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Squeezing with Fiber Sagnac Loop and Sub-Shot-Noise Measurement

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Squeezed states of light are minimum uncertainty states for which the mean square fluctuations in phase and in quadrature with respect to a reference signal are unequal. Among other interesting properties, they provide improved sensitivity of optical interferometric phase measurements. To understand this potential, one must note that quantum theory imposes measurement uncertainty only on a pair of noncommuting variables; the measurement of any one quantum observable could be done with no uncertainty.

Engineering systems usually employ large numbers of photons per measurement to arrive at an acceptable signal to noise ratio. In such situations, the evolution of the operators in the Heisenberg representation can be linearized by writing each operator as the sum of a large c -number and an operator of small expectation value. If higher than first order terms are neglected, the operator equations are linearized. Linear equations do not contain products of operators and thus issues of operator ordering do not arise. But then the equations are indistinguishable from classical linear equations and have the same solutions. In this way a close analogy is established between the quantum problem and the system equations of the classical counterpart. Classical transfer functions can be used, and the superposition principle applies.

Since the application of squeezing is for the reduction of noise in interferometric measurements, it is important to understand how squeezed vacuum can lead to such noise reduction. The measurement of the phase imbalance of a Mach-Zehnder interferometer is made on the output beam splitter on the side which has zero output under balanced conditions (the signal side). The noise of the measurement is due to the zero-point fluctuations entering the "unexcited" side of the input beam splitter. If the measurement of the output signal is with a phase sensitive balanced homodyne detector, squeezed radiation of proper phase fed into the input can reduce the noise. This interpretation of the noise reduction is congruent with the interpretation that the shot noise in a balanced homodyne detector is due to the zero-point fluctuations entering its input port, and not due to the local oscillator photon noise; a balanced detector cancels the local oscillator fluctuations. This point of view follows from the consistent application of the linearization of the operator equations in the Heisenberg representation.

Next consider squeezing by a nonlinear Mach-Zehnder interferometer^[1]. A phasor of a coherent state, represented by the probability distribution (Wigner distribution) of its complex amplitude in the phasor plane, entering the interferometer acquires a distribution of phase shift. When the event is represented by a point in the phasor plane of increased amplitude the phase shift is larger, and a smaller phase shift occurs when the point corresponds to a smaller amplitude. The circularly symmetric distribution distorts into an ellipse tangential to the original circle as shown with the two parallel lines that approximate

the circle in the limit of large phasor amplitude. In Figure 1 we remove the net "classical" phase shift due to the average amplitude of the phasor. The inserts follow the evolution of the Wigner distributions through the Mach-Zehnder. The vacuum output port removes the average phasor and produces radiation of zero expectation value. The Mach-Zehnder configuration "filters" out the pump radiation and produces squeezed vacuum.

A simple implementation of the nonlinear interferometer is the fiber Sagnac loop with a 50/50 coupler as shown in Fig. 2^[2,3,4]. This configuration is selfstabilized against any index fluctuations on a time scale longer than the traversal time. An input pulse is reflected back into the input port. The vacuum port is excited by the vacuum fluctuations and emits squeezed radiation. Figure 3 shows the evidence for squeezing. In this experiment, the "stabilizing" mirror is swept and the phase between L.O. and squeezed vacuum is changed continuously. The noise is measured with a filter of 40 kHz center frequency and 2 kHz bandwidth. The shot noise level is established by blocking the squeezed vacuum from entering the balanced detector. Any attenuator then injects standard zero-point fluctuations. It is clear from comparison between the two traces, one establishing the shot noise level, the second with repetition of the squeezed radiation, that noise is less than the shot noise level at the instants of favorable phase.

Figure 4 shows the noise spectrum of shot noise and squeezed noise stabilized at the minimum level. The squeezing yields 5.1 dB reduction of the noise below the shot noise level.

These experiments^[2,3] were conducted with a fiber that happened to leave the frequency range of 40-90 kHz free of Guided Acoustic Wave Brillouin Scattering (GAWBS)^[6]. This scattering is due to the acoustic modes of the fiber near cutoff that are phase matched to the forward Brillouin scattered waves. The GAWBS spectrum is a very sensitive function of the fiber geometry and it is found that in most fibers the convolution of GAWBS to the low frequency measurement window cannot be avoided.

Two ways of overcoming the GAWBS are:

- When two pump pulses delayed by less than 1 ns are used, and one of the pulses is phase reversed before being used as the local, oscillator, the GAWBS cancels.
- With a high pulse repetition rate (> 1 GHz) the GAWBS spectrum does not convolve into the low frequency window.

These schemes have both been tested experimentally and will be reported in detail^[6,7].

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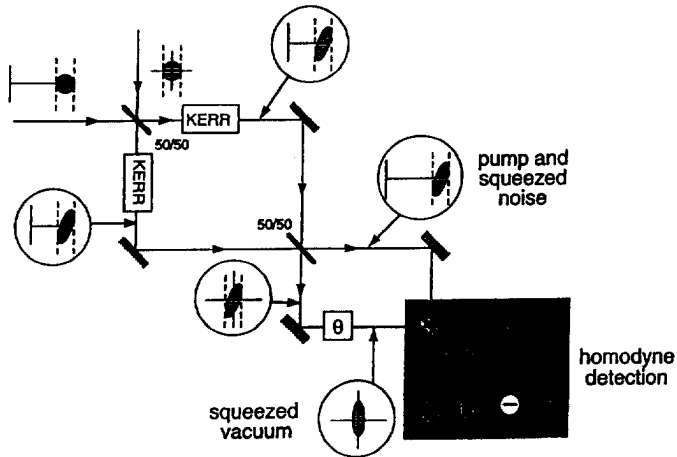


Fig. 1 Squeezing by means of the nonlinear Mach-Zehnder interferometer.

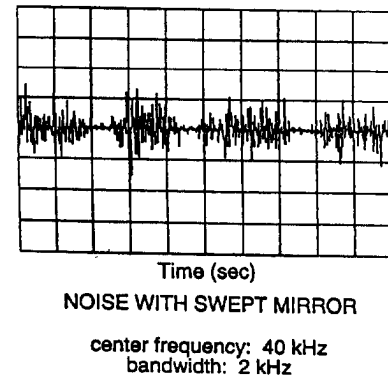
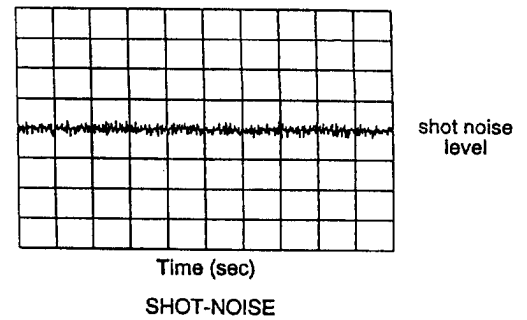


Fig. 3 Evidence of squeezing

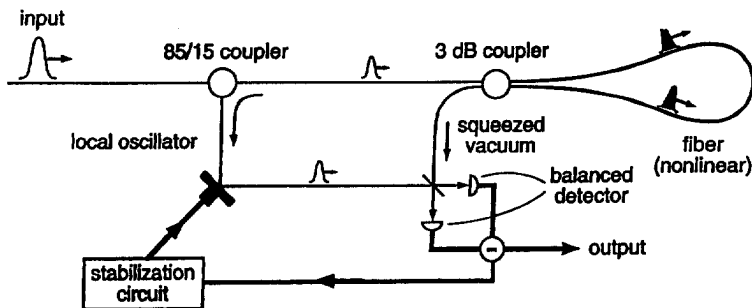


Fig. 2 Experimental configuration

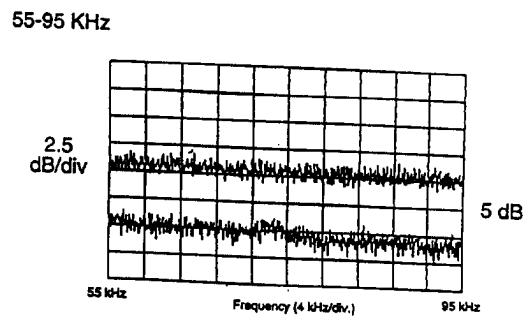


Fig. 4 Quantum noise in homodyne detection with standard zero point fluctuations and with squeezed vacuum.