

# Optics Letters

## Measurement of the squeezed vacuum state by a bichromatic local oscillator

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We present the experimental measurement of a squeezed vacuum state by means of a bichromatic local oscillator (BLO). A pair of local oscillators at  $\pm 5$  MHz around the central frequency  $\omega_0$  of the fundamental field with equal power are generated by three acousto-optic modulators and phase-locked technology and used as a BLO. The squeezed vacuum light is detected by a phase-sensitive balanced-homodyne detection with a BLO. The baseband signal around  $\omega_0$  combined with a broad squeezed field can be detected with the sensitivity below the shot-noise limit, in which the baseband signal is shifted to the vicinity of 5 MHz (the half of the BLO separation). This work has important applications in quantum state measurement and quantum information. © 2015 Optical Society of America

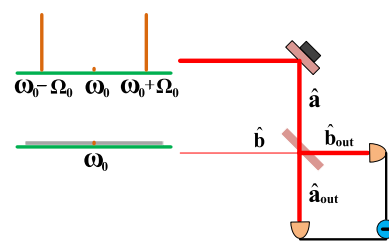
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The squeezed state of the light is an important resource of quantum information [1–9] and quantum metrology [10–14]. Especially, in the modern research focus, the squeezed state becomes crucial for gravitation wave detection. In recent years, some significant improvements have been made in this field, such as 12.7 dB squeezing being obtained [15], the very lower frequency squeezing measurement being realized, and the frequency-dependence squeezing being investigated [16]. A single broadband squeezed light can be split into  $N$  pairs of upper and lower single sideband fields with spatial separation, which correspond to  $N$  independent Einstein–Podolsky–Rosen (EPR) entangled fields [17]. This scheme was demonstrated experimentally by using a pair of frequency-shifted local oscillators to measure this EPR entanglement [18,19]. The theoretical scheme based on a bichromatic local oscillator (BLO) to detect the squeezed state was proposed [20] in which several advantages and applications were given. The phase-sensitive detection with a BLO or a double-sideband signal field were

studied [21–23]. In this Letter, we utilize a BLO to detect a broadband squeezed light with a phase-sensitive balanced-homodyne detection. This work demonstrates quantum correlation between the upper and lower sideband modes [17] of a single broadband squeezed light from another perspective. Generating and measuring the low-frequency squeezing for the terrestrial gravitational wave detectors are very difficult because of the extreme challenges in the technique. The BLO technique can circumvent the challenge of detecting low-frequency squeezing, which is usually obscured by technical noise. We present the result that the baseband signal is shifted into the vicinity of 5 MHz (half of the BLO separation), and subshot-noise detection is implemented. Thus, this work with the BLO and broadband squeezing can be used to enhance the signal-to-noise ratio (SNR) of an interferometer for lower-frequency phase measurement [24,25].

The schematic diagram of the detection is shown in Fig. 1. A strong BLO (at  $\pm\Omega_0$  around the central frequency  $\omega_0$  of the fundamental field with equal power) is mixed with the signal light field at a 50/50 beam splitter. The relative phase  $\theta$  of the local oscillator and the signal field can be controlled by the reflective mirror mounted on a PZT (piezoelectric transducer). The annihilation operators of the BLO and the signal field can be written as  $\hat{a}(t) = \hat{a}_+(t) \exp[-i(\omega_0 + \Omega_0)t] + \hat{a}_-(t) \exp[-i(\omega_0 - \Omega_0)t]$  and  $\hat{b}(t) = \hat{b}_0(t) \exp(-i\omega_0 t)$ , where



**Fig. 1.** Schematic diagram of measuring a single broadband squeezed light with the central frequency  $\omega_0$  using a phase-sensitive balanced-homodyne detection with a BLO.

$\hat{a}_{+(-)}(t)$  and  $\hat{b}_0(t)$  are the slow varying operators of the fields. The output fields of the 50/50 beam splitter are

$$\hat{a}_{\text{out}}(t) = [\hat{a}(t)e^{i\theta} + \hat{b}(t)]/\sqrt{2}, \quad (1)$$

$$\hat{b}_{\text{out}}(t) = [\hat{a}(t)e^{i\theta} - \hat{b}(t)]/\sqrt{2}. \quad (2)$$

Therefore, the normalized difference of the photocurrents of the two detectors may be

$$\hat{i}(t) = \frac{1}{\sqrt{2a}} [\langle \hat{a}^\dagger(t) \rangle \hat{b}(t)e^{-i\theta} + \langle \hat{a}(t) \rangle \hat{b}^\dagger(t)e^{i\theta}], \quad (3)$$

where the fields satisfy  $\langle \hat{a}_+ \rangle = \langle \hat{a}_- \rangle = a \gg \langle \hat{b}_0 \rangle \sim 0$ . Therefore, the signal field may be the vacuum state or the squeezed vacuum state. And the BLO is a pair of strong and equal coherent states.

The difference of the photocurrents analyzed at the radio frequency  $\Omega$  is expressed as

$$\hat{i}(\Omega) = \frac{1}{\sqrt{2}} [\hat{b}(\Omega_0 - \Omega) + \hat{b}(-\Omega_0 - \Omega)]e^{-i\theta} + \frac{1}{\sqrt{2}} [\hat{b}^\dagger(\Omega_0 + \Omega) + \hat{b}^\dagger(-\Omega_0 + \Omega)]e^{i\theta}. \quad (4)$$

Here, we express the quadrature component of the signal field around the central frequency  $\omega_0$ , which easily compares with the measurement with a single local oscillator at  $\omega_0$ . Therefore, the quadrature component of the signal field can be defined as  $\hat{Q}_S(\nu, \theta) = \hat{b}(-\nu)e^{-i\theta} + \hat{b}^\dagger(\nu)e^{i\theta}$  at the analysis frequency  $\nu$ , which includes the up and down sideband modes  $\pm\nu$ . The quadrature amplitude ( $\theta = 0$ ) can be  $\hat{X}_S(\nu) = \hat{b}(-\nu) + \hat{b}^\dagger(\nu)$  and the quadrature phase ( $\theta = \pi/2$ ) can be  $\hat{Y}_S(\nu) = -i[\hat{b}(-\nu) - \hat{b}^\dagger(\nu)]$ . The difference of the photocurrents with the BLO [Eq. (4)] will give the information of the quadrature component of the signal field:

$$\hat{Q}_B(\Omega, \theta) = \frac{1}{\sqrt{2}} [\hat{Q}_S(|\Omega_0 - \Omega|, \theta) + \hat{Q}_S(\Omega_0 + \Omega, \theta)]. \quad (5)$$

Here,  $\Omega$  is the analysis frequency of the BLO detection. We can know from here that there are two pairs of the sideband modes  $\pm|\Omega_0 - \Omega|$  and  $\pm(\Omega_0 + \Omega)$  to be measured by the BLO. The arbitrary quadrature component of the signal field can be measured by scanning the relative phase of  $\theta$ . So when  $\theta = 0$ , the difference of the photocurrents will give the information of the quadrature amplitude of the signal field  $\hat{X}_B(\Omega) = \frac{1}{\sqrt{2}} [\hat{X}_S(|\Omega_0 - \Omega|) + \hat{X}_S(\Omega_0 + \Omega)]$  and when  $\theta = \pi/2$ , the quadrature phase  $\hat{Y}_B(\Omega) = \frac{1}{\sqrt{2}} [\hat{Y}_S(|\Omega_0 - \Omega|) + \hat{Y}_S(\Omega_0 + \Omega)]$ .

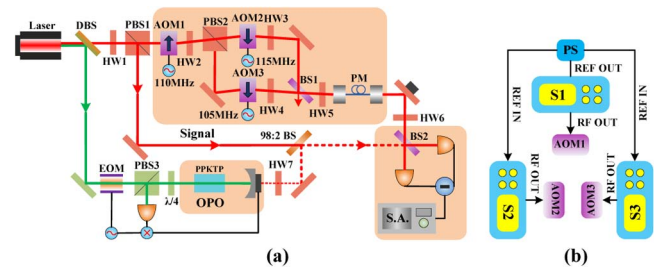
For the broad quadrature phase squeezing as the input signal field, the quadrature components satisfy  $\langle \Delta^2 \hat{Y}_S(|\Omega_0 - \Omega|) \rangle = \langle \Delta^2 \hat{Y}_S(\Omega_0 + \Omega) \rangle = e^{-2r} < 1$  and  $\langle \Delta^2 \hat{X}_S(|\Omega_0 - \Omega|) \rangle = \langle \Delta^2 \hat{X}_S(\Omega_0 + \Omega) \rangle = e^{2r} > 1$ , where  $r$  is the squeezing parameter. Correspondingly, we can obtain the variance of the quadrature components of the signal field by means of a BLO,

$$\langle \Delta^2 \hat{Y}_B(\Omega) \rangle = e^{-2r} < 1, \quad \langle \Delta^2 \hat{X}_B(\Omega) \rangle = e^{2r} > 1. \quad (6)$$

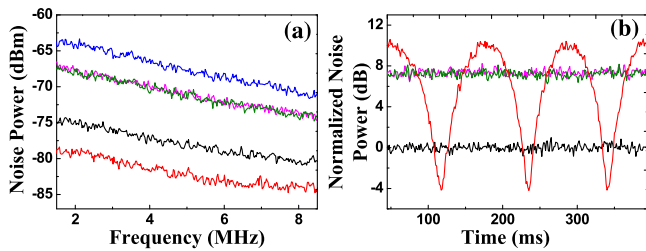
So the difference of the output photocurrents at the analyzed frequency  $\Omega$  presents quadrature phase squeezing of the two pairs of the sideband modes  $\pm|\Omega_0 - \Omega|$  and  $\pm(\Omega_0 + \Omega)$ . Thus, when the squeezing spectrum of the input field can reach the frequency of  $2\Omega_0$ , we may obtain the baseband signal around  $\omega_0$  of the input field below the shot-noise limit at the analyzed frequency  $\Omega_0$  of the measured noise spectrum.

Figure 2 shows the experimental setup. The laser source, which is a diode-pumped external-cavity frequency doubled laser, provides the second-harmonic light of 450 mW at 532 nm and the fundamental light of 200 mW at 1064 nm simultaneously. The second-harmonic light is used to pump the OPO (optical parametric oscillator). The fundamental light is separated into two parts. One is utilized as the auxiliary beam to adjust the interference of the local oscillator and the detected field. The other is used to generate the BLO by three acousto-optic modulators (AOMs) and phase-locked technology. The frequency shifts of AOM1, AOM2, and AOM3 are +110, -115, and -105 MHz, respectively. The two frequency-shifted laser beams at  $\omega_0 \pm \Omega_0$  ( $\Omega_0 = 5$  MHz) are combined on 50% BS1 with the same polarization. The bichromatic laser field is coupled into a single-mode polarization-maintaining fiber to filter the spatial modes. As mentioned above, only when the up- and down-shifted frequencies ( $\Omega_+$  and  $\Omega_-$ ) around the central frequency  $\omega_0$  of the BLO are the same ( $\Omega_+ = \Omega_- = \Omega_0$ ) and the relative phase is fixed, the measurement for the broad squeezed light becomes the balanced homodyne detection. The two methods of locking the relative phase between up- and down-shifted laser fields have been developed in our previous work [22]. Here, we employ the clock synchronization of the signal generators. The three signal generators for driving the AOMs can be locked together in frequency and phase by using the same reference (clock) frequency.

The resonator for the squeezed light is a semimonolithic triple-resonant OPO. The cavity is 38 mm long and consists of a 10 mm long periodically poled potassium titanyl phosphate (PPKTP) crystal. The front facet of the crystal acts as the input coupler, has a transmittance of 5% for 532 nm, and is highly reflective for 1064 nm. The rear facet is antireflective for both 532 and 1064 nm. The output mirror of the OPO has a transmittance of 12.5% for 1064 nm and is highly reflective for 532 nm. The cavity bandwidth is around 70 MHz. The PPKTP is a type I quasi-phase-matching crystal and its phase-matching condition is achieved by the temperature controller [26,27]. The OPO cavity is locked according to the Pound-Drever-Hall technique; the error signal is derived from the reflected pump field. By adjusting the reflective mirror of the local oscillator mounted on PZT, the relative phase  $\theta$



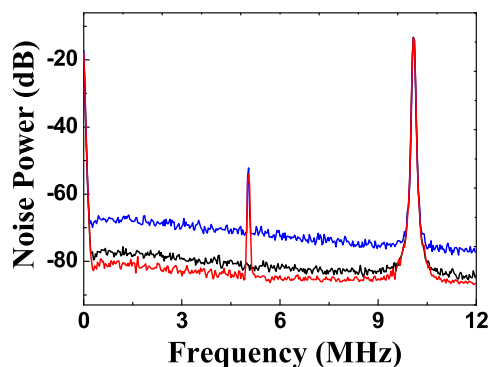
**Fig. 2.** (a) The setup for the experimental realization of measuring vacuum squeezing by a phase-sensitive balanced-homodyne detection with a BLO. DBS1, dichroic beam splitter; HW1–4, half-wave plate; BS1,2, 50/50 beam splitter; AOM1–3, acousto-optic modulator; PM, single-mode polarization-maintaining optical fiber; EOM, electro-optical modulator; OPO, optical parametric oscillator; SA, spectrum analyzer. (b) The scheme for locking the relative frequency and phase of the double sidebands. PS, power splitter for radio frequency.



**Fig. 3.** Measured noise-power spectra. (a) The noise-power spectra at the analysis frequencies from 1.5 to 8.5 MHz with the resolution bandwidth of 100 kHz and the video bandwidth of 300 Hz. Blue line, the anti-squeezing component; red line, the squeezing component. (b) The noise-power spectra at the analysis frequency of 5 MHz are measured by scanning the relative phase of  $\theta$ . Red line, the quadrature component; black line, shot-noise limit; green and pink lines, the noise-power spectrum when the single sideband of the BLO is used, respectively. Here, the electric (dark) noise is about 14 dB below SNL.

between the BLO and the squeezed light field is changed. The squeezed state is mixed with the BLO on the 50/50 beam splitter with the interference fringe visibility of 98%. Last, the two output fields of the beam splitter are measured by two balanced detectors.

Figure 3 shows the noise-power spectra measured by means of a BLO. The power of the pump field of the OPO is about 40 mW. The total power of the BLO is set to 4.0 mW. In the analysis frequency regime from 1.5 to 8.5 MHz, the squeezing value is  $4.1 \pm 0.2$  dB ( $\langle \Delta^2 \hat{Y} \rangle = 0.39 \pm 0.02$ ), and the anti-squeezing is about  $10.1 \pm 0.2$  dB ( $\langle \Delta^2 \hat{X} \rangle = 10.2 \pm 0.5$ ) higher than the shot noise limit (SNL) [Fig. 3(a)]. The noise-power spectra at the analysis frequency of 5 MHz with zero span are measured by scanning the relative phase of  $\theta$  [Fig. 3(b)]. It demonstrates that the BLO is a phase-sensitive balanced-homodyne detection, and the arbitrary quadrature



**Fig. 4.** Noise spectra at analysis frequency from 0 to 12 MHz with a baseband signal field around  $\omega_0$ . Red line, the baseband signal peak at 5 MHz with the squeezed quadrature component; blue line, the baseband signal peak with the antisqueezed quadrature component; black line, shot-noise limit. The peak at 10 MHz is due to the beatnote of the BLO. Here, the electric (dark) noise is about 14 dB below SNL. The power of the local oscillator and the signal is 4 mW and about 200 nW, respectively. RBW = 30 kHz, VBW = 1 kHz, sweep time = 200 ms.

components can be measured [the red line in Fig. 3(b)]. When one of the BLO is blocked to become a single local oscillator, the detection is changed into the heterodyne detection and the noise spectrum is  $7.3 \pm 0.2$  dB higher than the SNL, which is insensitive to the relative phase of  $\theta$  (the green and pink lines in Fig. 3). It is consistent with the estimation  $7.25$  dB [ $(\langle \Delta^2 \hat{Y} \rangle + \langle \Delta^2 \hat{X} \rangle)/2 = 5.3$ ] according to the above measurements.

When a baseband signal field around  $\omega_0$  is added into the squeezed vacuum field by a 98/2 beam splitter, the noise spectra at analysis frequency from 0 to 12 MHz is given in Fig. 4 by means of the BLO detection. The baseband signal peak appears at 5 MHz, for which the sensitivity is 4.1 dB below the shot-noise limit when the squeezed quadrature component is detected (the red line in Fig. 4). It demonstrates that the baseband signal is shifted into the vicinity of 5 MHz (half of the BLO separation), and subshot-noise detection is obtained.

In conclusion, we study phase-sensitive balanced-homodyne detection with a BLO. The baseband signal field around  $\omega_0$  with a broad squeezed field is detected and the sensitivity of the signal can be below the shot-noise limit. This detection scheme can be employed in gravitational-wave detection and the quantum information process.

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