Squeezed-Light–Enhanced Polarization Interferometer

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Enhancement of the sensitivity of a polarization interferometer beyond the limit set by vacuum fluctuations of the electromagnetic field has been obtained with use of squeezed light generated by a $KTiOPO_4$ optical parametric amplifier. The increase in signal-to-noise ratio relative to the shot-noise limit is 2 dB. The corresponding improvement in the response time of the interferometer is measured to be a factor of 1.6.

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The ultimate performance in the measurement of very small optical phase shifts is currently of great interest because of the realization of extremely sensitive devices, such as gravitational wave antennas[1] and laser gyroscopes.[2] These devices can already operate at the so-called "shot-noise limit" (SNL); i.e., the noise in the measurement of a phase shift ϕ is due to the quantum fluctuations of the light injected into the interferometer. This measurement noise for an optimally designed interferometer is

$$(\Delta\phi)_{\rm SNL} = 1/\sqrt{N}, \qquad (1)$$

where N is the number of photons from the input beam detected during the chosen integration time.

As discussed theoretically by many authors,[3-9] squeezed light can be used to enhance the sensitivity of interferometers beyond the SNL. This can be seen by our realizing that the beam splitter, which is generally used in an interferometer to split the input coherent light, is actually a two-port input device. One port is used for the input light, while only the "vacuum" state of the field usually enters the other, "dark" port. A quantum analysis of the interferometer then shows[3] that the measurement noise can be entirely attributed to one quadrature component of this vacuum field. One can thus improve on the SNL by injecting a field into the dark port which has less fluctuation in this quadrature component than the vacuum field, i.e., a squeezed state of light.

In this Letter we describe an experiment that demonstrates enhancement of an interferometer beyond the SNL, by injection of squeezed light into its dark port. In this experiment the interferometer is sensitive to very small polarization rotations. Without the use of squeezed light at the dark port, the SNL is achieved in a frequency range where the fluctuations of the input light are quantum mechanical in origin and not due to technical sources of noise (vibrations, acoustical noise, etc.). For example, in the present experiment, polarization rotations at frequencies above 60 kHz can be measured with quantum-limited noise.

Figure 1 shows the polarization interferometer used in our experiments. The first polarizer (P1) is a polarization-dependent beam splitter. The coherent laser light and the squeezed light have orthogonal polarizations, so that this beam splitter directs these two beams along the input direction of the interferometer. A half-wave plate rotates these polarizations by 45° and the second polarizer (P2) acts as the beam splitter for a balanced homodyne detector at the output of the interferometer. The coherent laser light serves as the local oscillator (LO) for this homodyne detector. When there is no polarization rotation between the polarizers, the differenced photo-

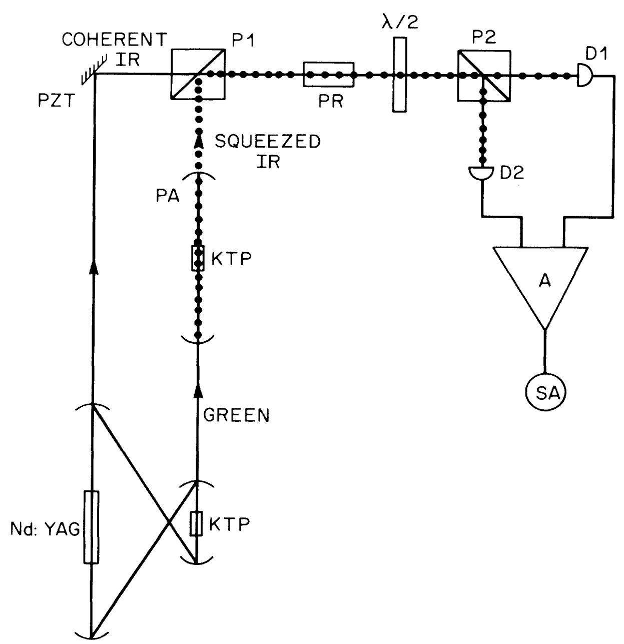

FIG. 1. Experimental setup. Coherent ir light from the cw Nd-doped yttrium-aluminum-garnet laser (left) and squeezed light from the parametric amplifier PA (right) are injected into the two input ports of the polarization interferometer (top) formed by polarizing beam splitters P1 and P2. A rotation of the polarization axes due to a polarization rotator PR is measured by an imbalance in detector currents D1 and D2 on a spectrum analyzer SA.

current i_D from the two balanced photodetectors fluctuates at the SNL. Any polarization rotation in the interferometer [due, for instance, to the Faraday effect in the polarization rotator (PR) in Fig. 1] will be detected as a change in the photocurrent i_D. This polarization interferometer is actually equivalent to a Mach-Zehnder interferometer,[10] where the spatially separated "arms" have been changed to copropagating left- and right-handed circular polarizations between P1 and P2 in Fig. 1. When no squeezed light enters the interferometer, the measurement noise for a polarization rotation ϕ (at frequencies above technical noise) is the SNL for phase measurement as given by Eq. (1). This measurement noise can also be expressed in terms of the power P_0 of the coherent beam, in units of photons per second, and the bandwidth B of the detector electronics, as

$$(\Delta\phi)_{\rm SNL}=(2B/\eta P_0)^{1/2}, \qquad (2)$$

where η is the quantum efficiency of the detectors. Typical values for these quantities in our experiment are $B=30$ kHz, $P_0=5\times10^{15}$ sec^{-1} corresponding to an optical power of 1 mW, and $\eta=0.9$. For these values,

$$(\Delta\phi)_{\rm SNL}\simeq3.5\times10^{-6}\ \text{rad}. \qquad (3)$$

Now consider the effect of squeezed light entering the dark port of the interferometer through the polarizing beam splitter. One can easily show[11] that the measurement noise becomes

$$(\Delta\phi)_{\rm squeezed}=(2B/\eta P_0)^{1/2}\sqrt{R}, \qquad (4)$$

where R is the degree of squeezing achieved for the input light. R is defined as the minimum ratio of noise powers obtained for a squeezed field entering the dark port of the input beam splitter relative to the vacuum field entering this port. The effective R value is increased by any losses in the optical system. These loss limitations in the present experiment are not due to the interferometer itself, but to imperfect detector efficiencies and to crystal losses in the optical cavity generating the squeezed light.

Squeezed light is generated by use of optical parametric amplification.[12] We use as a primary source a cw ring Nd-doped yttrium-aluminum-garnet laser, operating at 1.064 μm in single transverse and longitudinal modes. This laser is not frequency stabilized; its free-running frequency jitter is small enough to allow direct locking to the optical cavity in which the squeezed light is generated. A frequency-doubling $KTiOPO_4$ (KTP) crystal in the laser cavity provides light at 0.532 μm, which is used to pump the parametric amplifier. The squeezing cavity is locked to this green pump light with use of an FM modulation technique.[13] The squeezing cavity is resonant for both the green and infrared light, with finesses for the empty cavity which are respectively 160 and 70. In this cavity we use two KTP crystals. This pairing of the nonlinear elements allows for compensation of the walkoff which occurs for non-90° phase matching[14] in a single nonlinear KTP element. The observed thresholds for parametric oscillation in this cavity range between 150 and 200 mW, depending on the quality of the KTP crystals and on the degree of focusing (the cavity is close to a concentric configuration). The phase-matching configuration in KTP is type II[14]; i.e., the signal and idler parametric decay fields have orthogonal polarizations. In this case, three different polarization modes must resonate together in the cavity: the ordinary and extraordinary polarizations for the infrared light, and the extraordinary polarization for the green pump light. This is achieved by the adjustment of both the temperature and the orientation of the crystals so that the single-pass optical-path shift between ordinary and extraordinary polarizations is equal to an integral number of wavelengths. When the resonant conditions are achieved, one can define two orthogonal-polarization modes, which are oriented 45° from the principal axes of the KTP crystals. These orthogonally polarized modes both have squeezed fluctuations.[11,15]

Figure 2 shows the output of the homodyne detector when the local-oscillator phase is varied with no Faraday rotation, for a center frequency of 400 kHz and an rf bandwidth 30 kHz. The maxima of phase-dependent amplification and deamplification from the vacuum noise level are respectively +3.4 and −2.0 dB. By the deconvolution of the photodetector amplifier noise, these values increase to +3.9 and −2.6 dB. When we take into account the 2% intracavity and 20% extracavity losses, this corresponds to a "lossless" squeezing value of ±5 dB. The extracavity losses include heterodyne efficiency (95%) and detector quantum efficiencies (90%). In this regime the observed squeezing is actually

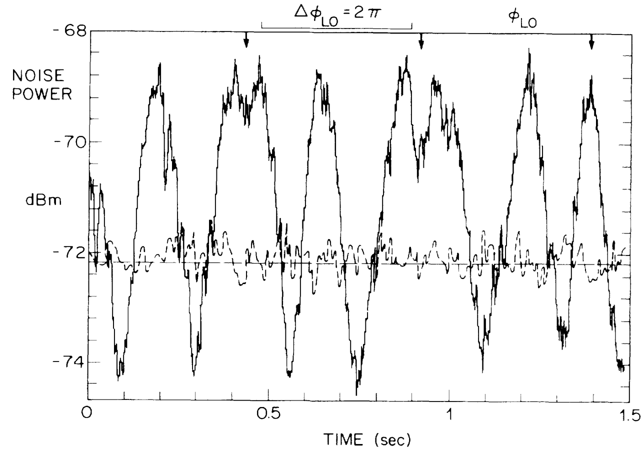

FIG. 2. Noise power at the output of the balanced detector, as a function of the local-oscillator phase. The dashed and solid lines correspond respectively to the squeezing cavity blocked and unblocked. The arrows on the ϕ_{LO} axis indicate the reversals of the lead zirconate titanate (PZT) motion. The center frequency is 400 kHz, the rf bandwidth is 30 kHz, and the video bandwidth is 30 Hz.

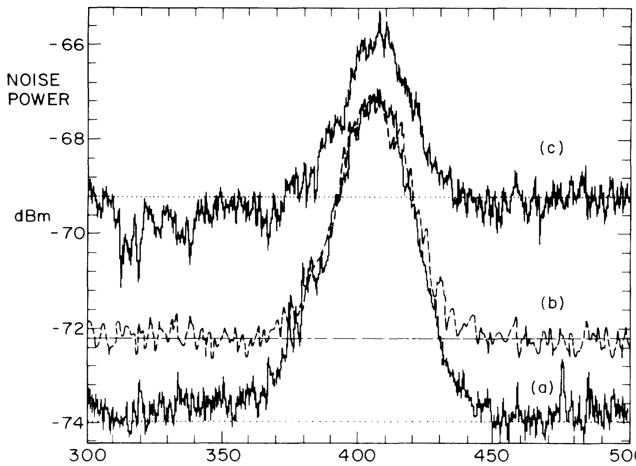

FIG. 3. Polarization-rotation signal-to-noise measurements. Current at a frequency of 400 kHz is applied on the Faraday rotator to produce an oscillating polarization angle. The spectrum analyzer is frequency scanned across the resulting signal (30-kHz rf bandwidth). Trace *a* is with LO phase adjusted for maximum squeezed-noise reduction, trace *b* is obtained with vacuum input at the dark port, and trace *c* is with LO phase adjusted for maximum noise increase. The horizontal lines indicate the noise levels with no polarization-rotation signal. Fluctuations in the base-line traces *a* and *c* are due to slow fluctuations in the LO phase. The duration of the scan is 1.5 sec.

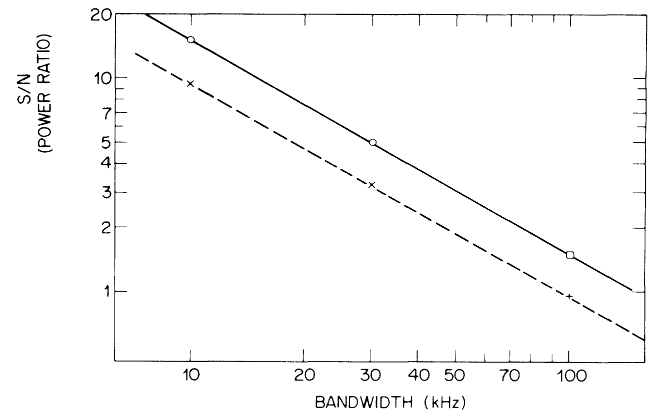

FIG. 4. Signal-to-noise power ratios as functions of the rf bandwidth. The dashed line corresponds to a vacuum input and the solid line to a squeezed-light input. These lines correspond to the expected $1/B$ dependence. The open-circle and cross data points have been measured at 400 kHz, and the open-square and plus-sign data points at 850 kHz. These results illustrate the improvement in response time of the interferometer due to the use of squeezed light.

limited by the parametric gain. The parametric gain is difficult to stabilize at higher gain values because of a thermal instability associated with green absorption in the KTP crystals.

The noise reduction in the interferometer is illustrated in Fig. 3. An oscillating current at 400 kHz is applied to the Faraday rotator, with an amplitude comparable to the SNL. The frequency of the spectrum analyzer is then scanned between 300 and 500 kHz. Without squeezed light, the signal-to-noise ratio is 5.2 dB (trace *b*). With squeezed light entering the interferometer, and LO phase at its optimum value for noise reduction, the signal-to-noise ratio improves to 7 dB; that is, a 1.8-dB improvement beyond the SNL is obtained. During shorter time periods than shown in Fig. 3, the noise decreases by 2 dB below the vacuum noise level (as shown in Fig. 2). On the other hand, a 90° LO phase shift from trace *a* increases the noise by about 3 dB (trace *c*) as expected for the antisqueezed quadrature.

To be more quantitative, we have studied the signal-to-noise ratio as a function of the spectrum-analyzer radio-frequency bandwidth. The results are plotted in Fig. 4, for both vacuum and squeezed-light inputs, with the signal amplitude and LO power held constant. These curves clearly show that a given S/N ratio can be obtained with the integration time reduced by a factor of 1.6, if squeezed light is used. Equivalently, one could choose to keep the bandwidth constant. A given S/N ratio is then obtained with an input coherent-light power 1.6 times smaller.

With respect to possible applications, an important further step would be to extend the noise reduction into the low-frequency domain, i.e., within the frequency range where the amplitude (technical) noise of the laser limits the interferometer sensitivity. This can be done with modulation techniques, in order to transfer the phase information to a frequency range where the technical noise is negligible. Both amplitude[8] and phase[9] modulations have been proposed in the literature.

In conclusion, we have demonstrated an interferometer that measures polarization rotation with a measurement noise 2.0 dB below the shot-noise limit. This enhanced precision is accomplished by the generation of squeezed light which is injected into the dark port of the interferometer. In these experiments, KTP has been used for the first time to generate the squeezed light. This crystal is readily available and has a very high damage threshold and moderately low linear absorption which make it attractive for the generation of quantum states of light. The pair-correlated photons from the squeezed cavity are orthogonally polarized and thus easily separable with a polarizing beam splitter. This property is useful in correlation experiments with quantum light.[16,17]

The enhanced sensitivity of this polarization interferometer should be especially useful for very rapid phase measurements where shot noise dominates because of the small number of photons in the measurement time interval. An interesting example is the shot-noise–limited polarization interferometers currently used to measure voltage or charge-density variations in semiconductors.[18,19] These measurements could benefit directly from the improvement in sensitivity that we have demonstrated.

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