Backaction Evading Measurements for Quantum Nondemolition Detection and Quantum Optical Tapping

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Backaction evading (BAE) measurements are described for optical parametric amplification with polarization mixing. Quantum correlations between the "signal" and "meter" outputs from the BAE device lead to an observed photocurrent variance 30% (1.5 dB) below the signal shot-noise level and to an inferred variance 44% below the vacuum-state level for determination of the signal field given the meter reading. Together with its efficient information transfer, this BAE detector functions as a quantum optical tap and is suitable for implementing quantum nondemolition detection.

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Quantum mechanics enforces limits on precision measurement both because observables of interest in general have nonzero dispersion and because the extraction of information from a physical system necessarily leads to an invasion of fluctuations from the external environment. In recent years considerable progress has been made with respect to the first of these problems by generating squeezed states [1,2], photon number states [3,4], and a wide variety of other manifestly quantum or nonclassical states [5,6], with dispersions below the vacuum-state level. As for the second problem of measuring an observable without disturbing it, Braginsky and coworkers [7–9] first proposed strategies for a backaction evading (BAE) measurement whereby the fluctuations arising from the coupling of a system to an external meter are directed to a conjugate variable in the system's Hilbert space and hence do not then "contaminate" the specified signal variable. Contemporary with progress in the generation of nonclassical states has been a series of experiments [10–14] directed toward the realization of BAE measurement and ultimately to the demonstration of quantum nondemolition detection (QND), for which an observable for a known initial quantum state is measured without disruption.

Within this context, most experiments [10–13] have considered principally the nonclassical correlation between "signal" and "meter" outputs [so-called quantum-state preparation (QSP)] without reference to overall gain or loss for the measurement interaction (that is, without regard to the preservation of the initial quantum state of the signal input) [12, 15]. Indeed it has proven quite difficult to achieve sufficiently strong quantum correlation while at the same time maintaining efficient low-noise propagation so as to allow repeated BAE measurement and hence QND measurement. Only recently have experiments been realized with both large nonclassical correlation for QSP and efficient throughput for high correlation between signal input and output [14].

The work that we report in this Letter represents a further significant step toward the eventual demonstration of the as yet unrealized goal of QND measurement. Specifically, by employing polarization rotation and parametric amplification for BAE measurement [11, 16, 17], we have achieved a high degree of nonclassical correlation between signal and meter outputs, with an observed variance 30% below the signal-beam vacuum-state level for the difference of amplitudes of signal and meter beams and with efficient throughput (83%) for the initial signal field. When corrected for finite propagation and detection efficiencies for the signal field *subsequent* to the BAE device, we are led to a conditional variance for the signal amplitude given the meter reading which lies 44% (2.5 dB) below the vacuum-state limit of the signal beam alone. Hence when combined with a second identical BAE detector, the capabilities that we have demonstrated should be sufficient for unambiguous QND measurement. Independent of this point, the BAE detector that we describe functions as a quantum optical tap [14,18,19] with small energy loss for the propagating signal and yet with high (nonclassical) signal-to-noise ratio for the extracted meter information.

In generic terms we consider BAE measurement as depicted in Fig. 1(a), where input fields are mapped to output fields as follows [16]:

$$X_S^{\text{out}}(\Omega) = X_S^{\text{in}}(\Omega) \,, \tag{1a}$$

$$Y_S^{\text{out}}(\Omega) = Y_S^{\text{in}}(\Omega) - f(\Omega) Y_M^{\text{in}}(\Omega) \,, \tag{1b}$$

$$X_M^{\text{out}}(\Omega) = X_M^{\text{in}}(\Omega) + f(\Omega) X_S^{\text{in}}(\Omega) \,, \tag{1c}$$

$$Y_M^{\text{out}}(\Omega) = Y_M^{\text{in}}(\Omega) \,. \tag{1d}$$

Here, $X_i(\Omega), Y_i(\Omega)$ denote Fourier components at frequency Ω of the quadrature-phase amplitudes of the input or output modes with $i = S$ designating the signal mode [Eqs. (1a) and (1b)] and $i = M$ the meter mode [Eqs. (1c) and (1d)]. Note that apart from an overall phase shift that has been absorbed into the definition of $(X_i^{\text{in,out}}, Y_i^{\text{in,out}})$, the field amplitude $X_S(\Omega)$ is unaffected by the measurement, while information about this "signal" is nonetheless encoded as the "meter" variable $X_M(\Omega)$. The function $f(\Omega)$ specifies the signal-to-meter coupling and determines the signal-to-noise ratio with which the meter variable can be read. For a vacuum state as the input to the meter mode, the signal-to-noise ratio R_M for the meter output X_M is $R_M^{\text{out}}(\Omega) =$

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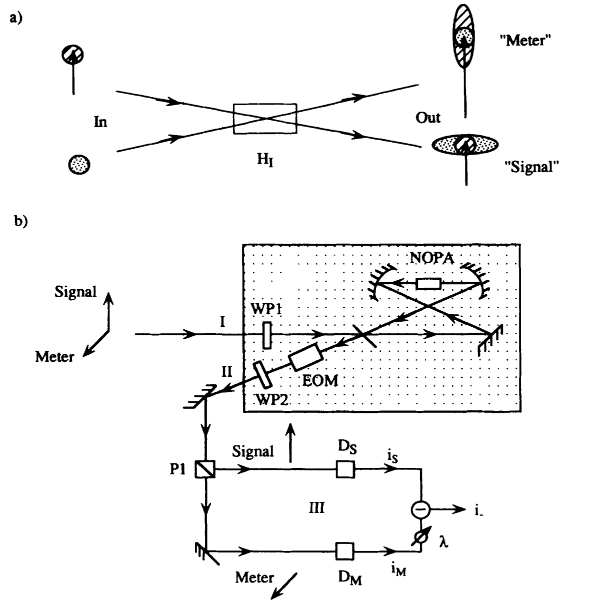

FIG. 1. (a) Simple diagram to illustrate backaction evading (BAE) measurement, with arrows representing coherent amplitudes, and circles and ellipses the quantum fluctuations of the various fields. Information from the amplitude of the signal beam is encoded onto the meter beam without disturbing the amplitude quadrature of the signal beam. The inevitable backaction noise from the interaction appears instead on the phase quadrature of the signal beam. (b) Principal components of the actual experiment for BAE measurement.

$|f(\Omega)\langle X_S^{\rm in}(\Omega)\rangle|^2/[1+|f(\Omega)|^2T(\Omega)]$, where $T(\Omega)$ is the spectral density of fluctuations associated with the $X_S^{\rm in}$ field, $\langle X_S^{\rm in}(\Omega), X_S^{\rm in}(\Omega')\rangle = 2\pi\delta(\Omega+\Omega')T(\Omega)$. Hence for $|f(\Omega)|^2T(\Omega) >> 1$, $R_M^{\rm out}(\Omega) \to |\langle X_S^{\rm in}(\Omega)\rangle|^2/T(\Omega)$, which is precisely the signal-to-noise ratio for the original signal input $R_S^{\rm in}(\Omega)$. As indicated in qualitative terms in Fig. 1(a), the inevitable measurement noise associated with the interaction of signal and meter modes appears in the conjugate variable $Y_S(\Omega)$ [Eq. (1b)], so that the backaction noise is evaded for the variable $X_S(\Omega)$.

As for the specific implementation of this general discussion, Fig. 1(b) presents an overview of our experiment. The transformation specified by Eqs. (1) is accomplished by nondegenerate parametric amplification in sequence with polarization rotation such that the signal field is first sampled, then amplified, and finally restored to its initial status [11,17,20]. Briefly stated, two orthogonally polarized (but frequency degenerate) field modes propagate through a $\lambda/2$ plate (WP1) with optic axis at angle θ with respect to the orthogonal polarization directions determined by the down-conversion process in a type II noncritically phase-matched crystal. The nonlinear crystal is part of a subthreshold nondegenerate optical parametric oscillator which functions as a narrow bandwidth nondegenerate optical parametric amplifier (NOPA) with signal gain $G(\Omega)$. Subsequent to the interaction in the NOPA, the fields propagate through a second $\lambda/2$ wave plate (WP2) at angle $-\theta$. The condition for BAE measurement of $X_S^{\rm in}(\Omega)$ is simply that $|G(\Omega)|\cos(4\theta) = 1$, in which case the transformation of quadrature-phase amplitudes is as specified by Eqs. (1), with $f(\Omega) = 2\sqrt{|G(\Omega)|^2-1}$. Explicit expressions for $G(\Omega)$ can be found in the literature [2, 21]; here we simply note that for lossless propagation and for frequencies Ω small compared to the damping rate of the NOPA cavity, then $f(0) \to 4\epsilon/(1-\epsilon^2)$, with $\epsilon^2 = P/P_{\rm th}$ expressed as the ratio of pumping power P to critical pump power $P_{\rm th}$ at threshold. Hence for $\epsilon \to 1$, $f(0) >> 1$, so that information about the signal beam is faithfully transferred to the meter beam, $R_M^{\rm out} \to R_S^{\rm in}$. Furthermore, the overall propagation efficiency ζ from the signal input at point I to the signal output at II is high for our actual BAE device ($\zeta \simeq 0.83$), so that signal input and output have a high degree of correlation.

The NOPA employed for our experiments is a traveling-wave cavity that utilizes potassium titanyl phosphate (KTP) for type II down-conversion at 1.08 μm. The orthogonally polarized signal (b-axis) and idler (c-axis) directions defined by the crystal form the basis for the specification of the modes $i = S, M$ as in Eqs. (1). Polarization mixing by way of the half wave plates WP1 and WP2 at angles $\pm\theta$ is accomplished relative to this basis, while the electro-optic modulator (EOM) shown in Fig. 1 serves to compensate for phase shifts between signal and meter beams after reflection from the NOPA. The NOPA is pumped by green light at 0.54 μm generated by external-cavity frequency doubling of the light from a frequency-stabilized Nd:YAP laser, with the NOPA cavity length actively servo controlled relative to the frequency of this laser. Simultaneous resonance for the signal and idler modes of the NOPA is achieved by adjusting the temperature of the KTP crystal. The pump field at 0.54 μm is itself resonant in a separate buildup cavity with enhancement $\sim 5\times$. A more detailed description of the NOPA is provided in Ref. [21].

As illustrated in Fig. 1(b), the fields emerging from the BAE device are separated by polarizer $P1$ and propagate with efficiency $\xi = 0.89$ to two independent balanced homodyne receivers (D_S, D_M), which are operated with homodyne efficiencies (η_S, η_M)=(0.98,0.97) and quantum efficiencies $(\alpha_S, \alpha_M) = (0.80, 0.90)$. The photocurrents (i_S, i_M) provide information about the output amplitudes $(X_S^{\rm out}, Y_S^{\rm out})$ and $(X_M^{\rm out}, Y_M^{\rm out})$, respectively, while the photocurrent $i_- = i_S - \lambda i_M$ is interrogated to yield the degree of correlation between the amplitudes for the two output modes. For example, in Fig. 2 we present data to quantify the transfer of coherent information from signal beam to meter beam for an initial signal input of the form $\langle a_S^{\rm in}(\Omega)\rangle \equiv \frac{1}{2}\langle[X_S^{\rm in}(\Omega) + iY_S^{\rm in}(\Omega)]\rangle = 2\pi A\delta(\Omega-\Omega_0)$. The signal beam detected at D_S produces a phase insensitive level Φ_S approximately 22 dB above the vacuum-state limit Φ_{0S} as the phase of the local oscillator is swept. By contrast, the meter beam detected at D_M exhibits a phase-sensitive level Φ_M rising above

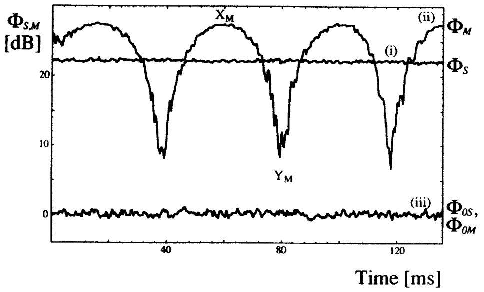

FIG. 2. Spectral densities $\Phi_{S,M}$ of photocurrent fluctuations for signal and meter beams as a function of time as local oscillator phase θ is varied with an approximately linear ramp. Trace (i) gives the phase insensitive level for the coherent signal output as recorded at D_S. Trace (ii) shows the phase dependent variation of the meter field at D_M. This trace represents BAE detection of signal information via the meter beam. Trace (iii) is the vacuum-state level for either signal (Φ_{0S}) or meter (Φ_{0M}) beams at D_S or D_M.

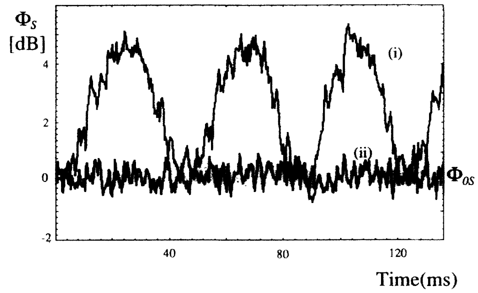

FIG. 3. Spectral density Φ_S of photocurrent fluctuations for signal field detected at D_S as the local oscillator phase θ is swept in time. Trace (i) gives the phase sensitive variation of Φ_S as a result of BAE measurement, with noise minima (maxima) corresponding to the variable X_S^{out} (Y_S^{out}). Trace (ii) gives the vacuum-state level Φ_{0S} for the signal beam. Note that the noise minima for Φ_S lie at Φ_{0S}, indicating BAE measurement of X_S.

and below Φ_S. Here the maxima in Φ_M correspond to the transfer of coherent information from signal to meter [$X_S^{\text{in}}(\Omega_0)$ to $X_M^{\text{out}}(\Omega_0)$, as in Eq. (1c)], while the minima reflect the approximately uncoupled status of the orthogonal meter output [$Y_M(\Omega_0)$ in Eq. (1d)]. The rise in Φ_M above Φ_S demonstrates that the signal-to-meter coupling $|f(\Omega)| > 1$.

In order to verify that the quadrature X_S of the signal beam is in fact unaffected by the measurement process (other than by the passive propagation losses), we present in Fig. 3 the variance of the signal output as recorded in the photocurrent i_S at D_S. Here the coherent signal input has been set to zero ($A = 0$) to examine more carefully the fluctuations of the signal and meter beams at the vacuum-state level. As shown in the figure, the variance of the signal field is phase sensitive with minima at the vacuum-state level (Φ_{0S}) corresponding to the variance $V_{SX}(\Omega)$ of the signal output $X_S(\Omega)$ [where $\langle X_S^{\text{out}}(\Omega), X_S^{\text{out}}(\Omega')\rangle = 2\pi V_{SX}(\Omega)\delta(\Omega + \Omega')$] and with maxima corresponding to the variance $V_{SY}(\Omega)$ of the orthogonal quadrature of the signal output [where $\langle Y_S^{\text{out}}(\Omega), Y_S^{\text{out}}(\Omega')\rangle = 2\pi V_{SY}(\Omega)\delta(\Omega + \Omega')$]. That $V_{SX}(\Omega_0) = 1$ (with unity as the vacuum-state level) means that the signal input to output transformation adds no fluctuations beyond the vacuum-state limit to the X_S quadrature. The "backaction" noise from the coupling of the signal and meter beams appears instead in the Y_S quadrature of the signal field, as indicated by the maxima in Fig. 3. Similar results to those in Fig. 3 are obtained for the fluctuations of the meter beam alone (as recorded at D_M). Note that the origin in time (and hence in local oscillator phases $\theta_{S,M}$ at $D_{S,M}$) is arbitrary; however, we have confirmed that the maximum noise level for the meter field (for X_M) coincides with the minimum noise level for the signal field (for X_S) (and conversely for minimum noise at Y_M and maximum noise at Y_S), in accord with Eqs. (1), and that the maxima for the detection of coherent modulation on the meter beam coincide with the minima for the fluctuations of the signal beam.

Figures 2 and 3 (together with a similar measurement as in Fig. 3 for the meter beam) allow us to quantify the transfer of signal information to the meter beam by way of transfer coefficients $T_{S,M} \equiv R_{S,M}^{\text{out}}/R_S^{\text{in}}$ for the signal-to-noise ratios for the signal (T_S) and meter (T_M) outputs relative to that of the signal input [12]. Note that for any "classical" device, $T_S + T_M \leq 1$, while for a "quantum" device $1 < T_S + T_M \leq 2$. We find that $(T_S + T_M)_{\text{detected}} = 1.16 \pm 0.05$ as directly determined from the relevant photocurrents. Furthermore, if an accounting is made for the efficiencies (ξ, η_s, α_s) of the signal beam from point II to the signal detector D_S, we are then led to the inference $(T_S + T_M)_{\text{inf}} = 1.42 \pm 0.05$ for the value of the signal field at the output of the BAE measurement device (point II) given the value of the photocurrent i_M for the meter beam at detector D_M. This performance demonstrates that our BAE device operates as a quantum optical tap for the extraction of signal information [14, 18, 19].

To complete the characterization of the BAE measurement, we examine in Fig. 4 the degree of quantum correlation between the signal and meter beams. Displayed is the spectral density of photocurrent fluctuations Ψ_- for the difference current $i_- \equiv i_S - \lambda i_M$ [trace (i)], together with the vacuum-state limit Φ_{0S} for the signal beam alone [trace (ii)]. Although the reduction of Ψ_- below $(1 + \lambda^2)\Phi_{0S}$ indicates nonclassical correlations between signal and meter fields, we require instead the more stringent condition $\Psi_- < \Phi_{0S}$ for a BAE detector, where in the current case $10 \ln(\Psi_-/\Phi_{0S}) = -1.5$ dB. Hence the variance $V_-(\Omega) = 0.70 \pm 0.02 \leq 1$ where $\langle [X_S(\Omega) - \lambda X_M(\Omega)][X_S(\Omega') - \lambda X_M(\Omega')]\rangle = 2\pi V_-(\Omega)\delta(\Omega + \Omega')$. Assuming Gaussian fluctuations, we then find that the conditional variance for the signal photocurrent given the value of the meter photocurrent is $W_{\text{QSP}}(\Omega_0) =$

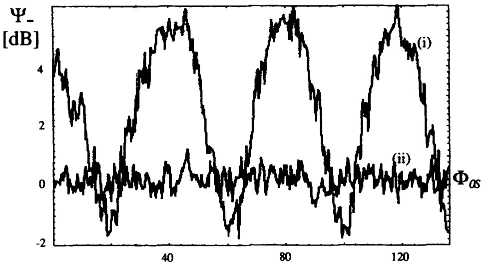

FIG. 4. Spectral density Ψ_- for the photocurrent $i_- = i_S - \lambda i_M$ as the local oscillator phase θ is swept. The vacuum-state level for the signal beam alone ($\lambda = 0$) is indicated by Φ_{0S} in trace (ii). Trace (i) for Ψ_- with $\lambda = 0.32$ drops below Φ_{0S}, from which the conditional variance W_{QSP} for quantum state preparation can be inferred.

$V_-(\Omega_0) = 0.70 \pm 0.02$, with W_{QSP} characterizing the degree of quantum-state preparation of the signal by way of measurement of the meter. Since for many applications one would be interested in the value of the *signal field* emerging from the BAE detector at point II given the reading of the *meter photocurrent* at detector D_M, it is worth quoting the inferred value W'_{QSP} deduced from W_{QSP} after correcting for propagation and detection loss of the signal field from point II to D_S. From data as in Fig. 4, we find $W'_{\mathrm{QSP}} \simeq 0.56$ (that is, 2.5 dB below the vacuum-state limit for the signal field).

Relative to other schemes for quantum measurement [10–14,22,23], we note that the experiment described here has achieved a small value for the conditional variance W_{QSP} (e.g., 0.70 reported here versus 0.85 in Ref. [14]), while at the same time having obtained efficient signal throughput and effective transfer of signal information to the meter [e.g., $(T_S + T_M)_{\mathrm{detected}} = 1.16$ here, while $(T_S + T_M)_{\mathrm{detected}} = 1.25$ in Ref. [14]]. While schemes for quantum tapping or duplication have demonstrated impressive performance (e.g., Refs. [22, 23]), it should be noted that these are not true BAE measurements since the interaction Hamiltonians do not commute with the measured observable. Indeed, although a variety of nonclassical interactions can satisfy the "QND criteria" as set forth in Refs. [12, 15], we emphasize that these criteria provide necessary conditions only and do not supplant the QND conditions set forth in Refs. [8, 9], even in an approximate sense. For example, a particular interaction that does satisfy the "QND criteria" of Refs. [12, 15] may not be suitable for QND measurement since input field states can in fact be demolished with information about signal inputs surviving only in the form of output fields with variances much larger than the vacuum-state limit. Although such a circumstance is not useful for a sequence of precise measurements with sensitivity beyond the standard quantum limit [8], it may be, however, quite well suited to certain other applications such as telecommunication, which indicates a developing richness to the field of quantum measurement. We stress that our own work is a faithful demonstration of BAE measurement [7–9] and should be suitable for repeated application with sequential improvements in sensitivity beyond the standard quantum limit with such successive BAE measurements. When combined with an identical second BAE detector, the capabilities described in this Letter should be sufficient for an unambiguous realization of QND measurement whereby a first BAE detector measures (prepares) the field state for a second BAE detector, which then attempts a measurement of a known state of the field. As expressed by Caves *et al.* [9], "the key feature of such a nondemolition measurement is *repeatability*–once is not enough!"

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