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Two-color squeezing and sub-shot-noise signal recovery in doubly resonant optical parametric oscillators

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A monolithic doubly resonant optical parametric oscillator produced signal and idler modes at widely separated wavelengths whose amplitude fluctuations were correlated $(53.6\pm1.0)\%$ below the vacuum-noise level. The system was used to detect modulated signals well below the shot-noise limit.

A squeezed state of light is one whose fluctuations of some state variable are less than that of the standard quantum limit, also variously known as the vacuum noise, or the shot-noise level.[1] This concept has been extended over the years to include not only two-mode squeezed states,[2] but also those states that approach number states[3,4] and to the squeezing of quantum correlations among more than two modes.[5] Parametric amplification and deamplification of the vacuum field is the archetypical process for two-mode squeezed-state generation.[6–8] In above-threshold parametric oscillators, quantum correlations arise from the simultaneous creation of "twin photons" so that the amplitude fluctuations of the signal and idler field modes are perfectly correlated.[9–13] This is similar to "four-mode" squeezing,[5] in that the spectral densities of amplitude and phase noise correlations at a given radio frequency f arise from field fluctuations in four sideband modes, offset by f above and below the signal and idler frequencies. In the case of the nondegenerate optical parametric oscillator, (OPO) the signal-idler intensity difference is "squeezed," while the "antisqueezed" variable is the phase difference of the signal and idler.[9]

Amplitude correlations below the vacuum level have been observed in doubly resonant OPO with type-II phase matching where the signal and idler modes were separated with a polarizer,[14] and noise reduction 69% below the shot noise has been recently observed.[15,16] In this paper we report on a tunable, above-threshold doubly resonant OPO (DRO) with observed amplitude correlations 53.6% below the shot-noise level in a type-I phasematched system where the signal and idler are at different colors and are separated by prism; thus our term "two-color squeezing." Insertion of an amplitude modulator in one beam allowed the demonstration of signal detection below the shot-noise limit.

The design and performance of our OPO system has been described in Refs. 17 and 18. A monolithic doubly resonant optical parametric oscillator fabricated from MgO:LiNbO$_3$ was pumped by the second harmonic (at 532 nm) of either a single-frequency, diode-laser-pumped Nd:YAG (YAG denotes yttrium aluminum garnet) laser, or an injection-locked high-power Nd:YAG laser at 1064 nm. A traveling-wave, ring path in the crystal resonator was used, although a standing-wave path was also available. The DRO was temperature tuned from 1007 to 1129 nm, operated on a single axial mode pair over most of the range, and could be electric field tuned by as much as 38 nm near degeneracy. In studies of the classical coherence properties of the DRO the linewidth of the signal was measured at less than 13 kHz, and the signal-idler heterodyne linewidth was 500 Hz.

For the two-color squeezing experiments three monolithic MgO:LiNbO$_3$ OPO resonators were available. The first had an output coupling of 0.5% at 1064 nm, a threshold of 12 mW, and had been used in the experiments of Refs. 17 and 18. The others had outcouplings of 1.2% and 1.8%, and had been used in earlier work on pulsed DRO's (Ref. 19) and external cavity resonantly enhanced second-harmonic generation.[20] All crystals had fixed, internal losses of 0.4–0.5 %, and all had had their ring paths damaged by residual photorefractive damage which could not be annealed out without harm to the soft dielectric coatings. In this work the standing-wave paths of the resonators were used to avoid the damaged regions.

The experimental layout is shown in Fig. 1. A high-power (> 10 W) injection-locked Nd:YAG laser[21] was frequency doubled in a 2-cm MgO:LiNbO$_3$ crystal; the second harmonic at 532 nm was separated with a prism, and was mode matched into the monolithic DRO resonator. An adjustable voltage was applied across the DRO crystal y axis to tune the cavity length and maximize the DRO power, which remained stable to within a few percent for tens of seconds with no active servo control. DRO output light was collimated with a lens, the polarization rotated with a periscope, and the signal and idler beams separated with a Pelin-Broca prism. The DRO signal wavelength was typically 1012 nm and the idler wavelength was 1120 nm. At a distance of 1.7 m from the prism the beams were separated by 7 mm and mirrors directed the beams through lenses and onto InGaAs pho-

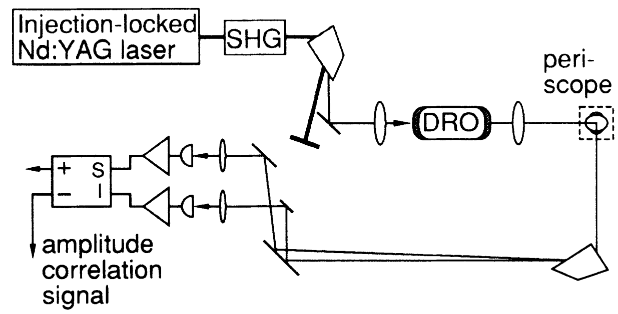

FIG. 1. Two-color squeezing experimental layout. SHG represents second-harmonic generation.

todiodes (Epitaxx ETX-300, 300-μm diameter, quantum efficiency of 84% at 1064 nm). The spot size on the detectors was 30 μm for both beams. The throughput of the optical system from the DRO to the detectors was measured to be 94%, yielding a net detection efficiency of 79%.

The photocurrent of each detector was divided by an *LC* crossover network so that the DC currents were passed through 100-Ω resistors, and the voltages across the resistors were monitored with digital voltmeters and an oscilloscope. The high-frequency current fluctuations were amplified by integrated transimpedance amplifiers (Signetics NE5212). The crossover networks, tuned to produce net amplifier response balanced to within 1 dB from 1–40 MHz, were necessary to protect the amplifiers from saturation by large power fluctuations at low frequencies. The difference signal was obtained by using a hybrid junction (Lorch Electronics JH-251A), and the gains of the two channels were balanced using variable attenuators (Arra 0682-10F) in each signal line. The OPO signal and idler beams typically had excess amplitude noise peaks 10 dB or more above the shot-noise level at frequencies below 10 MHz attributable to acoustic modes in the crystal. Common-mode rejection was estimated to be 16 dB at 4 MHz and at least 10 dB from 2 to 20 MHz.

The shot-noise level for our experiment was determined by illuminating the detectors with a small portion of the Nd:YAG laser beam after splitting by a 50/50 beamsplitter in a balanced detection arrangement, so as to produce identical dc photocurrents as in measurements of the OPO noise. In this case, any excess noise on the laser beam is eliminated on the difference signal from the hybrid junction, yielding the vacuum-noise level, while the sum signal exhibits the excess laser noise.[22] When the laser was operated in injection-locked mode, the sum signal was within 3 dB of the difference signal for frequencies above 3 MHz. With our common-mode rejection, this suggests that the difference signal accurately reflects the vacuum-noise level. When the laser was free running the low frequency noise due the diode-pumped master oscillator was not present, and the sum signal and difference signal were both at the same level to within 0.1 dB as the difference signal for injection-locked operation. The difference signal level was very repeatable and showed no sensitivity to the position of the beam on the detector. Thus we are confident that we are accurately calibrating the shot-noise level for frequencies above 2 MHz.

The spectrum of squeezing for our system is given by[10,13]

$$R(f)=1-\eta_D\eta_{\mathrm{OC}}\frac{1}{1+\left[\dfrac{f}{f_c}\right]^2} \tag{1}$$

where $R(f)$ is the noise power normalized to the shot noise, η_D is the detection efficiency, η_{OC} is the outcoupling efficiency equal to the output coupling divided by the total round-trip loss (sometimes called the escape efficiency), and f_c is the power bandwidth of the cavity resonance. In general, there is an enhancement of the noise near zero frequency due to unequal cavity losses,[10] and in our experiment there is an additional low-frequency noise contribution from the large classical amplitude fluctuations of the DRO below 2 MHz which are not entirely canceled out by the balanced detection system.

The 0.5%-outcoupled DRO exhibited two-color squeezing $(32\pm2)\%$ below shot noise ($R=0.68\pm0.02$) at a frequency of 4 MHz. The prediction from Eq. (1) with $\eta_{\mathrm{OC}}=0.5$, $\eta_D=0.79$, and $f_c=8.1$ MHz is $R=0.68$, in good agreement with the measured value. Values for the outcouplings and losses are taken from earlier measurements.[16,18,19] The spectrum of squeezing was also in good agreement, with the DRO noise level reaching the shot-noise level for frequencies greater than 40 MHz.

The best two-color squeezing was seen in the DRO with 1.2% output coupling. Threshold for this device was 24 mW at 532 nm. Spectrum analyzer traces of the difference signal for this DRO are seen in Figs. 2(a) and 2(b), where the trace in Fig. 2(b) shows the spectrum of squeezing as obtained by subtracting the shot-noise (laser) trace from the DRO trace on a log scale. The DRO signal noise level is greater than 3 dB below the shot noise. Figure 3 shows the data from the traces of Figs. 2(a) and 2(b) along with data from two other sets for this crystal plotted on a linear scale to show $R(f)$. The spectrum analyzer marker function was used to record the data and determine the error bars for nine frequencies adjacent to each frequency data value. The mean value for $R(f)$ at 4 MHz was 0.464 ± 0.010, so that the squeezing was $(53.6\pm1.0)\%$ below the shot-noise level. The error is the calculated standard deviation for the three data sets, and does not include any systematics. The curve is of $R(f)$ as calculated using the values $\eta_{\mathrm{OC}}=0.75$, $\eta_D=0.79$, and $f_c=13.8$ MHz. There were no free parameters used in the calculation of the theoretical curve.

The 1.8%-outcoupled DRO was expected to yield the greatest amount of squeezing, with R(6 MHz) calculated to be 0.43, but experimentally we observed only R(6 MHz)$=0.54$. This could be due to excessive losses out of the nominal high reflector port, or to some process in the crystal such as photoconduction which has been suggested as a mechanism that destroys squeezing in systems with high circulating powers. Threshold pump power for this DRO was 80 mW.

The good agreement of the experimental spectral line shapes with theory, and the amount of squeezing (for the first two crystals), are favorable signs that we have indeed observed sub-shot-noise quantum correlations. To rule out the possibility of any amplifier saturation, we measured the squeezing spectrum for photocurrents of 3.00 mA for the 1.2%-outcoupled DRO as described above. We then inserted a 50% attenuating neutral density filter so that the photocurrents were reduced to 1.50 mA, although the DRO was operating at the same power level. The amount of squeezing with the filter in place was reduced to 26%, as expected from Eq. (1), with detection efficiency halved by the neutral density filter. We then reduced the pump power incident on the DRO and operated it at a power level so that the photocurrents were 1.50 mA without the optical attentuator. The full quantum correlation was recovered, with noise reduction again greater than 50%. The reduction of squeezing with optical attenuation and the independence of $R(f)$ on the power level are both hallmarks of quantum intensity correlations and a noise level below the vacuum. This measurement also supports the validity of the detection system shot-noise level calibration using 1064-nm light.

To demonstrate the potential utility of our tunable two-color squeezing apparatus, we placed an amplitude modulator consisting of a Pockels cell and a polarizer in one of the DRO beams and applied an 800-mV_{pp} modulation voltage at 5 MHz so that for a resolution bandwidth of 30 kHz the signal was clearly detectable, and yet well below the shot-noise level. Figure 4 shows the detection of the sub-shot-noise signal. Here there is only 2.2 dB of

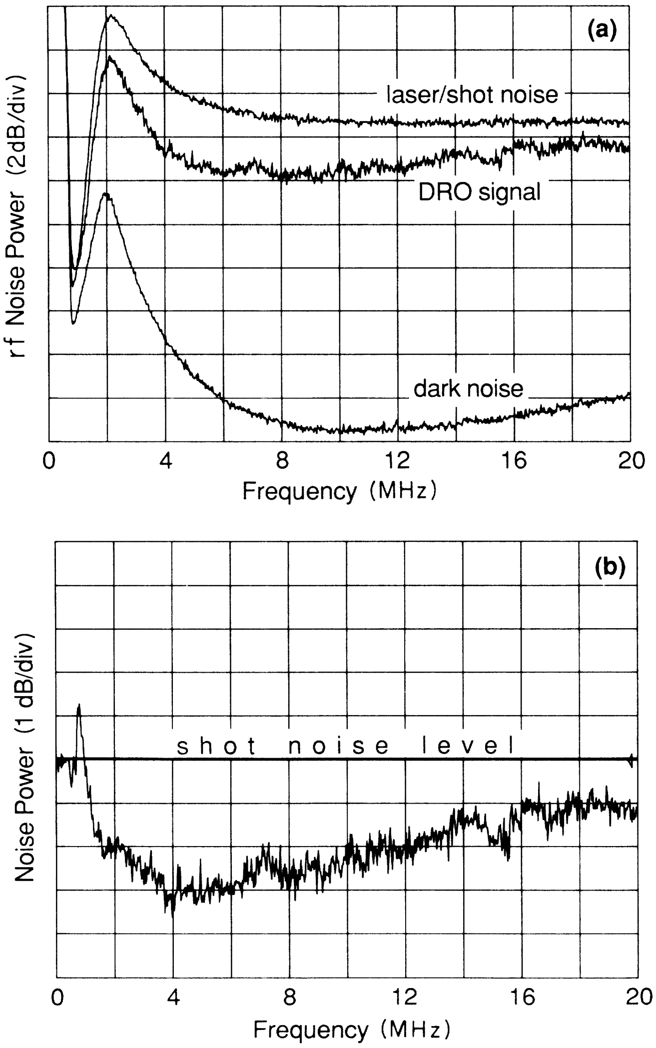

FIG. 2. (a) Spectrum analyzer traces for the differential laser signal (shot noise), the differential DRO signal for the 1.2%-outcoupled DRO, and the electronics (dark noise). The DRO signal is clearly below the shot-noise level over a wide frequency range. The peaking at 2 MHz is caused by the *LC* crossover networks. Resolution bandwidth is 100 kHz. (b) The noise level of the DRO signal as compared to the shot noise in dB units, obtained by subtracting the first and second traces of (a).

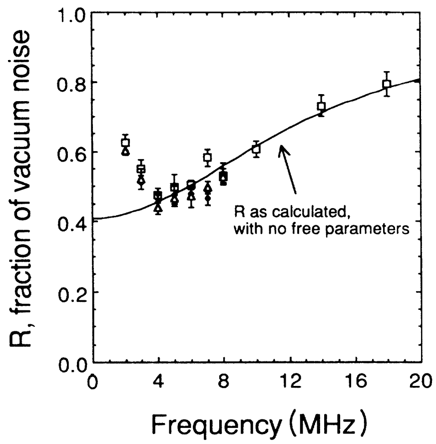

FIG. 3. Two-color squeezing data from several experimental runs plotted on a linear $[R(f)]$ scale. The average experimental value of $R(f)$ at 4 MHz is 0.464 ± 0.010. The calculated curve has no free parameters.

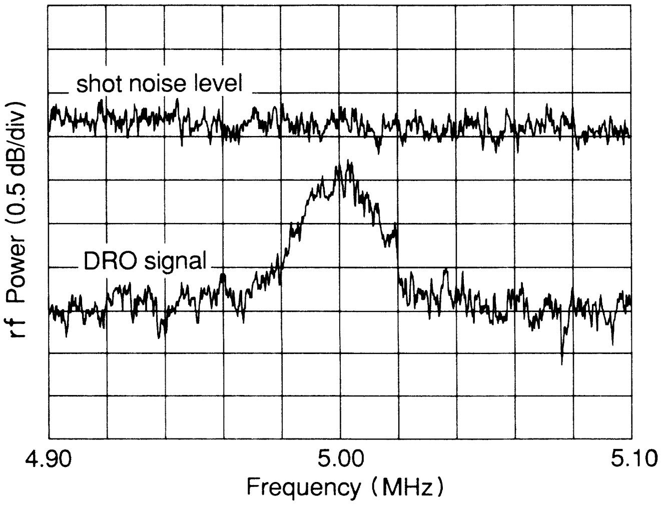

FIG. 4. Sub-shot-noise signal recovery with balanced differential detection. The DRO signal noise floor is 2.2 below the shot noise. The resolution bandwidth is 30 kHz.

squeezing of the DRO noise floor due to the ~1-dB insertion loss of the modulator.

In systems using vacuum squeezed states to improve detection sensitivity, the improvement in signal-to-noise ratio could be immediately observed in a quantitative way.[8,23] Such a comparison was not made in the current series of experiments because the sensitivity of the modulator response with alignment precluded identical conditions from being achieved with the equivalent laser balanced-detection system. In such a system, where the DRO is replaced by a beamsplitter and the two output beams from the beamsplitter are detected by the balanced detectors, the best achievable noise level is the shot-noise limit for the total two-detector photocurrent. If the modulator is placed in one of these beams and the performance compared to that for the DRO system with the same modulation index and optical power through the modulator, one finds that the signal-to-noise ratio of the DRO measurement relative to the balanced laser system is given by

$$\frac{(S/N)_{\mathrm{DRO}}}{(S/N)_{\mathrm{laser}}}=\frac{1}{R(f)}\ . \tag{2}$$

Thus the OPO is always an improvement over the laser-based scheme. For direct detection with a shot-noise-limited laser or balanced homodyne detection where the modulated beam is incident on the input port to the balanced detector, this comparison is a factor of 2 less favorable for our measurement scheme. In these cases the sub-shot-noise detection system would actually need 50% or more squeezing to compare favorably.

Further work and applications of two-color squeezing might include improved squeezing with higher-quality crystals and more efficient detectors, detection of idler fluctuations with feedforward to an active amplitude modulator on the signal to create a single beam in a two-mode amplitude-squeezed state,[3,11,24] and high-sensitivity absorption measurements.[25] The doubly resonant OPO system we have described would be especially suitable for this latter application to high-sensitivity, high-resolution spectroscopic studies, due to the ease of temperature and electro-optic tuning, and its excellent coherence properties.[18]

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