Experimental Realization of a Quantum Measurement for Intensity Difference Fluctuation Using a Beam Splitter

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(Received 18 August 1998; revised manuscript received 24 November 1998)

A new quantum measurement scheme of intensity difference fluctuation between two light beams of equal mean intensity is presented. In this system a beam splitter is used as the coupling device and the twin beams with high quantum correlation are injected into its dark port as the input meter wave instead of the usual vacuum field. A measurement satisfying all the quantum nondemolition criteria is experimentally achieved. The measured sum of the transfer coefficients and the conditional variance are, respectively, $T_s + T_m = 1.31$ and $V_{s/m} = -2.1$ dB. [S0031-9007(99)08445-8]

PACS numbers: 42.50.Dv, 03.65.Bz

Quantum nondemolition (QND) measurements have attracted extensive interest [1]. Since 1986, a variety of QND-type measurements have been successfully demonstrated in optical experiments [2–9]. In most experiments measurements of the quadrature phases of the probe field were involved to provide the information of signal observables. In a recent paper Harrison *et al.* [10] have proposed a QND scheme, in which the signal and probe observables are the intensity difference between twin beams on the left and right hand sides of a double ended nondegenerate optical parametric oscillator; therefore, only the field intensities need to be measured rather than the quadrature phases [10]. So far there is no published experimental realization of this QND-type measurement.

It is well known that a beam splitter is the simplest optical coupling device [11]. Recently Bruckmeier *et al.* [9] have realized a quantum measurement satisfying the quantum nondemolition criteria by injection of a 3.7 dB quadrature squeezed wave into the usual vacuum port of a beam splitter. The good results of signal transfer $T_s + T_m = 1.29$ and the conditional variance $V_{s/m} = -1.3$ dB were obtained. On the other hand great reductions of quantum fluctuations in the intensity difference between twin beams produced by a nondegenerate parametric oscillator were achieved in several groups [12–14]. The above-mentioned successful experiments motivated us to design a quantum measurement scheme using a beam splitter, the dark port of which is filled by quantum correlated twin beams instead of a quadrature squeezed wave as in Ref. [9]. When the twin beams with quantum noise reduction in the intensity difference of 76% below the standard quantum limit (SQL) are injected into the vacuum port of a beam splitter, the measurement of intensity difference fluctuation in the quantum domain is experimentally realized. The measured $T_s + T_m = 1.31$ and $V_{s/m} = -2.1$ dB fulfill the QND criteria introduced by Holland *et al.* [15] and Poizat *et al.* [16].

At first we simply present the measurement principle of the proposed scheme. S^{in} and M^{in} are, respectively, the signal and meter input waves incident upon the beam splitter (BS) from opposite sides with small angles of incidence; S^{out} and M^{out} are, respectively, the output signal and meter waves. Both S^{in} and M^{in} consist of two orthogonal polarized modes (S polarization and P polarization) of equal mean intensity. The phase (φ) at the BS and frequency (ω) of S- and P-polarization modes in S^{in} are, respectively, identical with that in M^{in}. The orthogonal modes in S^{in} are two independent coherent states without quantum correlation, but on the contrary those in M^{in} are quantum correlated twin beams with the intensity difference fluctuation below the corresponding SQL [12–14]. The input signal and meter observables $\delta X_s^{\text{in}}(t)$ and $\delta X_m^{\text{in}}(t)$ are the fluctuations of the intensity difference between the orthogonal polarized modes; that is,

$$\begin{aligned}\delta X_{s(m)}^{\text{in}}(t) &= \delta[I_{s(m),1}^{\text{in}}(t) - I_{s(m),2}^{\text{in}}(t)] \\ &= \overline{A}_{s(m)}^{\text{in}} \delta[A_{s(m),1}^{\text{in}}(t) - A_{s(m),2}^{\text{in}}(t)]/2 \\ &= \overline{A}_{s(m)}^{\text{in}} \delta r_{s(m)}^{\text{in}}(t)/\sqrt{2}\,. \end{aligned} \tag{1}$$

The symbols in the subscripts are as follows: "s" stands for the signal and "m" for the meter wave while "1" denotes the S-polarized mode and "2" the P-polarized mode. $I_{s(m),1}^{\text{in}}(t)$ and $I_{s(m),2}^{\text{in}}(t)$ are intensities for S- and P-polarization modes in S^{in} (M^{in}), respectively. $A_{s(m),1}^{\text{in}}(t)$ and $A_{s(m),2}^{\text{in}}(t)$ are the corresponding quadrature amplitudes. $\delta r_{s(m)}^{\text{in}}(t)$ is the fluctuation of corresponding amplitude difference in the time domain, i.e., $\delta r_{s(m)}^{\text{in}}(t) = \delta[A_{s(m),1}^{\text{in}}(t) - A_{s(m),2}^{\text{in}}(t)]/\sqrt{2}$. For the signal input wave $\langle|\delta r_s^{\text{in}}(\omega)|^2\rangle = 1$, while for the meter input wave $\langle|\delta r_m^{\text{in}}(\omega)|^2\rangle < 1$. $\overline{A}_{s(m)}^{\text{in}}$ is the mean amplitude of S^{in} (M^{in}); we have taken $\overline{A}_{s(m)}^{\text{in}} = \langle A_{s(m),1}^{\text{in}}(t)\rangle = \langle A_{s(m),2}^{\text{in}}(t)\rangle$ in Eq. (1).

The relation between output and input quadrature amplitudes at BS can be expressed as

$$\begin{pmatrix} A_{s,1(2)}^{\text{out}} \\ A_{m,1(2)}^{\text{out}} \end{pmatrix} = \begin{pmatrix} -\sqrt{R} & \sqrt{T} \\ \sqrt{T} & \sqrt{R} \end{pmatrix} \begin{pmatrix} A_{s,1(2)}^{\text{in}} \\ A_{m,1(2)}^{\text{in}} \end{pmatrix}, \tag{2}$$

where T and $R \equiv 1 - T$ are the power transmission and reflectivity of BS, respectively. Similarly with the definition of input obervables, the output signal and

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meter observables δX_s^{out} and δX_m^{out} are the fluctuations of intensity difference between the orthogonal polarized modes of the output wave.

From Eq. (2), we obtain

$$\delta X_s^{out} = \overline{A}_s^{out}[-\sqrt{R}\,\delta r_s^{in}(t) + \sqrt{T}\,\delta r_m^{in}(t)]/\sqrt{2}, \quad (3)$$

$$\delta X_m^{out} = \overline{A}_m^{out}[\sqrt{T}\,\delta r_s^{in}(t) + \sqrt{R}\,\delta r_m^{in}(t)]/\sqrt{2}, \quad (4)$$

where $\overline{A}_s^{out}$ and $\overline{A}_m^{out}$ are the mean amplitude of output signal and meter waves, respectively: $\overline{A}_s^{out} = (-\sqrt{R}\,\overline{A}_s^{in} + \sqrt{T}\,\overline{A}_m^{in})$ and $\overline{A}_m^{out} = (\sqrt{T}\,\overline{A}_s^{in} + \sqrt{R}\,\overline{A}_m^{in})$.

Combining Eq. (1) with Eq. (3) and Eq. (4), respectively, we obtain the input-output relations for our measurement device:

$$\delta X_s^{out}(t) = g_s \delta X_s^{in}(t) + B_s, \quad (5)$$

$$\delta X_m^{out}(t) = g_m \delta X_s^{in}(t) + B_m. \quad (6)$$

g_s and g_m are the gain of signal and meter amplifiers, respectively, due to the mutual coupling at BS:

$$g_s = \sqrt{R}(\sqrt{R} - k\sqrt{T}); \qquad g_m = \sqrt{T}(\sqrt{T} + k\sqrt{R}), \quad (7)$$

where $k = \overline{A}_m^{in}/\overline{A}_s^{in}$, $B_s = \sqrt{T}(-k^{-1}\sqrt{R} + \sqrt{T}) \times \delta X_m^{in}(t)$, and $B_m = \sqrt{R}(k^{-1}\sqrt{T} + \sqrt{R})\delta X_m^{in}(t)$ are the added noise coming from the "dark" port of the BS.

From Eqs. (3) and (4), we obtain the normalized variances:

$$V_s^{out} = RV_s^{in} + TV_m^{in}; \qquad V_m^{out} = TV_s^{in} + RV_m^{in}, \quad (8)$$

where $V_{s(m)}^{out(in)} = Var(\delta X_{s(m)}^{out(in)})/2\overline{I}_{s(m)}^{out(in)}$ have been normalized to their respective shot noise $2\overline{I}_{s(m)}^{out(in)}$ ($\overline{I}_{s(m)}^{out(in)} = \langle I_{s(m),1}^{out(in)}(t)\rangle = \langle I_{s(m),2}^{out(in)}(t)\rangle$), in this case, $V_{s(m)}^{in} = \langle|\delta r_{s(m)}^{in}(\omega)|^2\rangle$. The expressions (8) show that the variances $V_{s(m)}^{out}$ arise from a weighted sum of the input noises of signal and meter waves.

The properties of a QND device are quantified by the signal and meter transfer coefficients (T_s and T_m, respectively) and the ability for quantum state preparation [15]. Using the definition of correlation coefficients introduced by Holland *et al.* [15], we calculate T_s and T_m from Eqs. (3) and (4)

$$T_s = \frac{R}{R + T\langle|\delta r_m^{in}(\omega)|^2\rangle}; \qquad T_m = \frac{T}{T + R\langle|\delta r_m^{in}(\omega)|^2\rangle}. \quad (9)$$

The ability for quantum states preparation is characterized by the normalized conditional variance [10,15]; that is,

$$V_{s/m} = V_s^{out}(1 - C_{sm}^2) = \frac{\langle|\delta r_m^{in}(\omega)|^2\rangle}{T + R\langle|\delta r_m^{in}(\omega)|^2\rangle}, \quad (10)$$

where C_{sm}^2 is a normalized correlation between the meter output and the signal output [15]. In the above three relations we have taken $\langle|\delta r_s^{in}(\omega)|^2\rangle = 1$. It is obvious, when the fluctuation of the injected meter wave is below the SQL, i.e., $\langle|\delta r_m^{in}(\omega)|^2\rangle < 1$, both the QND criteria of $T_s + T_m > 1$ and $V_{s/m} < 1$ are fulfilled at the same time.

Figure 1 shows the experimental setup. An intracavity frequency-doubled and frequency-stabilized cw ring Nd:YAP laser is used as the pump source. The output second-harmonic wave at 0.54 μm enters the semimonolithic optical parametric oscillator (OPO), consisting of an α-cut potassium-titanyl-phosphate (KTP) crystal (10-mm long) and a concave mirror (curvature radius 50 mm) from one face of the crystal, coated to be used as the input coupler. The OPO produces twin beams at 1.08 μm through a frequency-down-conversion process above the oscillation threshold [17]. The standing-wave OPO cavity (52-mm long) is actively locked to deliver a nearly constant output intensity. The concave mirror is the output coupler with 5% transmission at 1.08 μm and high reflectivity at 0.54 μm. The output coupling efficiency of the OPO is 85% at 1.08 μm.

Intensive twin beams of 36 mW are obtained at the pump power of 110 mW. The noise in the intensity difference between the twin beams is reduced by 7 ± 0.1 dB below the SQL from 2 to 5 MHz; the noise measurements are limited above 1 MHz to avoid the influence of the technical laser noise which appears usually on the side of low frequency. A small part of the twin beams reflected by the mirror M1 (4% reflectivity), Fig. 1, is used as the signal wave. The angle of incidence on M1 is smaller than 3° to ensure the balance of the reflectivity between S- and P-polarized waves (the difference is less than 1/1000). The 96% fraction of the twin beams transmitted by M1 acts as the input meter wave (M^{in}, Fig. 1) of the quantum measurement scheme. The beam splitter (BS, Fig. 1) with reflectivity 50% ± 1% is the coupling device. The noise reduction in the intensity difference between the twin beams at BS is decreased to 6.2 ± 0.1 dB due to the transmission loss.

The orthogonal polarized modes in the signal wave, which are e_1 and e_2 modes in KTP crystal and correspond

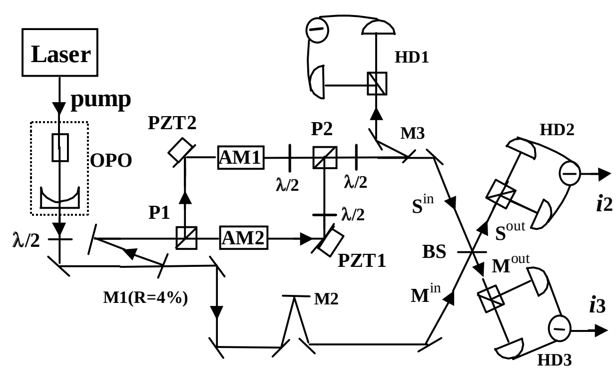

FIG. 1. Experimental setup. HD: balanced self-homodyning detector; AM: modulator; PZT: piezoelectric transducer; $S^{in(out)}$: signal input (output) wave; $M^{in(out)}$: meter input (output) wave.

to S- and P-polarized modes on plane mirrors, are separated by the polarized beam splitter (P1), then are modulated, respectively, by the amplitude modulators AM1 and AM2 (Fig. 1) at the same modulation frequency of 3.4 MHz, with the opposite phase and the same modulation depth. The three half-wave plates ($\lambda/2$) on the optical path of the signal wave are used to make polarization rotations of 90°. The one behind P2 ensures the S- and P-polarized modes of S^{in} at BS will be, respectively, parallel with the corresponding modes of M^{in}. The balanced self-homodyning detectors (Fig. 1) (without local oscillator) HD1, HD2, and HD3, respectively, consist of a polarized beam splitter, two focusing lenses, two InGaAs photodiodes (ETX500T), and a 180° power combiner. The noise of the photocurrent difference is recorded by a spectrum analyzer (HP8590D for HD1, HP8590L for HD2 and HD3). The total detection efficiencies of HD1, HD2, and HD3 are nearly identical ($\eta = 89\%$). They, respectively, detect the signal input (S^{in}), the signal output (S^{out}), and the meter output (M^{out}) at the coupling device.

Considering the influence of nonunitary detection efficiency η, the measured data should be well described by the following theoretical results:

$$T_s = \frac{R}{R + T\langle|\delta r_m^{\text{in}}(\omega)|^2\rangle + \frac{1-\eta}{\eta}}; \tag{11}$$

$$T_m = \frac{T}{T + R\langle|\delta r_m^{\text{in}}(\omega)|^2\rangle + \frac{1-\eta}{\eta}}; \tag{12}$$

$$V_{s/m} = \frac{1 - \eta + \eta\langle|\delta r_m^{\text{in}}(\omega)|^2\rangle}{\eta[T + R\langle|\delta r_m^{\text{in}}(\omega)|^2\rangle] + 1 - \eta}. \tag{13}$$

The modulated signal wave from P2 is separated by the partially reflective mirror M3 with a power reflectivity of $R = 50.10\%$. The reflected beam is detected by HD1, and the transmitted beam is employed as the input signal (S^{in}). Since the modulated signals in the orthogonal polarized modes of S^{in} are out of phase the signal intensity of the photocurrent difference is doubled. The signal-to-noise ratio (SNR) of S^{in} at BS (SNR_s^{in}) can be calculated from the measured SNR by HD1:

$$\text{SNR}_s^{\text{in}} = \text{SNR}_{\text{HD1}}(1 - R)/R\eta\,. \tag{14}$$

The S^{in} and M^{in} are mixed at BS. The optical paths of signal and meter waves from OPO to BS are made as equal as possible, and the residual difference is carefully corrected by the movable mirror M2. The residual difference between the two optical paths is kept less than 5 mm. In this way, good mode matching of $M = 99\%$ between S^{in} and M^{in} at BS is obtained (measured by the interference contrast), and the influence of the slow frequency shift of the twin beams is minimized.

The incidence angles on the mirror M3 and BS are less than 3° (as on M1). The measured noise power spectra of the sum and the difference in photocurrent in HD1 are equal and at the corresponding SQL level. The driving voltages on PZT1 and PZT2 are used to ensure that the S and P modes of S^{in} are in phase with the corresponding modes of M^{in}, respectively, at BS (i.e., $\varphi_{s,1}^{\text{in}} = \varphi_{m,1}^{\text{in}}$; $\varphi_{s,2}^{\text{in}} = \varphi_{m,2}^{\text{in}}$), then the relative phases of them are locked.

In experiments, the signal and meter transfer coefficients T_s and T_m, respectively, are characterized by the fraction of the SNR of the output signal and meter waves to that of the input signal wave [5]. This definition is equivalent to that introduced by Holland *et al.* based on the correlation coefficient [5,15]. Figure 2 shows the noise power spectra of the intensity difference fluctuation measured by the detectors HD1, HD2, and HD3. The measured signal-to-noise ratio of the S^{in} is $\text{SNR}'_{\text{HD1}} = 17.22$ dB [Fig. 2(a)]. Because of the relatively low intensity of the S^{in} ($\sim$0.6 mW) the

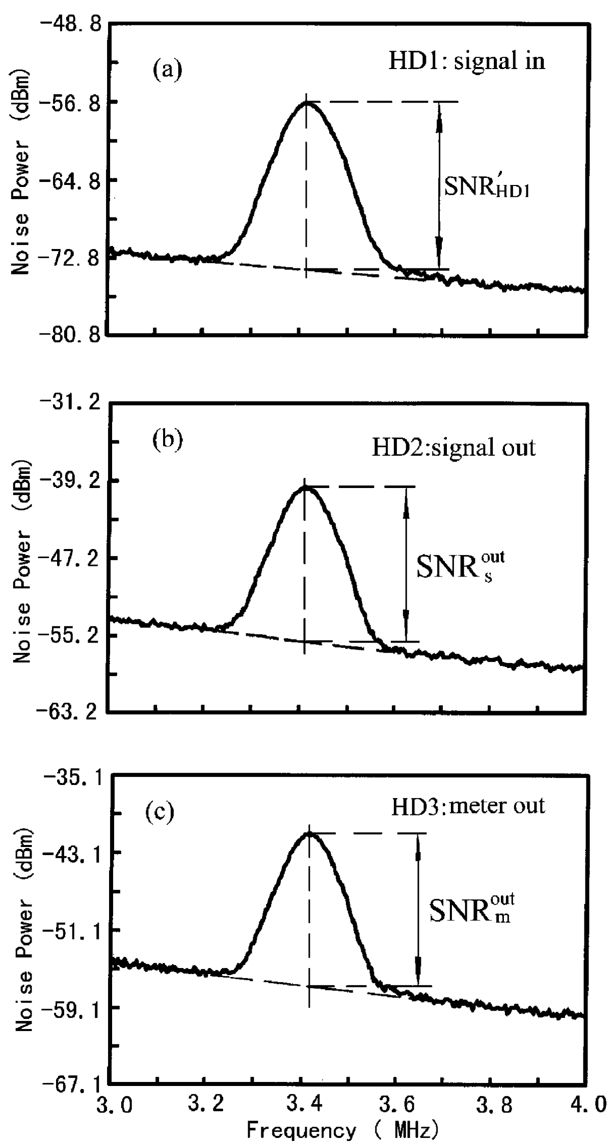

FIG. 2. Noise power spectra of the intensity difference. (a), (b), and (c) are the spectra of intensity difference noise detected, respectively, by HD1, HD2, and HD3.

influence of the electronic noise on the measured shot noise level has to be considered; the corrected $\mathrm{SNR}_{\mathrm{HD1}}$ is 17.25 dB. The calculated result from Eq. (14) is $\mathrm{SNR}_s^{\mathrm{in}} = 17.74$ dB. The signal-to-noise ratios of the S^{out} and M^{out} measured by HD2 and HD3 are $\mathrm{SNR}_s^{\mathrm{out}} = 15.96$ dB [Fig. 2(b)] and $\mathrm{SNR}_m^{\mathrm{out}} = 15.85$ dB [Fig. 2(c)]. From the measured data we obtain the signal and meter transfer coefficients, $T_s = \mathrm{SNR}_s^{\mathrm{out}}/\mathrm{SNR}_s^{\mathrm{in}} = 0.66$ and $T_m = \mathrm{SNR}_m^{\mathrm{out}}/\mathrm{SNR}_s^{\mathrm{in}} = 0.65$, respectively. The signal transfer property of $T_s + T_m = 1.31$ beyond the classical limit of 1 has been achieved. The experimental data are close to the result $T_s + T_m = 1.35$ calculated from Eqs. (11) and (12).

The quantum-state preparation ability of this device is shown in Fig. 3. Trace (1) is the shot noise level of S^{out} detected by HD2. Trace (2) is the lowest noise power spectrum of the difference between the output signal photocurrent and the attenuated (β), as well as phase-shifted (ϕ), output meter photocurrent ($i_2 - \beta e^{i\phi} i_3$), which is obtained by continuously adjusting the attenuation β and selecting the appropriate phase shift ϕ of i_3. With an attenuation of the order of $\beta = 7$ dB, the minimum combined noise power goes to 2.1 dB below the shot noise level of S^{out}. This minimum is nothing but the conditional variance, i.e., $V_{s/m} = -2.1$ dB that is less than the classical limit of 1 [16,18]. The conditional variance calculated from Eq. (13) is $V_{s/m} = -3$ dB which is better than the experimental result. The difference might derive from the fact that the measured minimum of ($i_2 - \beta e^{i\phi} i_3$) is not exact due to the coarse electronic phase shifter used in our experiment.

In conclusion, we have presented a new quantum measurement in which the intensity difference fluctuation is the measured observable and a beam splitter with quantum correlated twin beams at its dark port is used as the coupling device. Although the proposed device is not a true QND operation regime since the signal gain g_s is a nonunity [16], all the criteria for the quantum nondemolition measurement proposed by Holland *et al.* [15] are fulfilled. Since twin beams with high quantum correlation are easier to produce than the quadrature vacuum squeezed state light [12–14] and in the presented scheme only field intensities are measured, the designed system is simple and robust. The measured results can be improved by using more efficient detectors. With the same system taking $\eta = 0.96$ as in Ref. [8] instead of 0.89, $T_s + T_m = 1.51$ and $V_{s/m} = -3.7$ dB can be predicted. To our knowledge, this is the first experimental presentation of a quantum measurement with the intensity difference fluctuation as the observables. In the last few years quantum correlated twin beams have been successfully employed to improve the sensitivity of signal recovery [19], weak absorption measurement [14], and two-photon absorption spectroscopy [20], in that the measurement precision has beaten the SQL. Combining the published measurement systems with the presented scheme the device can be developed as a noiseless optical tap to be used in practical optical information and measurement.

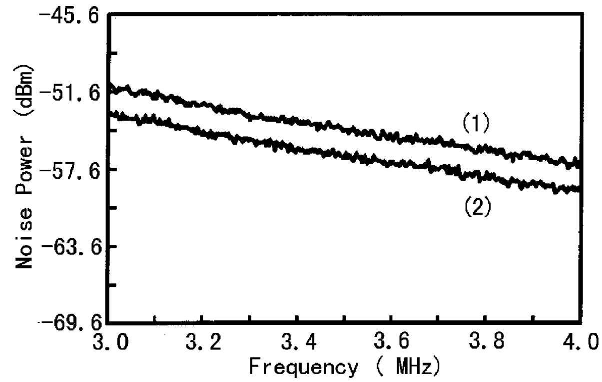

FIG. 3. Conditional variance. (1) Shot noise level of S^{out}; (2) lowest noise level of the difference ($i_2 - \beta e^{i\phi} i_3$).

The financial support of this work was partially provided by the Nation Natural Science Foundation of China (Approval No. 69438010) and the Shanxi Provincial Science Foundation.

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