

Sub-Shot-Noise-Limited Optical Heterodyne Detection Using an Amplitude-Squeezed Local Oscillator

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We experimentally demonstrate a novel sub-shot-noise-limited heterodyne detection scheme to measure a weak optical signal field by employing amplitude-squeezed light as the local oscillator (LO) field. The amplitude-squeezed LO field at 428.8 nm is generated from a high efficiency single-pass second-harmonic generation in a KNbO₃ crystal pumped by femtosecond (130 fs) pulses at 857.6 nm, and the signal field is combined with the generated squeezed LO field through the crystal. An enhancement of 0.7 dB (1.4 dB inferred) in signal-to-noise ratio beyond the shot-noise limit is directly observed. [S0031-9007(99)09410-7]

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Coherent heterodyne detection is now widely used to detect weak scattered or reflected radiation in many electromagnetic spectral regions including radiowave, microwave, infrared, and optical spectra. In the optical region, heterodyne detection has been used in coherent laser radar (Lidar) [1], communications, spectroscopy, and radiometry due to its advantages in high sensitivity, frequency selectivity, and strong directionality. As a detection technique, heterodyne detection can measure the amplitude and phase of an incident signal field (at frequency ν_S) with the help of a strong local oscillator (LO) field (at frequency ν_{LO}). In a typical one-port heterodyne detection scheme, the signal and LO fields are combined by an optical beam splitter combiner and received by a photodetector. The information of the signal field can be extracted from the photocurrent signal at the intermediate frequency (IF) $\nu_{IF} = \nu_S - \nu_{LO}$. Assuming that both the signal and LO fields are in coherent states, the mean square IF signal current is $\langle i_S^2 \rangle = 2(e\eta/h\nu)^2 P_{LO} P_S$, where η is the detector quantum efficiency, $h\nu$ is the photon energy, and P_{LO} and P_S are the powers of the LO and signal fields, respectively. The average photocurrent is $\langle i_{dc} \rangle = e\eta P_{LO}/h\nu$. As the LO power is increased, the standard shot-noise power of the LO field ($\langle i_n^2 \rangle = 2e^2\eta B P_{LO}/h\nu$) associated with the average photocurrent $\langle i_{dc} \rangle$ exceeds the other technical noises in the detection system (e.g., dark current of the detector and thermal noise of the electronic amplifier) and eventually becomes the dominant noise source of the detection system. The signal-to-noise ratio ($SNR = \langle i_S^2 \rangle / \langle i_n^2 \rangle$) of the shot-noise-limited heterodyne detection is given by [2]

$$\langle i_S^2 \rangle / \langle i_n^2 \rangle = \eta P_S / (h\nu B), \quad (1)$$

which gives a minimum detectable signal power of $P_{S(\min)} = h\nu B / \eta$, where B is the receiver bandwidth. If the LO field has additional (classical) intensity fluctuations, a balanced heterodyne detection [two-port heterodyning shown in Fig. 1(a)] [3] can be used to eliminate the LO intensity noises, and the SNR in Eq. (1) can be recovered.

An amplitude-squeezed state of light is a good radiation source for using as the LO field in heterodyne detection applications since it has less quantum fluctuations in intensity than the standard shot-noise limit while still keeping high optical power. Recently, amplitude-squeezed light with a large amount of squeezing has been generated from the second-harmonic generation (SHG) process (up to 5.2 dB squeezing) [4,5], pump-noise-suppressed semiconductor lasers (up to 10 dB squeezing) [6,7], optical parametric amplifier (7.2 dB squeezing) [8], and asymmetric fiber interferometer (6.2 dB squeezing) [9]. However, one major difficulty of using squeezed LO in the standard heterodyne detection lies in the combination of the weak signal beam and the strong squeezed LO. When an optical beam splitter is used to combine these two

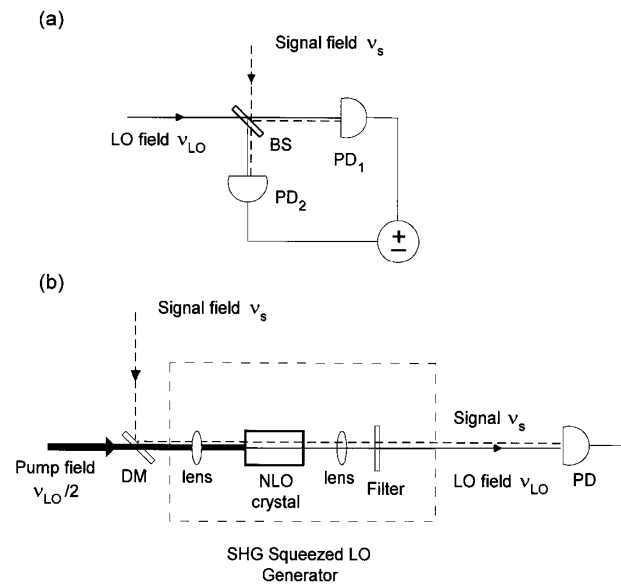


FIG. 1. (a) Balanced heterodyne detectors. BS: beam splitter; PD₁, PD₂: photodetectors. (b) Sub-shot-noise-limited heterodyne detector with an amplitude-squeezed local oscillator combining with the signal field through the NLO crystal by a dichromatic mirror (DM).

beams as shown in Fig. 1(a), the IF signal is to be extracted from the difference photocurrent of the balanced detectors, and the dominant noise source in the detection system is no longer determined by the LO shot noise but by the vacuum field fluctuations entering from the signal entrance port [3]. In such case, the amplitude-squeezed LO field will not affect the SNR.

Although squeezed states of light (including amplitude-squeezed states and quadrature-squeezed states) have been generated many years ago [10], their applications are very limited due to the extremely sensitive nature of squeezing over losses. The recent applications of squeezed light to enhance the measurement sensitivity in interferometer [11], spectroscopy [12,13], and laser Doppler anemometry [14] are also constrained by the fact that the squeezed light has to pass through the medium to be probed, which generally causes additional optical losses to degrade squeezing. Recently, quantum-correlated twin beams are used to demonstrate the quantum nondemolition measurement [15].

In this Letter, we describe a new scheme which overcomes the difficulty in combining the signal field and an amplitude-squeezed LO field in a general heterodyne detection system. Our sub-shot-noise-limited heterodyne detection scheme, shown in Fig. 1(b), is based on the combination of the signal field and the (generated) amplitude-squeezed LO field through the SHG crystal. We choose amplitude-squeezed light generated in SHG to demonstrate this sub-shot-noise heterodyne detection, because this system has the potential to generate a high degree of squeezing [4,16], and because it is technically simple to combine the signal field with the generated squeezed LO field in this system. Since the squeezed light is used locally as part of the detector system, the optical losses can be well controlled, and therefore, the degradation of squeezing can be minimized.

In our heterodyne detection scheme, the amplitude-squeezed LO field (at frequency ν_{LO}) is generated from a high efficiency SHG in a nonlinear crystal pumped by a fundamental field (at frequency $\nu_{LO}/2$). Unlike the usual heterodyne detection scheme, the signal field and the LO field are not combined by an optical beam splitter. Instead, the signal field (frequency shifted by a few MHz from the LO field) is introduced from the entrance port of the crystal with a dichromatic mirror, passes through the crystal, and combines with the generated squeezed LO field. The transmitted fundamental field is blocked by an optical filter. Since the crystal only converts photons at the fundamental frequency into the photons at the LO frequency through SHG, the signal beam can pass through the crystal with little loss. On the other hand, since the generated squeezed LO field is detected immediately after the SHG, maximum squeezing of the LO field can be maintained and optimum heterodyne detection sensitivity can be achieved. The light received by the photodetector comprises a strong LO component (at ν_{LO}) and a much

weaker signal field component (at ν_S). The photocurrent is $i(t) \approx \eta e [I_{LO} + 2(I_S I_{LO})^{1/2} \cos(2\pi\nu_{IF}t)]$, where $I_{LO} = P_{LO}/h\nu$ and $I_S = P_S/h\nu$ are the photon number fluxes of the LO and signal beams, respectively. The mean square heterodyne signal current at frequency ν_{IF} is given by $\langle i_S^2 \rangle = 2me^2\eta^2 I_S I_{LO}$, where m is the mixing efficiency determined by the mode matching of the signal and LO fields on the detector. The mean square noise current is given by $\langle i_n^2 \rangle = (2e^2\eta I_{LO} B)F_{LO} + N_e$, where the first term is the quantum noise of the squeezed LO field with a Fano factor of F_{LO} , and the second term N_e contains the sum of all electrical noise sources. The SNR is then given by

$$\langle i_S^2 \rangle / \langle i_n^2 \rangle = 2me^2\eta^2 I_S I_{LO} / [(2e^2\eta I_{LO} B)F_{LO} + N_e]. \quad (2)$$

When the mixing efficiency is perfect ($m = 1$) and the LO power is strong enough such that the second term (N_e) can be neglected, the SNR can be expressed as

$$\langle i_S^2 \rangle / \langle i_n^2 \rangle = \eta P_S / (h\nu B F_{LO}). \quad (3)$$

Comparing to Eq. (1), the SNR of the heterodyne detection is increased by a factor of $1/F_{LO}$ if an amplitude-squeezed LO field is employed ($F_{LO} < 1$). This gives a lower detectable signal power of $P_{S(\min)} = h\nu B F_{LO} / \eta$.

Typical measured results of this new heterodyne detection scheme are shown in Fig. 2. When the signal field is blocked, the noise power of the LO field [curve *ii* in Fig. 2(a)] is found to be 0.7 dB below the shot-noise level [curve *i* in Fig. 2(a)] with the same average (dc) photocurrent. This gives a measured Fano factor of $F_{LO} = 0.85$ before correcting for the amplifier noise level (curve *iii*) and overall detection efficiency. When the signal field is added, the heterodyne signal is shown as curve *ii* in Fig. 2(b). Since the LO noise power is 0.7 dB below the shot-noise level, the SNR is 0.7 dB above the shot-noise limit. From the measured signal height (1.7 dB above the LO noise power), the SNR is calculated to be 0.48. From Eq. (3), we calculate the incident power of the signal field as $P_S = 2.5 \times 10^{-13}$ W, given that $B = 300$ kHz, $m = 0.30$, $\eta = 0.75$, and $\lambda = 428.8$ nm. Since our signal field is a pulse train with a repetition rate of 81 MHz, this signal power corresponds to 6.7×10^{-3} photons per pulse on average.

The amplitude-squeezed LO field used in this experiment is generated from a high-efficiency single-pass second-harmonic generation with femtosecond pulses [17]. The fundamental pulses (~ 130 fs wide at an 81-MHz repetition rate) emitted from a mode-locked Ti:sapphire oscillator are focused onto an *a*-cut, 10-mm-thick KNbO₃ crystal with a lens of 5-cm focal length. The entrance surface of the KNbO₃ nonlinear crystal is AR coated for 860 nm and the exit surface is AR coated for 430 nm. The crystal is kept at room temperature (~ 25 °C) and is type I noncritical phase matching for SHG to 428.8 nm. The center wavelength of the

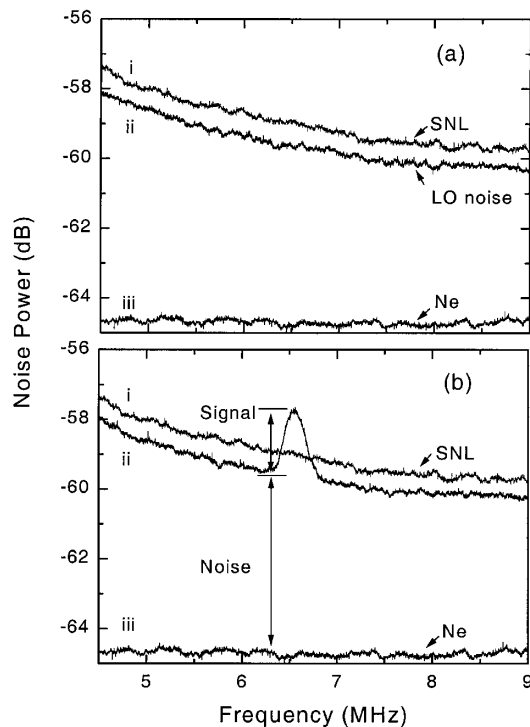


FIG. 2. The noise power spectral densities of the squeezed LO heterodyne detector for the cases of (a) when the signal beam is blocked; (b) when the signal beam is added. N_e is the sum of all electrical noise sources when both the signal and LO beams are blocked.

Ti:sapphire oscillator is tuned to 857.6 nm, and the input average power is variable from 0 to 250 mW. The generated blue light from the crystal is collected with a lens and serves as the LO field. To demonstrate sub-shot-noise-limited heterodyne detection, a small portion (less than 1%) of the generated blue light is split by a beam splitter (Brewster angle placed). This weak field passes through two acousto-optic modulators (AOM) and an optical delay path, and, then, reenters into the crystal to combine with the main portion of the generated blue light. This field acts as the signal field. The frequency of the signal field is shifted from the LO field by 6.5 MHz (AOM1 shifts the frequency up by +80.0 MHz and AOM2 down by -73.5 MHz). Since the fundamental pump pulse train has a repetition rate of 81.03 MHz, the generated blue signal pulse has to be delayed exactly by 3.702 m to meet the next generated LO pulse. As the signal pulses are delayed by a few meters, the transverse beam shape of the signal field has changed slightly compared to that of the LO field, which reduces the heterodyne mixing efficiency m (about 0.30).

The combined signal and LO beams are detected by a balanced detector comprising a 50-50 beam splitter and two identical photodiodes (Hamamatsu S2387). The noise power of the amplified sum or difference of the two photocurrents is measured with a spectrum analyzer. The use of the balanced detector is to calibrate the shot-noise level

(when the difference of the two noise photocurrents is measured) and is identical to one photodiode for heterodyne detection when the sum of the two noise photocurrents is measured. The quantum efficiency of the photodiodes is 0.85 (with a carefully arranged retroreflecting mirror [17]) at 430 nm. The overall detection efficiency of the blue light (from the exit surface of the crystal to the output photocurrents of the photodiodes) is estimated to be 0.75. The output photocurrent from each photodiode is coupled to a low pass filter (DC-32 MHz) to reduce the 81-MHz signal due to the laser repetition rate and, then, ac coupled to a low noise preamplifier. The amplified difference current ($i_- = i_1 - i_2$) gives the shot-noise limit, and the amplified sum current ($i_+ = i_1 + i_2$) gives the amplitude noise of the light field incident onto the balanced detector [3,5].

We measured the quantum noise properties of the generated blue LO field by blocking the signal beam. Figure 3(b) shows the dependence of the Fano factor at 6.0 MHz on the input pump power, and Fig. 3(a) shows the conversion efficiency from the input fundamental IR power to the output blue power. Up to 60% conversion efficiency (at the exit of the crystal) was observed at the 80-mW input power. The optimum measured Fano factor is $F_{LO} = 0.79$ (21% squeezing) after correcting the amplifier noise level at the input power of 80 mW. Taking the overall detection efficiency of 0.75 into account by $F_{LO} = \eta S + 1 - \eta$, where S is the actual Fano factor (squeezing) of the LO field and η the overall detection efficiency; this corresponds to 1.4 dB squeezing.

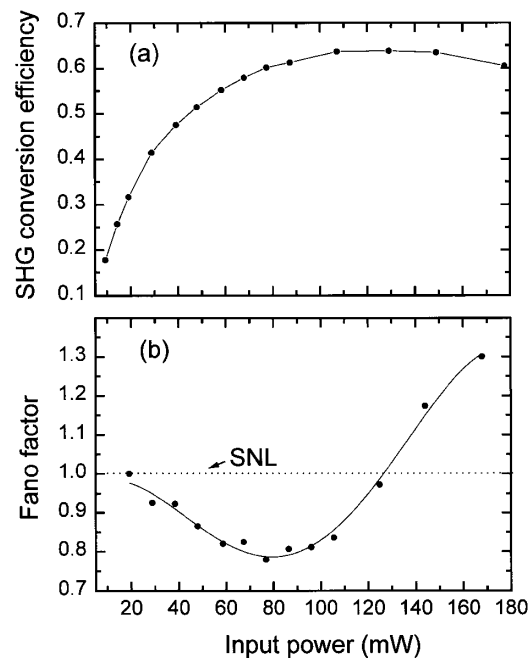


FIG. 3. (a) Dependence of SHG conversion efficiency on the average input power of the fundamental field. (b) Dependence of the measured Fano factor at 6.0 MHz on the input power of the fundamental field.

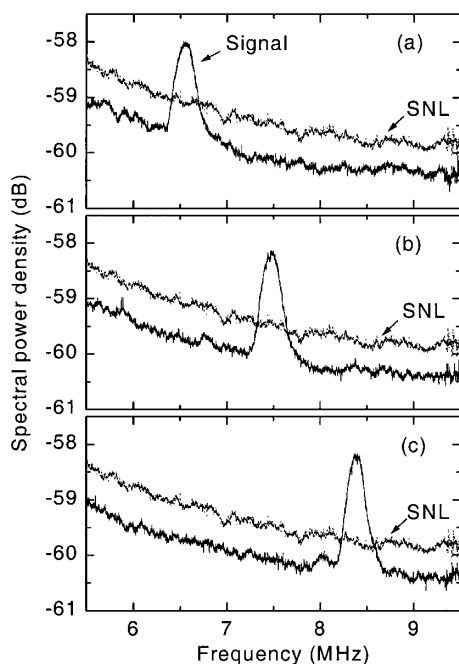


FIG. 4. Detection of heterodyne signals with sub-shot-noise-limited sensitivity at the frequencies of (a) 6.5 MHz, (b) 7.5 MHz, and (c) 8.5 MHz. The output LO power is 41.9 mW, and the input fundamental power is 80 mW. The power of the signal beam is about 2.5×10^{-13} W.

This amount of squeezing is small due to the use of femtosecond pulses in the SHG experiment [17].

As the signal field is introduced, we are able to measure its amplitude and frequency from the heterodyne signal with a sub-shot-noise-limited sensitivity. Figure 4 shows the heterodyne signals at 6.5, 7.5, and 8.5 MHz, respectively, when the driver frequency of AOM2 is tuned. The input pump power is 80 mW and the output blue power is 41.9 mW (after the filter). The dc currents of the balanced detectors are $I_1 = I_2 = 6.3$ mA. The resolution bandwidth of the spectrum analyzer was set at 300 kHz and the video filter at 10 Hz. These results show that the SNR of the heterodyne measurement is improved beyond the shot-noise limit by a factor of 0.7 dB.

In summary, we have described and demonstrated a new sub-shot-noise-limited optical heterodyne detection technique that uses amplitude-squeezed light as the local oscillator. This technique is based on the combination of the signal field with the generated amplitude-squeezed LO field in SHG. Improvement in the signal-to-noise ratio of 0.7 dB (1.4 dB inferred) beyond the standard shot-noise limit has been directly observed. Although, the present experiment is done in the single-pass SHG with femtosecond laser pulses and the observed squeezing is limited, this new heterodyne detection technique can be done in a continuous-wave intracavity SHG system,

in which there is no theoretical limit on the squeezing (larger than 9.8 dB) of the generated LO field (5.2 dB squeezing has been experimentally observed [5,16]). This new scheme opens up new possibilities to use squeezed light in practical applications (including long-range laser radar and small signal detection in optical fibers) in which optical heterodyne detection is involved.

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