlinearity allows for a single-pass geometry, in the absence of an optical cavity devoted to nonlinearity enhancement in the Continuous–Wave regime. This is specially important for spatially multimode quantum effects involved, for example, in quantum imaging.[15, 16]

In this paper we present results concerning an extensive exploration of the performances (in terms of quantum noise reduction) of intensity–correlated beams generated by 4WM in a hot ⁸⁵Rb cell with an experimental setup largely inspired by previous successful experiments[13, 14] . We have thus explored in detail the parameter space, aiming to find regions where the largest noise reductions can be found. The paper is organized as follows: in section 2, we give a brief description and characterization of the experimental set–up while in Sec. 3, we report and comment the behavior of the amount of quantum noise reduction as a function of the experimental parameters, namely the temperature of the cell T, the pump power, the one (Δ) and two–photon (δ) detunings with respect to the atomic resonances. This approach allowed us to obtain up to 9.2 ± 0.5 dB of quantum noise reduction on the intensity difference between the signal and idler modes.

2. EXPERIMENTAL SET–UP

The main ingredients of the experiment are schematized in Fig. 1: an intense pump tuned near the D_1 line is mixed with a weak signal beam inside a cell containing isotopically pure ^{85}Rb. As a result of the 4WM process, at the output of the cell, the signal beam can be amplified and a conjugate beam created. Quantum correlations between the two beams (relative–intensity squeezing) are measured by a pair of high quantum-efficiency photodiodes coupled to a spectrum analyzer (see Fig. 1).
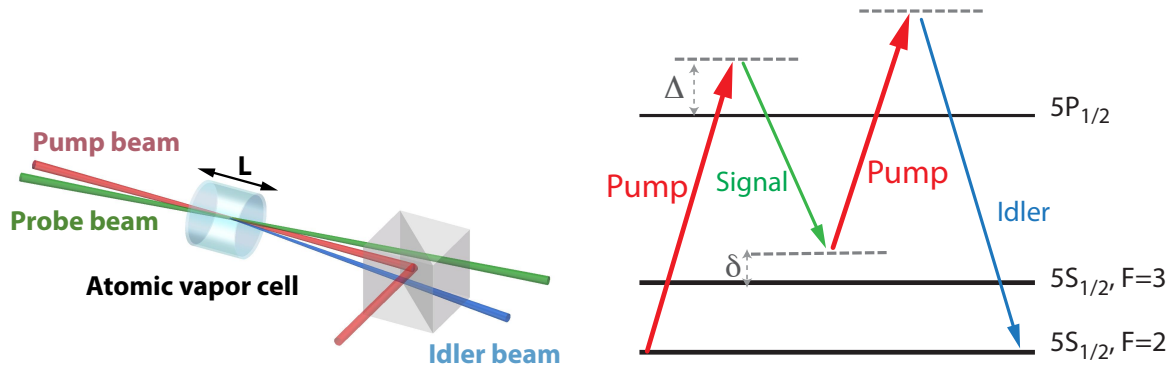

Figure 1. Left: schematic beam path of the 4WM experiment. Right: Relevant levels of the ^{85}Rb D_1 line. We define Δ as one–photon detuning and δ as two–photon detuning.

As in the experiment presented in[13] the setup is based on a continuous–wave ring–cavity single–mode Ti:Sa laser (Coherent MBR, in the present case) stabilized close to the D_1 line ($5S_{1/2} \rightarrow 5P_{1/2}$) of ^{85}Rb. The laser delivers up to 3 W with a linewidth smaller than 1 MHz. The major part of the power (2.5 W) can be used as a pump beam. The probe beam is obtained by diffracting the the remaining power in a double-pass acousto-optic modulator (AOM) operating around 1.5 GHz (Brimrose GPF-1500) obtainig optical powers in the range 0–300 μW. Thus, the frequency detuning between pump and signal beams can be adjusted around the hyperfine splitting of the ^{85}Rb ground state (3.036 GHz). The pump and probe beams are collimated over respectively 650 μm and 350 μm beam waists (radius at $1/e^2$) and crossed at very small angle ($\simeq 1$ mrad) inside a $L = 12.5$ mm long Rubidium cell heated at temperatures ranging from 80 °C to 200 °C. Pump and probe beams are linearly cross polarized so that we can filter out most of the pump beam with a polarizing beam splitter (extinction ratio $\simeq 10^{-5}$, Fichou). Our detection scheme is based on a commercial balanced detection system (Thorlab PDB150) where two silicon photodiodes are placed in a configuration where their photo–currents are substracted. The difference photocurrent is converted to tension with a transimpedance ampliflier with a switchable gain (typically 10^5 V/A) and sent to a spectrum analyser (Agilent N1996A) to perform a frequency analysis at a fixed frequency denoted ω. In the last part of this study we replaced the original detector by a couple of two very low noise, high quantum efficiency photodiodes that have been opened (no protecting glass) and placed at Brewster angle. Unless otherwise noted, all measurements were made with a resolution bandwidth of 100 kHz and a video bandwidth of 10 Hz.

Some particular attention has been devoted to the noise on the input signal beam.

2.1 Input technical noise on signal beam

Similarly to what occurs in optical parametric amplifiers, the technical fluctuations of the input beam are important.[19] As mentioned above, the input beam is produced by a double pass in an AOM. As shown in Fig. 2, in our setup the type of RF source driving the AOM plays a crucial role on the measured fluctuations on the output beam.

Figure 2 shows the excess noise on the input signal beam at the output of the AOM as a function of the pump power for two types of RF sources, namely

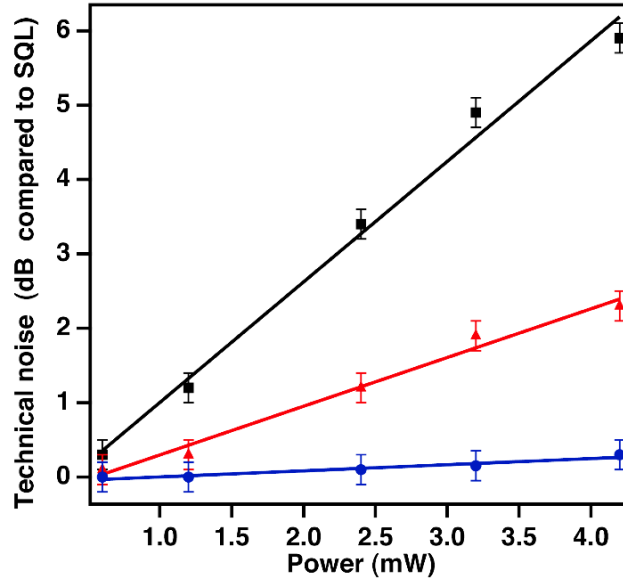- an unstabilized Voltage–Controlled–Oscillator (VCO) with a 30 dB amplifier operating in the non–saturated regime;

Figure 2. [Color Online]Excess noise as a function of input optical power for three types of RF sources, Voltage–Controlled-Oscillator (black squares), synthesizer and non–saturated amplifier (red triangles), synthesizer and saturated amplifier (blue circles).

- a synthesizer (Rohde & Schwarz SMA100A) with a 30 dB amplifier operating in the saturated or non–saturated regime.

As can be expected, the largest amount of technical noise is observed with the unstabilized VCO as compared to the synthesizer. For the synthesizer, Fig. 2 shows that it is crucial to drive the AOM with an amplifier in the saturated regime. Let us mention that in the case where either the VCO or the unsaturated amplifier were used, the excess noise on the input beam prevented us from observing noise reduction.

3. INFLUENCE OF THE EXPERIMENTAL PARAMETERS ON QUANTUM NOISE REDUCTION

Several parameters play a significant role on the observed quantum correlations. An extensive study has been led of which we detail here the most significant results. Let us mention that, whereas in the reported figures the parameters seem to span quite short intervals, we explored a larger region in the multi-dimensional parameter–space. We report here only the significant curves traced around the most favorable working parameters, having in mind that for a slight change in the parameters that are not scanned, one can easily recover quantum noise reduction regime by re-adjusting the bias on the parameter of interest.

3.1 Cell temperature

The cell temperature modifies the atomic density, the Doppler width and the transit time in the beams.

Across the presented temperature range (110°C to 126°C), the Doppler width and the transit time change only by 2 %.

On the contrary, the atomic density changes dramatically. The density is derived from the Clausius–Clapeyron formula and assuming ideal gas so that

$$n_{at} = \frac{1}{k_b T} p_0 \exp(-A \times T) \tag{1}$$

where p_0 and A are given in.[18] For these parameters, the density varies between $n = 1.1 \ 10^{13}$ atoms/cm^3 for $T = 110°$ C and $n = 2.8 \ 10^{13}$ atoms/cm^3 for $T = 126°$ C.

The effect of the temperature and thus on the number of atoms on the gain and quantum correlations is shown in Fig. 3.
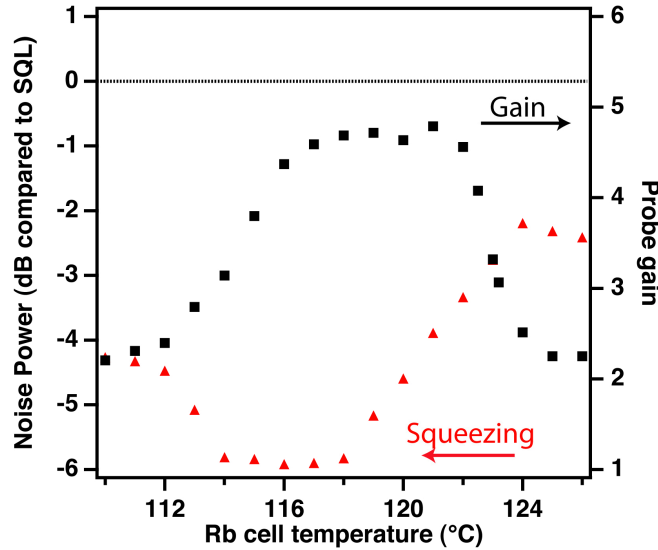

Figure 3. Normalized noise power of the intensity difference of the signal and idler as a function of the temperature. Other parameters are $P_{pump} = 500$ mW, $\delta = +10$ MHz, $\Delta = 800$ MHz, $\omega = 1.5$ MHz.

This curve displays an optimal region which can be understood taking into account two effects. At low temperature / density, the number of atoms interacting with the laser beams is too small which limits both the gain and the quantum correlations. At higher temperature, higher other nonlinear effects (for instance self–focusing) occur which rapidly degrade the quantum correlations.

3.2 One photon detuning

Another crucial parameter for the gain and the quantum correlations is the one photon detuning Δ between the pump and the $5S_{1/2}, F = 3 \rightarrow 5P_{1/2}$ transition. Let us note that the excited level's hyperfine structure can be neglected as it is much smaller than the explored detuning range. The effect of this parameter is displayed in Fig. 4.

The dependence of noise reduction on one photon detuning can be understood in the following way. Close to resonance, absorption becomes large which reduces the quantum correlations. Far from resonance, the non linearity decreases thus also reducing the correlations. The typical bandwidth is given by the Doppler broadening (350 MHz, FWHM).

3.3 Two photon detuning

We now turn our attention to the effect of two–photon detuning, δ (see Fig. 5).

Both the gain and the quantum correlations display an optimum value around zero two–photon detuning as can be expected from resonant enhancement. However, no simple physical picture accounts for the observed shift ($\approx$ 10 MHz) between the optimal gain and the optimal noise reduction.

3.4 Pump power

We consider now the effect of the input pump power whose effect is displayed on Fig. 6.

In this figure, one observes that both the gain and the quantum correlations increase with the pump power, in agreement with the expected enhancement of the optical non linearity. Note that however the self–focusing effects sets an experimental limit to the pump power.
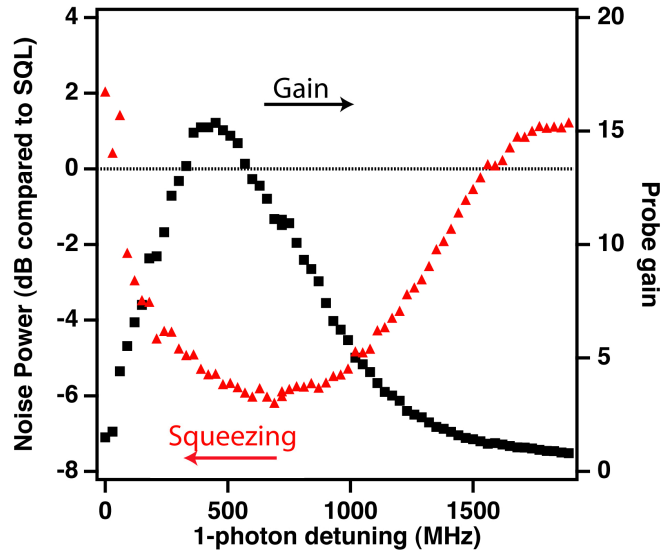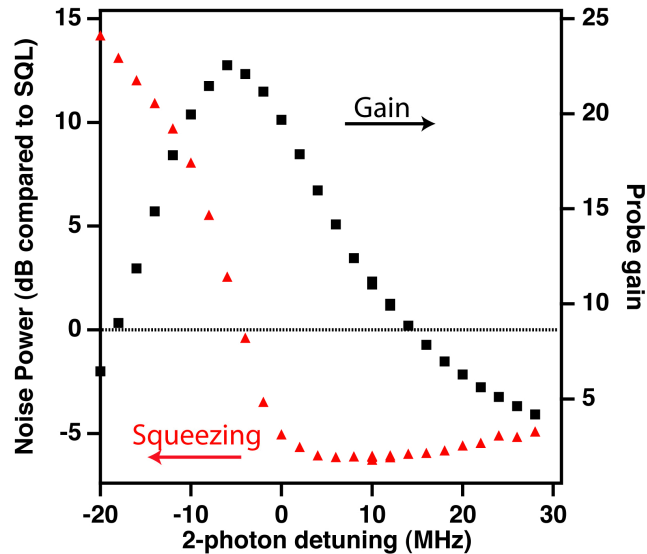
Figure 4. Normalized noise power of the intensity difference of the signal and idler as a function of the one–photon detuning Δ. Other parameters are $P_{pump} = 800$ mW, $\delta = +10$ MHz, $T = 114°$C, $\omega = 1.5$ MHz.

Figure 5. Normalized noise power of the intensity difference of the signal and idler as a function of the two–photon detuning δ. Other parameters are $P_{pump} = 800$ mW, $\Delta = 800$ MHz, $T = 114°$C, $\omega = 1.5$ MHz

Let us note that the relevant parameter is not the absolute power but the intensity per unit surface (proportional to the Rabi frequency). Varying this Rabi frequency can be done either by changing the pump power or the beam radius. However, lowering the beam radius shortens the interaction time with the atoms which might lead to spurious effects.[20]

3.5 Optimal noise reduction

We present here recent results obtained with improved photodiodes, Hamatsu S3883 (in particular with the protection window removed). We plot in Fig. 7 the noise power of the intensity difference of the signal and idler as a function of the frequency after correction of the electronic noise: a noise reduction of 9.2 dB of quantum noise reduction on the intensity difference of the signal and idler modes is observed. To our knowledge, this is the largest noise reduction observed to date with an atomic medium.
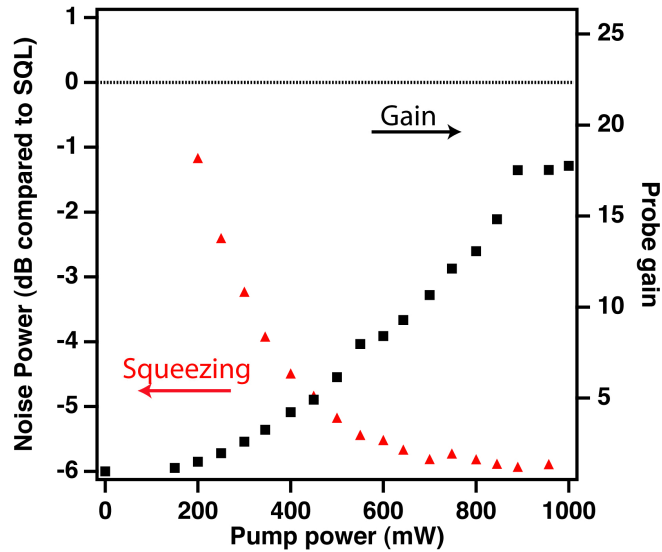
Figure 6. Normalized noise power of the intensity difference of the signal and idler as a function of the pump power. Other parameters are $\Delta = 800$ MHz, $\delta = +10$ MHz, $T = 114°$C, $\omega = 1.5$ MHz
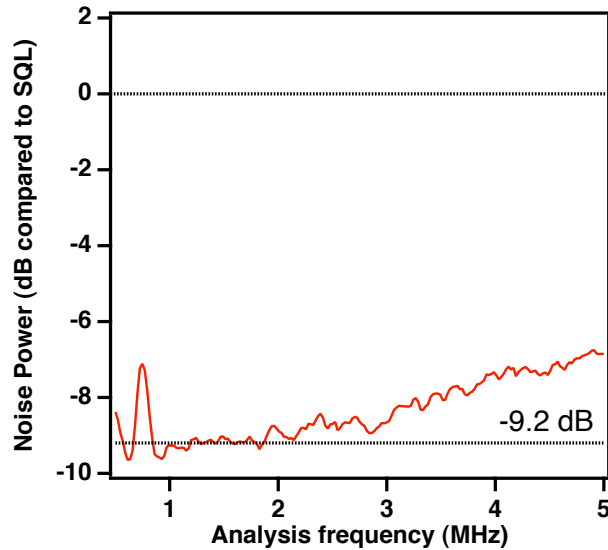

Figure 7. Noise power of the intensity difference of the signal and idler as a function of the frequency after correction of the electronic noise. A reduction of 9.2±0.5 dB is reached around 1 MHz. Other parameters are $\Delta = 750$ MHz, $\delta = +6$ MHz, $T = 118°$C, $P_{pump} = 1200$ mW

In practice, this noise reduction is mostly limited by the losses sustained by the two beams. These losses are the following:

- reflection on the cell's output window, measured at 1.5 ± 0.5 %;

- cumulative losses on the polarizing beamsplitter used to separate the pump beam from the signal and idler beams, on the iris used to spatially filter the signal and idler modes, and on the mirrors used to deflect those two beams, estimated at 3 ± 1%;

- limited quantum efficiency of the photodiodes. This value is difficult to measure as the gain of the photodetection system is unknown.

If one considers a perfect quantum efficiency for the photodiodes, thus taking into account only the cell and propagation losses, a conservative estimation of the noise reduction is -11.0 dB±0.7 dB below the standard quantum limit for independent beams.

4. CONCLUSION

We have studied the effects of the temperature of the cell, the pump power, the one and two–photon detunings with respect to the atomic resonances on the amount of quantum correlations produced by four–wave mixing in a rubidium vapor cell. For each of these parameters, optimal value are presented which allow for the observation of large quantum correlations, corresponding to 9.2 ± 0.5 dB of quantum noise reduction on the intensity difference of the signal and idler modes (-11.0 dB±0.7 dB, taking into account the propagation losses).

Such a source provides a simple and efficient source of large CW quantum correlations required by quantum information or quantum measurement protocols in the absence of any optical cavity.

This study opens the way for a better comprehension of this system. This would require a detailed model of the quantum properties of the system including the various sources of decoherence. Such a model would allow for optimal conditions to be found as well as predicting its extension to other operating conditions (other lines, alkali, etc.)

Acknowledgments

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