Experimental Realization of a Quantum Optical Tap

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We have realized a system which is able to read out information encoded on the amplitude of a laser beam without degrading the signal-to-noise ratio of the carrier. This has been implemented using the two-photon cross-phase-modulation effect of a three-level system in a sodium atomic beam located in a doubly resonant optical cavity. We have achieved an improvement by a factor of 1.35 of the overall information transfer compared to any classical optical tap, where a perfect quantum duplicator would reach the ideal value of 2.

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A quantum measurement usually perturbs the quantity being measured by adding noise in the system under study. The purpose of a quantum nondemolition (QND) measurement is to control this backaction noise, by feeding it back exclusively into the observable complementary to the one being measured [1]. Quantum optics is a particularly well suited domain for performing QND measurements [2] since quantum-noise-limited sensitivity can easily be achieved, and good nonlinear media are available. The standard configuration is the measurement of a quadrature component of a laser beam (signal beam) by coupling it to a quadrature component of another laser beam (meter beam) in a nonlinear medium [3,4]. The aim of a QND measurement is then to read out the information carried by the input signal field, without this information being degraded by the measurement process. The effectiveness of a QND measurement can be characterized by three properties [5–8]: (1) The signal should not be excessively degraded by the measurement (nondemolition property). (2) The meter beam should pick up some information about the signal beam so that a measurement is actually performed (efficiency of the measurement). (3) The meter output should be quantum correlated with the signal output so that the readout of the probe does give some information about the outgoing signal (output quantum correlation).

It is to be noticed that the two first properties involve the input signal beam, whereas the third one does not. As a matter of fact, most experimental realizations so far [9–11] have focused on the quantum correlations of the two output beams characterizing the quantum-state preparation ability of the device, but the two in-out properties were not precisely discussed (see, however, Refs. [12,13]).

Actually, the two in-out correlations are the relevant properties to consider for the realization of a quantum optical tap. An optical tap is a device that is able to extract the information encoded as a classical modulation on a given quadrature of a carrier optical wave, leaving the information readable by other users down the line [5]. In order to investigate the quantum properties of such a device, the quantum noise of the different beams must be taken into account. One defines then the signal-to-noise ratio (SNR, or simply R in the equations) as the ratio of the intensity of a classical modulation at a given frequency by the quantum noise power at the same frequency for a given quadrature,

$$R = \langle X\rangle^2/\langle \Delta X^2\rangle \,, \tag{1}$$

where X is the modulated quadrature and where all quantities are defined in the frequency domain [8].

A simple classical optical tap would naturally be the beam splitter. Let us analyze its quantum properties. For a beam splitter whose transmittivity is t^2, the relations between the various signal-to-noise ratios are the following:

$$R_{\rm sig}^{\rm out} = t^2 R_{\rm sig}^{\rm in} \,, \qquad R_{\rm met}^{\rm out} = (1-t^2) R_{\rm sig}^{\rm in} \,, \tag{2}$$

where the subscript "sig" is for the signal and "met" for the meter.

Let us define now the following transfer coefficients [14]:

$$T_{\rm sig} = \frac{R_{\rm sig}^{\rm out}}{R_{\rm sig}^{\rm in}}, \quad T_{\rm met} = \frac{R_{\rm met}^{\rm out}}{R_{\rm sig}^{\rm in}} \,. \tag{3}$$

For a beam splitter we thus have $T_{\rm sig}+T_{\rm met}=1$, and more generally, it can be shown that $T_{\rm sig}+T_{\rm met}$ cannot exceed unity for any classical device [12,15]. In this case, the more information is extracted from the signal through the meter, the more the signal is degraded: One has then to compromise. But quantum mechanics allows us to avoid this compromise by authorizing in principle the conservation of the input SNR in both outputs in the case of a perfect QND measurement. For a real life but quantum situation, we have

$$1 < T_{\rm sig} + T_{\rm met} \le 2 \,. \tag{4}$$

The interest of such a system for tapping information in a multiuser telecommunication network is therefore obvious. Shapiro raised the problem as early as 1980 [5] in terms of SNR transfer and proposed means of implementing such a device by entering squeezed light through the usually unused second input channel of a beam splitter.

In this Letter, we report a QND experiment using a cross-phase-modulation effect [3,4,16], where the quantum optical tap properties are clearly evidenced through direct measurement of the transfer coefficients for the signal-to-noise ratios.

The experimental setup used for this experiment (Fig. 1) is an improvement of those used in Refs. [11,12]. The nonlinear coupling of the signal and meter fields is obtained in a beam of three-level atoms in a ladder configuration ($3s_{1/2}$-$3p_{3/2}$-$3d_{5/2}$ levels of sodium atoms). The atomic beam provides a density of 5×10^{11} atoms/cm^3, over an interaction length of 1 cm, with a Doppler width of about 200 MHz (FWHM). Two cw electronically stabilized dye lasers are tuned around 589 nm (meter beam) for the lower transition and 819.5 nm (signal beam) for the upper one. The nonlinearity is enhanced by placing the nonlinear medium in a doubly resonant optical cavity (5.2 cm long, 5 cm mirror radius) with a good finesse (100 for each wavelength) and low losses. One of the mirrors [17] is a high reflector at 589 nm ($t^2=7\times10^{-4}$) and is the input-output mirror for the 819.5-nm beam ($t^2=7\times10^{-2}$) while the other one is a high reflector at 819.5 nm ($t^2=5\times10^{-4}$) and is the input-output mirror for the 589-nm beam ($t^2=7\times10^{-2}$), so that the cavity is single ended at each wavelength. The total losses are characterized by the on-resonance cavity reflection coefficient which is 0.95 for the 819.5-nm beam and 0.90 for the 589-nm laser beam. One mirror is piezoelectrically mounted, allowing the length of the cavity to be adjusted. In order to have a phase-sensitive low-intensity detection, a homodyne detection with local oscillator power of 800 μW and fringe visibility of 0.92 is used on the meter beam, while the signal output is directly detected. The detectors are *p-i-n* silicon photodiodes with quantum efficiency of 0.78 at 589 nm and 0.93 at 819.5 nm followed by low-noise preamplifiers.

We use the *ghost transition* configuration of Ref. [18] (see also Ref. [19]). The meter beam is tuned around the lower atomic transition and has a very small power (5 μW) compared to the signal beam (about 300 μW) which is tuned around the upper transition. In this configuration, the absorption of the signal beam is very small. This guarantees a nearly perfect nondemolition interaction while the coupling between the amplitude of the signal and the phase of the meter beam can be quite large [18].

The experimental procedure is the following. The cavity length being scanned, the detuning, and eventually the power of the lasers are adjusted in order to find a good working point. A good working point is obtained when the cavity is resonant at both wavelengths with a reasonably strong nonlinear coupling between the two fields. A typical situation is shown in Fig. 2: The meter beam is "attracted" to resonance by the strong signal beam due to the nonlinear phase shift induced by the signal field. The latter is itself not perturbed by the meter beam (of much weaker intensity) therefore avoiding two-photon bistability [20]. A typical detuning of the meter beam is -1.5 GHz, while the signal beam is tuned at about $+0.5$ GHz of the upper atomic transition [21]. When a good working point has been found, the scanning of the cavity is

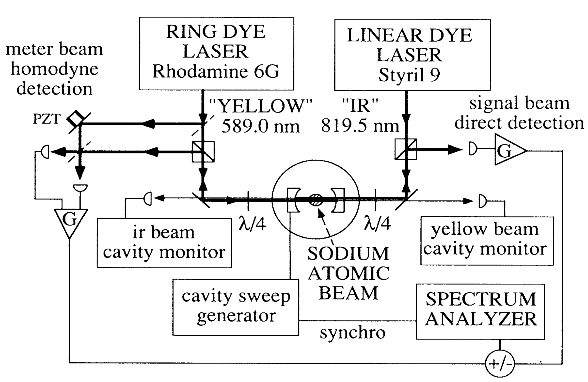

FIG. 1. Experimental setup. Each laser beam goes through a prism polarizer, is circularly polarized by a λ/4 plate, then resonates in the cavity, comes back through the λ/4 plate, and is reflected off the prism polarizer. The ir signal beam is directly detected, whereas a homodyne detection is used for the yellow meter beam. The phase of the local oscillator is scanned using a piezoelectric transducer (PZT). The intracavity intensities can be monitored using the leaks of each high reflector mirror.

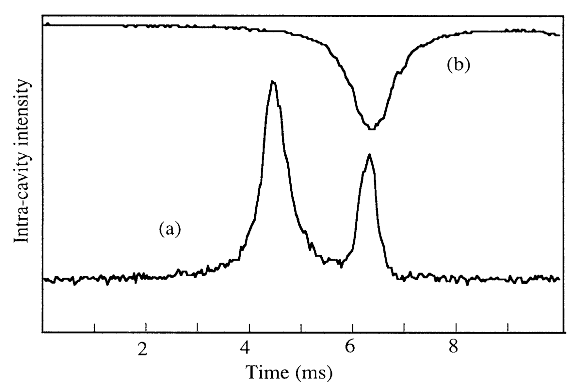

FIG. 2. Behavior of the intracavity mean fields. The length of the cavity is swept in time. Traces *a* and *b* are, respectively, the intracavity intensity of the meter and the signal beam. The signal intracavity intensity (*b*, inverted for clarity) has the usual Airy shape and is not perturbed by the weak meter beam. The lower peak on the meter intracavity intensity (*a*) is "attracted" by the resonance peak of the signal, due to the cross nonlinear phase shift. The other peak (on the left-hand side) is the resonance of the meter beam alone. The distance between the two peaks gives a measure of the nonlinear phase shift induced by the signal on the meter beam. The signal power is 265 μW, the meter power is 5 μW, the meter atomic detuning is -1.5 GHz, and the two-photon detuning is around -1 GHz.

switched off, and the cavity is tuned to the double resonance. A classical amplitude modulation at 10 MHz is applied by an electro-optical modulator on the signal beam and the measurement is read out on the phase of the 589-nm laser beam. The levels of the modulations transferred onto the output signal and meter beams are then compared with the signal input modulation level using a spectrum analyzer (Fig. 3). The level of the signal modulation reflected off the off-resonant cavity is taken as the reference input modulation level.

Typical results are presented in Fig. 3. The level difference between the peak and the background noise corresponding to the signal beam (recorded off resonance) gives the input signal-to-noise ratio $R_{\rm sig}^{\rm in}$ (trace *a*). The readout of the meter beam is achieved via the homodyne detection, whose phase is continually scanned, giving the fringes in trace *b* of Fig. 3. By comparing them with the interference pattern between the local oscillator and the output meter beam, we have checked that the superior envelope of these fringes corresponds to the phase quadrature, which is the one picking up the modulations of the signal beam. These modulations can either be the quantum fluctuations of the signal beam or the classical modulation inscribed on it. The observed phase noise for the meter beam corresponds to the transfer of the quantum noise of the signal, in addition to the input vacuum noise and some unwanted extra noise. The level of the transfer of the classical modulation encoded on the signal beam onto the meter beam is to be read as the peak level of the superior envelope of trace *b*. The transferred signal-to-noise ratio $R_{\rm met}^{\rm out}$ is then measured as the level difference between the peak and background noise of the phase quadrature. From Fig. 3, the raw transfer from the signal onto the meter is -3 dB which gives, after corrections due to amplifier noise, a measurement transfer coefficient $T_{\rm met}=0.45$. This correction is due to the fact that the shot noise levels are about 8 dB above the amplifier noises, so the amplifier noises must be subtracted from the experimental noise levels. On the other hand, no significant degradation of the signal could be observed. Therefore the signal degradation can be estimated according to overall losses due to the imperfection of optical elements along the propagation of the beam. This gives a raw SNR transfer for the signal $T_{\rm sig}=0.9$. As a consequence, we obtain a sum of the signal and measurement SNR transfers $T_{\rm sig}+T_{\rm met}=1.35$, which can be seen as a 1.3 dB improvement of the overall information transfer of any classical optical tap (a beam splitter, for example). A perfect quantum optical tap would have $T_{\rm sig}=T_{\rm met}=1$ which would give a perfect 3 dB improvement, and could also be regarded as a quantum duplicator.

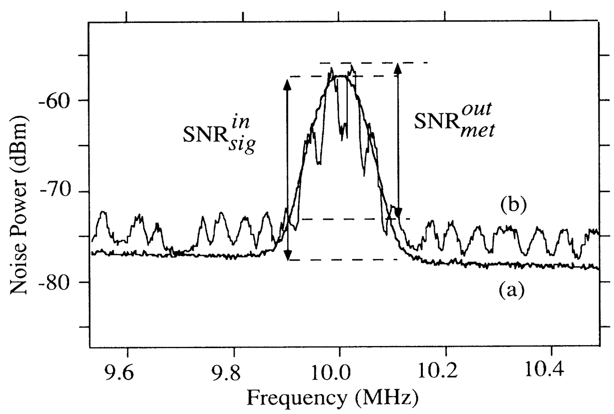

FIG. 3. Transfer of the classical modulation from the signal input to the meter output beam. The parameters are the same as in Fig. 2. Trace *a* is the noise power spectrum of the modulated signal. The height of the peak gives $R_{\rm sig}^{\rm in}=20$ dB. Trace *b* is the noise power spectrum of the meter beam. The fringes are due to the sweeping in time of the phase of the local oscillator of the homodyne detection. At the same time, the spectrum analyzer scans the frequency. The height of the peak of the superior envelope gives $R_{\rm met}^{\rm out}=17$ dB, leading to a raw SNR transfer of -3 dB. The shot noises of both beams are set at the same level.

The experimental results concerning the quantum-state preparation ability of this device can be characterized by the conditional variance introduced in Ref. [7]. This quantity is measured by the noise reduction of the signal when corrected by the adequately attenuated photocurrent coming from the meter beam [12,22]. As can be seen in Fig. 4, the noise drops by 0.6 dB, leading to a conditional variance of 0.85.

The theoretical model we have developed [18,23,24] is a fully quantum three-level model. The comparison of the experimental results with this model is rather satisfactory for the SNR transfers using the parameters that reproduce best the peaks of Fig. 3. The height of the "at-

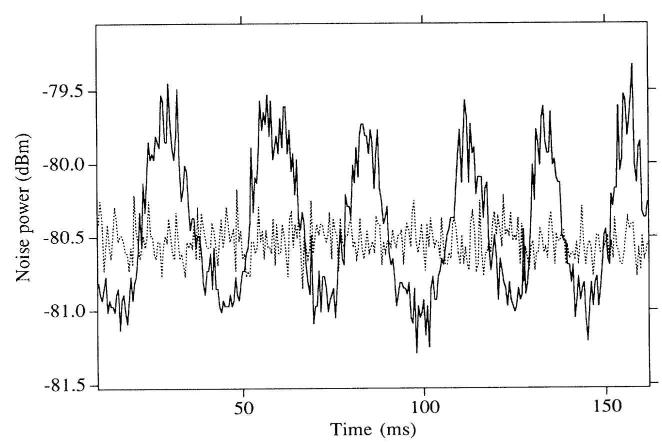

FIG. 4. Conditional variance. The parameters are the same as in Fig. 2. The dotted trace is the shot noise of the signal alone. The solid trace is the recombination of the signal photocurrent with the 12 dB attenuated meter photocurrent. The phase of the meter homodyne detection is scanned insuring addition or subtraction of the two photocurrents.

tracted peak" is related to the induced two-photon absorption of the meter beam, while the distance between the two peaks gives the nonlinear phase shift characterizing thereby the strength of the nonlinear coupling. We find then a good agreement between the experimental values for the signal and measurement SNR transfers and our theoretical model with these parameters. However, a puzzling discrepancy remains for the quantum correlation of the two output beams. The experimental conditional variance we have obtained is 0.85 (-0.6 dB) while the theoretical prediction goes down to 0.65 (-2 dB). We have not found so far the precise reason for this discrepancy, but it may be related to excess phase noise of the meter beam, which could be attributed either to resonant collisions or to atom number fluctuations in our high density atomic beam.

As a summary, we have used the recently developed *ghost transition* scheme [18] in three-level atomic systems to implement a device where all the properties of a QND meter are fulfilled. A significant improvement compared to previous results was obtained, especially regarding quantum optical tap properties. Further enhancement of these results should be made possible by using the new techniques of laser manipulation of atoms to improve the quality of our atomic medium.

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