Experimental Realization of a Semiconductor Photon Number Amplifier and a Quantum Optical Tap

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Two configurations involving high quantum efficiency photodetectors and light emitting diodes have been investigated. A light beam was detected with a photodetector and its photocurrent was used to measure the incoming beam. Simultaneously, the photocurrent was used, with and without amplification, to regenerate the absorbed beam. With these schemes photon number amplification, duplication, and information tapping without introducing any significant noise to the downstream propagating beam could be experimentally realized.

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Noiseless amplifiers and quantum "state" duplicators are of great fundamental and practical interest. State duplication is forbidden for general states [1–3], but eigenstate duplication (and amplification $|n\rangle \rightarrow |Gn\rangle$, where G is a fixed integer) [2, 4] is allowed. A topic related to this is quantum nondemolition (QND) measurement, where a signal is measured without being disturbed, by imposing the measurement noise on the conjugate observable [5–11].

In this work, two simple configurations involving light emitting diodes (LEDs) and photodetectors have been investigated, which are able to measure photon number (or a small signal intensity modulation) and regenerate it into one or, in principle, multiple beams. These regenerated states can be independently chosen at any wavelength where high quantum efficiency light emitters are available. In our setup they are roughly at the same wavelength.

Suppose a light beam (input signal) exhibiting shot noise [i.e., noise at the standard quantum limit (SQL)] and with a small intensity modulation is incident on the leftmost photodiode of Fig. 1(a). If the detection quantum efficiency is η_d, the degradation in signal-to-noise ratio (SNR) from the optical input signal to the photocurrent is η_d. The photocurrent I_{P1}, measured as a voltage across the resistor R, can be amplified electrically and read out (meter signal). Simultaneously, the signal may be regenerated (output signal) using a laser or a LED. If the quantum efficiency of this emitter is η_g, the overall degradation in SNR is $\eta_d\eta_g$. Since any phase information is destroyed and lost in the photodetection, quantum mechanics permits noiseless readout and duplication onto new light beam(s) of the intensity information of the input light beam. Note that the thermal noise and electrical amplifier noise can be neglected if the condition $4kTF/R \ll 2q\langle I_{P1}\rangle$ holds, where q is the elementary charge, $\langle I_{P1}\rangle$ is the average photocurrent, and F is the noise figure of the amplifier A_1.

By a simple modification of the circuit [see Fig. 1(b)], the signal can be amplified before being regenerated. For practical reasons, only the ac component of the detected light is amplified and regenerated, whereas the dc component I_d is supplied through a separate noise suppressed current source. If the thermal noise and the *electrical* amplifier noise are negligible, as discussed above, the degradation in SNR will be determined only by η_d. This is because the amplified output signal generally becomes classical, i.e., well above the shot-noise level. Provided that the quantum efficiencies are high (a photodetector can have $\eta_d > 90\%$), this amplification beats the 3 dB quantum limit on noise figure imposed when using linear phase insensitive amplifiers [12]. When $\eta_d \rightarrow 1$ this circuit will realize the noiseless photon number amplifier proposed by Yuen [2] and realize the function of the quantum optical tap proposed by Shapiro [13]. Furthermore, the setup of Fig. 1(b) can implement the transparent,

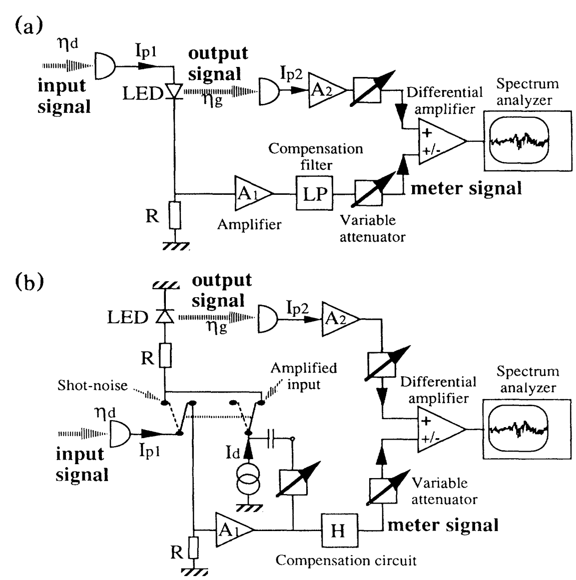

FIG. 1. Schematical illustration of the experimental setups. In (a), the current I_{P1} is used for the regeneration. In (b) only the ac component of the detected and amplified signal is regenerated, whereas the dc component I_d is supplied through a separate noise suppressed current source. Using electrically controlled microswitches, the shot-noise level and the amplified noise could be measured separately.

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noiseless, optical network discussed by Yuen [14]. These results are a consequence of the quiet photon-to-electron conversion in a *p-n* junction [15–17], and the fact that electrical noise at low (radio) frequencies can be lower than quantum (shot) noise at optical frequencies, when retranslated to the optical domain by a laser or LED [15–18].

Despite the absorption of photons in the photodetection, these schemes also fulfill the quantitative criteria for QND measurements [11, 19]. However, as shown in this work, these criteria are not sufficient to qualify an experiment as being a QND measurement. Our experiment clearly destroys the input state and then regenerates an approximate copy, while in true (in the sense of [5, 6], and in implementations by [7–11]) but nonideal QND measurements the output state is the degraded input state. In addition, our setup always imposes maximum backaction (the input- and output-state phases are totally uncorrelated). Moreover, what may be a fundamental weakness in our experiment is that the same current is used for readout and regeneration of the signal, implying that no additional information of the input state can be gained through repeated measurements. However, in an ideal $\eta_d = \eta_g = 1$ setup these differences are removed, and therefore, although our setup admittedly is not a true QND measurement, we believe it is sufficiently close to be associated with QND. In some applications, specifically in information transmission, our setup may have a comparable performance with a QND meter [14]. Specifying our results in the QND formalism of [11, 19] allows us to assess the performance of our schemes as quantum optical taps, and facilitates a comparison to recent results on quantum optical taps and observable amplifiers, based on KTP parametric amplifiers [20], and two photon cross-phase modulation of a three level system in a sodium atomic beam [21].

The necessary QND measurement criteria [11, 19] can be summarized in two conditions: The meter and output signals should be quantum mechanically correlated ("quantum state preparation" condition) and in addition the input signal should be strongly correlated with both the output and the meter signals ("quantum optical tap" condition). To separate quantum from classical behavior, the best classical device, a lossless linear optical beam splitter, can serve as a yardstick.

The condition for quantum state preparation is conveniently expressed using the conditional variance $W_{\rm QSP}$ of the output beam X_o given the meter signal X_m. For a lossless beam splitter $W_{\rm QSP}$ is unity, and for quantum state preparation $W_{\rm QSP}$ should be below unity. Expressed in spectral densities $W_{\rm QSP}$ can be written in a form identical to the noise reduction below SQL obtained through optimum noise suppression [22]

$$W_{\rm QSP} = \frac{S_{X_o}}{S_{\rm SQL}}(1 - |C_{X_m,X_o}|^2) \; , \tag{1}$$

where S_{X_o} is the noise level of the output beam, $S_{\rm SQL}$ is the shot-noise level, and C_{X_m,X_o} is the normalized correlation between the meter and the output [22]. Theoretically this gives, using the quantum efficiencies pertaining to our experiment, $\eta_g = 0.3, \eta_d = 0.9$, for the setups of Figs. 1(a) and 1(b), $W_{\rm QSP} = 1 - \eta_g \approx 0.7$.

The second "quantum optical tap" criterion, can be given from the normalized correlations between the input and the output C_{X_i,X_o} and the input and the meter C_{X_i,X_m}, respectively. Experimentally, these correlations can be computed either from the measured spectra using the same technique as described in Refs. [23, 24] or by applying a deterministic small signal modulation, and observing the degradation in SNR (for a shot-noise limited input). Writing the correlation in terms of SNR one gets

$$\begin{aligned} T_{\rm sig} &= |C_{X_i,X_o}|^2 = \frac{{\rm SNR}_{X_o}}{{\rm SNR}_{X_i}} \; , \\ T_{\rm met} &= |C_{X_i,X_m}|^2 = \frac{{\rm SNR}_{X_m}}{{\rm SNR}_{X_i}} \; , \end{aligned} \tag{2}$$

where $T_{\rm sig}$ and $T_{\rm met}$ have been introduced to follow the notation in [20, 21]. For a lossless beam splitter $T_{\rm sig} + T_{\rm met} = 1$ (irrespective of transmittivity), and the condition for a quantum optical tap is $1 < T_{\rm sig} + T_{\rm met} \leq 2$. Theoretically, for our present setup, we have for Fig. 1(a) $T_{\rm sig} = \eta_d \eta_g, T_{\rm met} = \eta_d$, giving $T_{\rm sig} + T_{\rm met} = 1.17$ and for Fig. 1(b) $T_{\rm sig} = T_{\rm met} = \eta_d$, giving $T_{\rm sig} + T_{\rm met} = 1.8$.

To verify these predictions, we have implemented the configurations of Figs. 1(a) and 1(b) and made experiments at a wavelength of 890 nm and a temperature of 77 K, using high quantum efficiency ($\eta_g > 0.3$ at 77 K) light emitting diodes (Hamamatsu L2656) and Siemens BP104 ($\eta_d = 0.90$) and BPY12 photodiodes. The signals were amplified (amplifiers A_1 and A_2, Plessey SL 550), and the measured sum and difference of the photocurrents I_{P1} and I_{P2} were formed by means of a Tektronix 7A26 differential amplifier, which was connected to a microwave spectrum analyzer. Each noise term could also be measured individually by attenuating the other signal by more than 60 dB. The shot-noise input signal was generated by illuminating the photodiode by a weakly coupled LED, which in turn was driven by a high impedance current source, i.e., pump noise suppressed [15, 17, 24]. The current-to-current quantum efficiency in this case was low, ≈12%, resulting in a nearly shot-noise limited photocurrent from the photodiode [24] (in fact, it was slightly squeezed ≈ 0.15 dB). This was verified in a separate calibration using a filtered tungsten halogen white-light source [24]. We also measured the photocurrent spectra from the LED at various optical attenuation levels to verify the absolute photocurrent noise level [24]. The electrical transfer characteristics of the LED had a cutoff frequency around 0.5 MHz. Therefore, in order to obtain optimum noise reduction after recombination [22], in the configuration of Fig. 1(a) this rolloff was compensated for by introducing a LP filter in the circuit branch of the electrical detection. In the second configuration, besides the LED rolloff, the transfer characteristics of the amplifier A_2 had to be compensated for. This is indicated in Fig. 1(b) by the circuit H which consisted of an amplifier similar to A_2 and a LP filter.

In a previous experiment, we demonstrated quantum correlation between two light beams from electrically coupled LEDs [18, 24], i.e., observable duplication. Figure 2(a) shows the experimental result for quantum correlation (quantum state preparation) between the detected meter current, measured over a 470 Ω resistor, and the output light beam from the LED, for the setup in Fig. 1(a). In this measurement $I_{P2} = 1.8$ mA and the thermal and amplifier noise were approximately 13 dB below the shot-noise level. The combined signal is at best approximately 1.2 dB below the shot-noise level. Theory predicts a noise reduction below SQL by a factor $1 - \eta_g \approx 1.5$ dB. It should be pointed out that by measuring the noise spectrum of I_{P1} *with* and *without* the regenerating LED it was verified that, in the frequency range of our measurements, the latter had no effect on I_{P1}. Figure 2(b) shows the experimental result for quantum correlation between the meter current and the output light beam for the setup in Fig. 1(b). The noise level of the amplified output beam was, as expected, well above the shot-noise level. The approximately 8 dB amplification in the low frequency limit, which was also verified through small signal modulation measurements, is proportional to η_g, the gain of the amplifier A_1 (28 dB) and the measurement resistance, i.e., 470 Ω in parallel with the input impedance of the amplifier A_1, and it is inversely proportional to the resistance in series with the LED. The shot-noise level was determined with the electrical amplifier disconnected, and driving the LED with the shot-noise limited current, adjusting the input power so that the dc photocurrent I_{P2} was the same as when measuring with the amplifier connected. In this measurement $I_{P2} = 1$ mA and the combined difference signal goes ≈ 1 dB below the shot-noise level of the output beam, which demonstrates quantum correlation between an amplified optical signal (which has excess noise) and an electrical signal. If we conservatively use the experimental results of Figs. 2(a) and 2(b) and Eq. (1), we obtain for the configuration of Fig. 1(a) $W_{\rm QSP} \approx 0.76 \pm 0.02$ and for the setup in Fig. 1(b) $W_{\rm QSP} \approx 0.79 \pm 0.02$. Both are in good agreement with theory, and thus the condition for quantum state preparation is fulfilled in both cases.

In Figs. 3(a) and 3(b), the experimental results for the SNR of the meter and the output beams are shown. Figure 3(a) is for the configuration without amplifier for a small signal modulation at 200 kHz. It can be observed that the degradation of the SNR between the meter signal and the output is 6 dB. This is in good agreement with the theoretical value ${\rm SNR}_{X_o}/{\rm SNR}_{X_m} = |C_{X_m,X_o}|^2 = \eta_g \approx 0.3$, and the experimental result of Fig. 2(a). In the amplifier configuration, Fig. 3(b), the SNR degradation is less than 0.6 dB. If the detection is shot-noise limited as in our case, the input SNR can

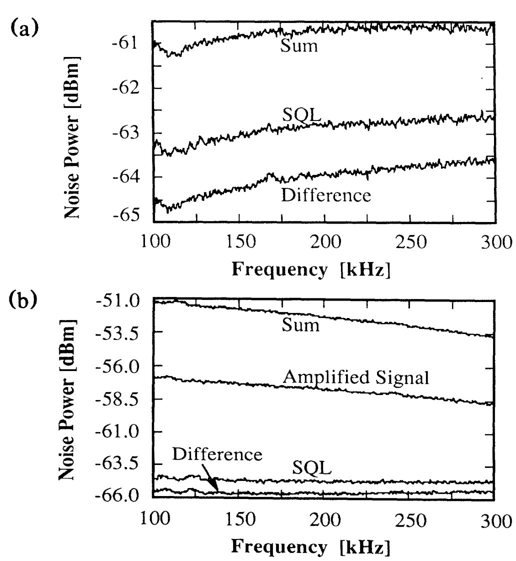

FIG. 2. Experimental results for quantum correlation for the configuration of Figs. 1(a) and 1(b), respectively: In (a) and (b) the combined spectra (sum and difference) of the optical output signal and electrical meter signal together with the SQL as reference are shown. In (b) the output signal (amplified SQL signal) has also been included.

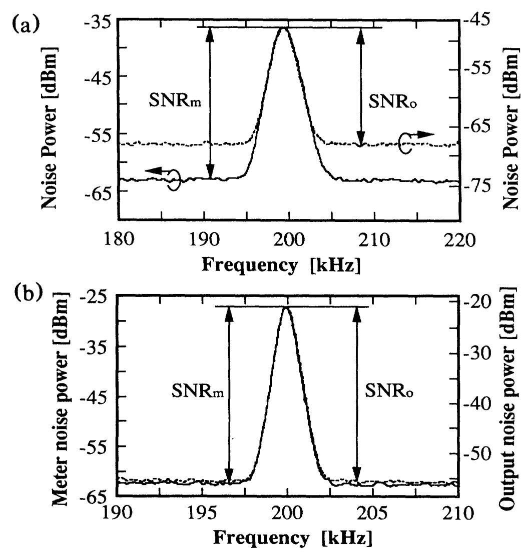

FIG. 3. Signal-to-noise ratios for the meter signal and the output signal. (a) and (b) correspond to the respective setup in Fig. 1. In (a) the output (power) is attenuated by a factor $\eta_g \eta_d \approx 0.27 = -5.7$ dB with respect to the input signal, and in (b) the output is amplified by 8 dB. The meter and output noise pedestals, representing the SQL, differ by the same amount in the respective figures.

be estimated simply by correcting the meter SNR for the quantum efficiency η_d. From the experimental data, with $\eta_d = 0.90 \pm 0.02$ we could estimate for the setup of Fig. 1(a) as $T_{\rm sig} = 0.23 \pm 0.05, T_{\rm met} = 0.90 \pm 0.02$, giving $T_{\rm sig} + T_{\rm met} = 1.13 \pm 0.07$ and for the setup of Fig. 1(b), $T_{\rm sig} = 0.79 \pm 0.02, T_{\rm met} = 0.9 \pm 0.02$, giving $T_{\rm sig} + T_{\rm met} \approx 1.69 \pm 0.04$. Both these agree well with theory, and as predicted, the condition for a quantum optical tap is satisfied in both cases.

The present results, to our knowledge, are slightly better than other results obtained so far for the combined operation of quantum state preparation and quantum optical tap. Note that these results have been given without any correction for the fact that the "shot-noise" level was slightly (≈ 0.15 dB) squeezed. Correcting for this would improve our results slightly [i.e., giving for the setup of Fig. 1(a) $W_{\rm QSP} \approx 0.73, T_{\rm sig} + T_{\rm met} \approx 1.15$ and for the setup of Fig. 1(b), $W_{\rm QSP} \approx 0.77, T_{\rm sig} + T_{\rm met} \approx 1.77$]. Furthermore, note that if laser diodes are used instead of LEDs, higher quantum efficiencies ($\eta_g \approx 0.8$–0.9) are in principle possible. Working with lasers would also allow operation at higher frequencies, in principle up to the relaxation oscillation frequency of the lasers, which for conventional devices lies above 10 GHz. Laser diodes, however, require careful elimination of spurious optical feedback and the high power levels needed to achieve high quantum efficiencies may cause problems with detector saturation.

A direct advantage of this setup is that it is fairly simple. The cryostatic cooling served essentially to enhance the quantum efficiency of the LED. Furthermore, multiple quantum correlated beams are easily generated, as we previously have demonstrated [18, 24]. However, it is clear that this setup is not suitable as a preamplifier to boost signal levels before detection, since a prerequisite for it to work is that the detection is not limited by thermal noise or dark currents.

In summary, we have demonstrated two semiconductor circuit configurations realizing photon number amplification, operation as quantum optical tap, and also fulfilling criteria for QND measurements.

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