# Quantum Optical Cloning Amplifier

J. A. Levenson, I. Abram, T. Rivera, and P. Fayolle
*Centre National d'Etudes des Télécommunications, 196 Avenue Henri Ravera, 92220 Bagneux, France*

J. C. Garreau [a] and P. Grangier
*Institut d'Optique, BP 147, 91403 Orsay, France*
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We demonstrate experimentally that a type-II pulsed optical parametric amplifier can duplicate (or, clone) a signal in the quadrature it amplifies. Although this device is an amplifier with large gain, it meets the quantitative criteria for quantum nondemolition measurements and, thus, operates in the nonclassical regime. It can be used as a noiseless amplifying optical tap which, at the same time, can overcome the noise introduced downstream by propagation and detection losses.

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Type-II parametric amplifiers are known to produce various quantum effects, such as twin beams [1,2], squeezing [3–5], quantum nondemolition (QND) measurements [6], and Einstein-Podolsky-Rosen correlations [7]. Pulsed operation of such amplifiers [2,4–6] is particularly attractive because it eliminates the need for a resonant cavity and its bandwidth limitations. However, the high intensities of pulsed operation produce distortions of the wave fronts of the amplified signals and make subsequent homodyne detection of squeezed light very difficult [8]. Thus, large quantum effects involving high-intensity pulses have so far been restricted to twin beams, obtained in a phase-insensitive configuration [2].

Another experimental configuration that should permit observation of significant quantum effects in pulsed operation consists, essentially, of a twin-beam setup with phase-dependent amplification. In this setup, an input beam is injected in a potassium titanyl phosphate (KTP) crystal at an angle of 45° from the crystal axes and undergoes phase-sensitive amplification. The output beam is split into two equal parts by a polarizer with transmission and reflection axes parallel to the crystal axes [see Fig. 1(a)]. When the input beam is amplified, the noise of the difference of the intensities of the two output beams drops below the shot-noise limit: This is the well-known "twin-beam" effect, due to the fact that the signal and idler photons are produced in pairs. This scheme can be reinterpreted in an alternate way by regarding the type-II parameteric amplifier as a pair of two type-I amplifiers of inverse gains, each acting on a separate polarization [see Fig. 1(b)]. One amplifier amplifies the input beam in a phase-sensitive (and, therefore, noiseless [9]) way, whereas the second amplifier deamplifies the vacuum that enters in the polarization orthogonal to the input signal. At the exit of the KTP crystal, the amplified signal is split by the polarizing beam splitter, with squeezed vacuum entering into the "unused" port. The squeezed vacuum has the appropriate modal shape and phase to minimize the beam splitting noise, as seen in the twin-photon viewpoint. Thus, in the overall setup, noiseless amplification is automatically followed by noiseless optical tapping. In the high gain limit, both the mean field and the fluctuations of the amplified quadrature component are "magnified" and copied onto the two output beams emerging from the polarizer which are, therefore, "clones," that is, identical to each other *for this quadrature component.*

The purpose of this Letter is to show two nonclassical properties of phase-sensitive pulsed parametric amplification. First, parametric amplification can overcome the quantum noise introduced by downstream losses (e.g., in the detector) preserving, thus, the signal-to-(quantum)-noise ratio (SNR) of the input beam, a feature that is of interest in improving low-quantum-yield receivers [10, 11]. Second, a parametric amplifier can produce a duplicate of the quadrature it amplifies, in a way that conserves the input SNR. It thus acts as an efficient Y coupler that may lead to the realization of a high-fidelity

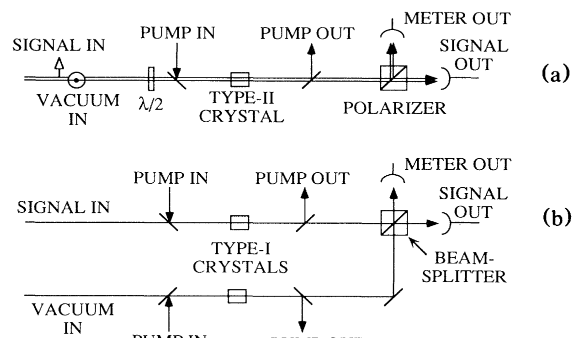


FIG. 1. (a) Experiment using a type-II crystal and an input beam polarized at 45° from the crystal axes and the polarizer axes. (b) "Unfolded" version of (a), using two type-I crystals each operating on a different channel. The phase relationships in the type-II crystal are such that when one crystal of the "unfolded" version displays maximum phase-sensitive amplification, the other crystal displays maximum phase-sensitive *deamplification.*

 

optical tap [12,13]. In order to quantify the fidelity of amplification and cloning, we use the criteria that have been introduced for characterizing QND measurements [14,15]. We therefore adopt the QND terminology and label the two output beams "meter" and "signal," even though in the phase-sensitive parametric amplifier these two output channels are equivalent, except for their polarization.

Our experimental setup is as follows. A frequency-doubled mode-locked $Q$-switched yttrium lithium fluoride (YLF) laser (Coherent Antares) pumps two KTP crystals in series (Fig. 2). The pump beam, at 527 nm, consists of 440-ns-long (FWHM) trains of 35-ps-long pulses, with a Gaussian train envelope, produced at a repetition rate of 400 Hz. The peak intensity of the central pulses in a train is 50 MW/cm$^2$, producing a parametric gain of up to 10 dB. An "input" beam at 1054 nm (consisting of 630-ns-long trains of pulses, synchronized with the pulses of the pump beam) is injected in the crystal as described above, and the two output beams are detected by means of two InGaAs photodiodes (Epitaxx ETX-300). Optical saturation of the photodiodes is avoided by limiting the optical gain and by adjusting the incident intensities so that the peak photocurrent never exceeds 10 mA, i.e., 0.5 V on 50 Ω. Also, the confocal parameter of all beams is adjusted to be much larger than the crystal length to minimize mode distortion and diffraction effects [8]. The output photocurrent from each photodiode is split 90/10 and one of the 10% portions is introduced into a spectrum analyzer (HP 8563A) set at 76 MHz: Measurement of the 76-MHz modulation of the mode-locked train provides a direct intensity reference. The 90% portions of the two photocurrents are subtracted from each other by means of a power combiner. The output of the combiner is introduced into a bandpass filter that transmits between 12 and 25 MHz, and has 90 dB attenuation outside this range. This filter prevents saturation of the subsequent low-noise amplifier (Trontech W110B-13) by the 76-MHz modulation and its harmonics. The amplifier output is fed into a second spectrum analyzer with 10 MHz rf bandwidth (Tektronix 2782) set at 18 MHz for the quantum noise measurements. The large bandwidth of the spectrum analyzer allows one to time resolve the envelope of the $Q$-switched pulse train, and only about seven mode-locked pulses at the center of the train are effectively registered (time window 100 ns). Video averaging is provided by two boxcars following each of the two spectrum analyzers; the boxcars are triggered by the $Q$-switch synchronization from the laser power supply. Each measurement involves about 5000 $Q$-switched trains, averaged by a computer that receives the data from the boxcars. All measurements are made by sweeping the relative phase of the pump and input beams, and by registering simultaneously the modulation (at 76 MHz) and the noise (at 18 MHz) for the output beams. These two quantities are then plotted as $x$ and $y$, respectively, with the phase as a parameter. The noise at 18 MHz gives a quantitive measure of the noise at the modulation frequency because of the large bandwidth of pulsed parametric amplification. At each output intensity the shot noise is measured by removing the pump beam and readjusting the intensity of the unamplified input beam so that it produces the same power of 76-MHz modulation. It is then checked that the sum and the difference of the two output photocurrents displayed the same noise level, a feature which is characteristic of shot noise.

In Fig. 3 we give the noise power of a single output channel as a function of the measured gain $G$ of the 76-MHz modulation. Both the signal and meter channels give similar results. The 0-dB level on both axes is measured by turning off the amplifier pump. On the same curve we plot the shot noise level of the measured output channel; this provides the standard quantum level (SQL)

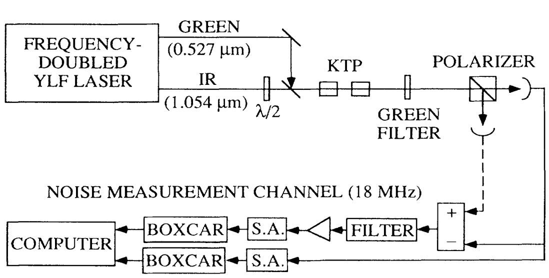


FIG. 2. Experimental setup. The KTP parametric amplifier is pumped at 527 nm and amplifies a signal at 1054 nm polarized 45° to the crystal axes. The polarizer axes are parallel to the crystal axes. The photodiode currents are subtracted in a power combiner and the noise and signal are each measured by a spectrum analyzer (S.A.) and boxcar combination.

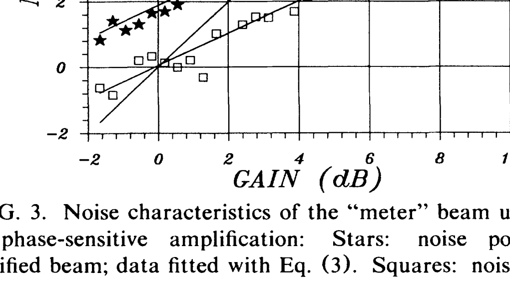


FIG. 3. Noise characteristics of the "meter" beam undergoing phase-sensitive amplification: Stars: noise power of amplified beam; data fitted with Eq. (3). Squares: noise power of coherent beam, fitted with Poisson noise.

of noise for a single-channel measurement. The curve is a straight line of slope 0.5 passing through the origin, as expected for shot noise. We note that the quantum noise curve of the amplified beam is also a straight line of slope 0.5, but is displaced vertically by 2 dB with respect to the SQL. This result may be understood by considering the quantum noise in traveling-wave parametric amplification [16]. The measured intensity of each polarization $\langle I_i \rangle$ (where $i=m,s$) as a function of the total input intensity $I_{\rm in}$ is

$$\langle I_i \rangle = \tfrac{1}{2}\eta I_{\rm in} G \,, \tag{1}$$

where $\eta$ is the overall quantum efficiency of single output channel, while $G$ is the phase-dependent gain

$$G=\cosh(2\gamma)+\sinh(2\gamma)\cos\phi \tag{2}$$

with $\gamma=\chi^{(2)}Ez$ being the parametric gain parameter and $\phi$ the relative phase of the pump and signal waves. In Fig. 3, the maximum gain attained (i.e., for $\phi=0$) is 9 dB, which implies that $\cosh 2\gamma=1.59$. The quantum noise power in a single output channel can be calculated as

$$\langle(\delta I_i)^2\rangle = \tfrac{1}{2}\eta I_{\rm in} G[\eta\cosh(2\gamma)+1-\eta] \,. \tag{3}$$

Clearly, the noise power of each output beam exceeds the SQL by a factor of $(\eta\cosh 2\gamma+1-\eta)$ and this accounts for the vertical displacement of the experimental points in Fig. 3. A fit of our results gives $\eta=0.82\pm0.04$.

An important point about this experiment is that, although a single output beam is more noisy than the SQL, its measured SNR in the quadrature $\phi=0$, displays an apparent improvement of 2.5 dB with respect to the SNR of the input to that channel, as if the input noise figure of the amplifier were $-2.5$ dB. This is evidenced in Fig. 3 by the data points that are below the line $x=y$ which gives, for each gain, the noise level that maintains the SNR to its unamplified value. It should be stressed that this SNR "improvement" upon amplification corresponds to the compensation of the noise introduced by the polarizing beam splitter and the detector losses. The measured SNR cannot be improved beyond the SNR of the full input beam at the entrance of the parametric amplifier. Indeed, in the quadrature $\phi=0$, the SNR at the detector can be calculated from Eqs. (1) and (2) as

$$\mathrm{SNR}_i = \frac{\eta}{\eta(1-e^{-2\gamma})+2e^{-2\gamma}}\mathrm{SNR}_{\rm in} \equiv T_i \mathrm{SNR}_{\rm in} \,, \tag{4}$$

where we have adopted a definition in terms of noise power, and defined the $i$th channel information transfer coefficient $T_i$ as the ratio of $\mathrm{SNR}_i$ to $\mathrm{SNR}_{\rm in}$. This equation indicates that the partition noise due to the polarizing beam splitter and to the losses dominates at low gains, whereas at high gains the SNR tends towards that of the full input beam. In our measurements, the information transfer coefficient in the quadrature $\phi=0$ is $T_i=0.66 \pm 0.05$ for both the signal and meter channels.

Figure 4 presents the results of the twin-beam experiment by plotting the noise power of the difference of the two beams against the gain $G$. The experimental points are, generally, close to the horizontal 0-dB axis which corresponds to the input noise difference. The SQL was measured by sending on the detectors two coherent beams of the same average intensity. The SQL corresponding to this experiment is, therefore, defined with respect to the noise of *two* beams. The SQL curve is a straight line of slope 0.5 going through the origin. The quantum noise measured is below the SQL for all positive gains and reaches 3.5 dB in the quadrature $\phi=0$. This value is limited by the gain. These results can be understood by considering that, since noiseless amplification of the input beam occurs on both output channels simultaneously, the two output beams are amplified but are identical versions of the input beam. Thus, the noise measured for their intensity difference is equal to the input noise, independently of the gain, as expected, also, from twin-photon considerations. In the presence of losses, the noise is

$$\langle(\delta I_s-\delta I_m)^2\rangle = \eta I_{\rm in}[\eta+(1-\eta)G] \,. \tag{5}$$

A plot of this curve (with $\eta=0.85$) fits the experimental points quite well.

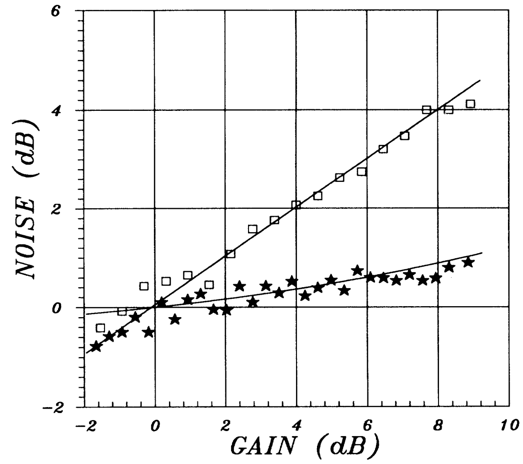


FIG. 4. Noise of the intensity difference of the "signal" and "meter" output channels. Stars: noise of amplified beams, fitted with Eq. (5). Squares: noise of coherent beams, fitted with Poisson noise.

The significance of our results can be better appreciated if our measurements are discussed in terms of the three criteria proposed for the evaluation of QND experiments [14,15]. The first QND criterion is that the meter beam provides a good measurement of one quadrature of the input beam, by following faithfully its fluctuations. The fidelity of the measurement can be quantified through the information transfer coefficient $T_m$ defined by Eq. (4). The measured value for the quadrature $\phi=0$, $T_m=0.66$, is clearly higher than 0.5, the transfer coefficient of the polarizing beam splitter. The second QND criterion is that the signal output reproduces faithfully the same quadrature of the input beam. In our case, there is no physical difference between the output signal and meter so that $T_s = T_m$. Classically, the input noise is, at best, distributed between the output channels so that $T_s + T_m \leq 1$. On the other hand, for a perfect quantum measurement in which each one of the two output beams reproduces exactly the input, we have $T_s + T_m = 2$. In our experiment, and for the $\phi = 0$ quadrature, $T_s + T_m = 1.32$ which is clearly in the quantum regime. Finally, the third QND criterion is that the meter and signal beams are faithful copies (clones) of each other, so that measurement of one beam gives information about the other. A quantitative measure of this fidelity is the uncertainty that remains on the value of the signal when the meter intensity is known. This quantity corresponds to the conditional variance defined as

$$W_{s|m} = \langle (\delta I_s)^2 \rangle_1 - \frac{|\langle \delta I_s \delta I_m \rangle_1|^2}{\langle (\delta I_m)^2 \rangle_1}, \quad (6)$$

where the subscript 1 indicates that the quantities are measured in units of the one-beam SQL. For a classical duplicator (i.e., a 50/50 beam splitter) we have $W_{s|m} \geq 1$, while for perfect quantum correlation between the two output beams $W_{s|m} = 0$. Equation (6) can be reexpressed in terms of the quantities measured in this experiment that is, the twin-beam noise difference [referenced to the two-beam SQL and denoted $\langle (\delta I_s - \delta I_m)^2 \rangle_2$] and the one-beam variance, as

$$W_{s|m} = \langle (\delta I_s - \delta I_m)^2 \rangle_2 \left[ 2 - \frac{\langle (\delta I_s - \delta I_m)^2 \rangle_2}{\langle (\delta I_m)^2 \rangle_1} \right]. \quad (7)$$

The conditional variance for the quadrature $\phi = 0$ is $W_{s|m} = 0.77$, clearly below the classical limit of 1.

In conclusion, we have shown that a type-II phase-sensitive amplifier can clone the signals in the quadrature that it amplifies. Although this device is not, strictly speaking, a QND device, since the output signal is actually a "magnified" copy of the input signal, all QND criteria introduced in the literature are satisfied. From a practical viewpoint, such an optical cloner can duplicate a signal channel without contaminating it, providing thus an efficient quantum optical tap. At the same time, the two outputs of this device are relatively immune to subsequent losses: The device acts both as a preamplifier and as a "presqueezer" that overcomes both the losses and the quantum noise that these losses introduce. This produces an apparent improvement of the measured SNR, up to the value of the input beam SNR. Such a device could, therefore, have interesting applications in optical information systems, if the constraints due to the phase sensitivity of parametric amplification can be mastered.

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[a]Present address: Laboratoire de Spectroscopie Hertzienne, Université des Sciences et Techniques de Lille, F-59655 Villeneuve d'Ascq CEDEX, France.

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