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OPTICAL PHYSICS

Phase-sensitive heterodyne detection of two-mode squeezed light without noise penalty

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Squeezed states of light can be detected for precision measurements with a heterodyne detector by use of a bichromatic field as the local oscillator, due to the phase-sensitive nature of the device. However, divergence consists of the theoretical description of the quantum noise performance of this detector. Two existing theoretical models are briefly reviewed, with one model predicting a 3 dB quantum noise floor change in detection of two-mode squeezed light if the local oscillator is replaced by a monochromatic one, whereas the other model foretells the same noise floor no matter which local oscillator is used. An experiment on heterodyne detection of two-mode squeezed light is carried out to put the two models under test. No significant difference in the noise floor level is observed between the two detectors, showing the noiseless property of both detectors. This work should be of importance for the understanding of noise origin in optical detection and of great interest in practical application for squeezing-enhanced audio band gravitational-wave signal searching.

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1. INTRODUCTION

The interest in sensitivity enhancement for the detection of audio band gravitational-wave (GW) signals [1,2], by using squeezed states to overcome the quantum noise of light [3–6], lends urgency to the development of optical detectors capable of receiving low-frequency signals below the shot-noise limit. Neither a homodyne detector nor a conventional heterodyne detector is suitable for this purpose, because the former is dominated by classical noise near DC and the latter is supposed to suffer 3 dB quantum noise penalty caused by image band vacuum [7–9]. Recently, a flurry of interest was stirred in the detection of squeezed light by phase-sensitive (PS) heterodyne detectors [10–17]. A PS heterodyne detector with a bichromatic local oscillator (BLO) was originally proposed for detection of two-mode squeezed light [10], and nine years later the proposal was experimentally demonstrated with two-mode squeezed light created by four-wave mixing in a hot atomic vapor [14]. It was also proposed that a PS heterodyne detector could be exploited to detect complex squeezing [15] that would be otherwise indiscernible if a homodyne detector were used. Because of the freedom to adjust the individual amplitude and phase of each BLO frequency component for optimized measurement, the detector for complex squeezing detection was named a synodyne detector in Ref. [15]. What is more interesting is that the PS heterodyne detection scheme with a BLO has proven useful for detection of low-frequency signals below the shot-noise limit [12,16–18].

However, before its practical usage in precision measurements, particularly in detection of audio band GW signals, a PS heterodyne detector with a BLO must be fully understood regarding its quantum noise property. As a matter of fact, theoretical description of this detector faces a fundamental dilemma [19]: On the one hand, the detector is believed to suffer extra quantum noise due to the existence of an image band vacuum [10,14]; on the other hand, as a PS device, the detector should be noise free [13,20].

In an effort to find a solution to the dilemma, an experiment was carried out to measure the noise figure (NF) of the studied detector, and the results showed that its NF was 0 dB when the detector was exposed to coherent light [19]. To understand the physics behind the experimental results, a theory based on the concept of the light field has been developed for the studied detection scheme [13]. While this theory is in good agreement with experiment as far as the NF of the detector is concerned, it is at variance with the previous theory based on the concept of image band mode [10]. The two theories predict different quantum noise floor levels for the detector measuring two-mode squeezed light. The discrepancy between the two theories is probably rooted in different understandings of the noise origin in heterodyne detection. In the traditional theory, the 3 dB extra noise results from image band modes in vacuum states [10,14]. In contrast, in the recently developed theory, the quantum noise originates from the detected light field, a continuum of infinite number of frequency modes, as a whole entity. Consequently, the image band modes are just parts of the signal field and do not contribute extra noise [13].

In this work, we study the PS heterodyne detector with a BLO through a direct comparison of its noise floor to that of another detector with a monochromatic local oscillator (MLO), toward a conclusion on whether the studied detector is noise free in detection of two-mode squeezed light.

In the next section, two theoretical models that are subject to experimental test are summarized. Both models have provided detailed calculations for the quantum noise floor of the studied detector, but the calculation results are different. This theoretical divergence evidences the aforementioned dilemma about the quantum noise nature of the detector. Section 3 is devoted to an experimental test on the two theoretical models. In detection of two-mode squeezed light, no significant deviation is observed between the quantum noise floor of the BLO heterodyne detector and that of the MLO one. In Section 4, we discuss how this work may impact on our understanding of the origin of quantum noise in optical detection and on experimental observation of audio band GW signals.

2. THEORETICAL MODELS

To elucidate the fundamental dilemma encountered by current theory in describing the quantum nature of a PS heterodyne detector, let us briefly review two theoretical models that are representatives of those established for optical heterodyne detection.

A. Model 1

To present a technique for detection of two-mode squeezed states of light, Marino *et al.* studied a PS heterodyne detector with a BLO, via the help of the concept of image band mode [10]. In the proposed detection scheme [Fig. 1(a)], the local oscillator is a bichromatic field,

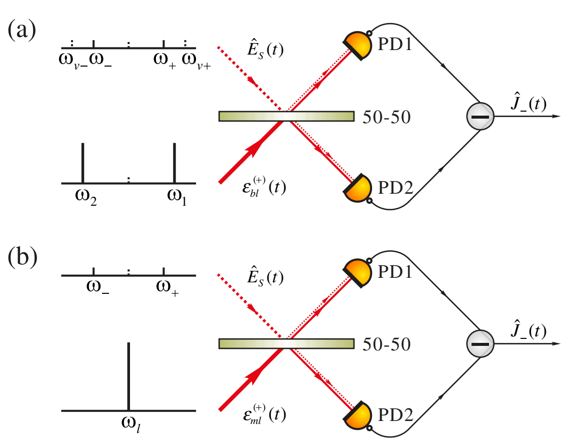

Fig. 1. PS heterodyne detection of two-mode squeezed light. (a) BLO detection scheme. $\omega_1+\omega_2=\omega_+ + \omega_-$, $\Omega_0 \equiv |\omega_1 - \omega_+|$ is the heterodyne frequency. (b) MLO detection scheme. $\omega_l = (\omega_+ + \omega_-)/2$, $\Omega_0' \equiv \omega_+ - \omega_l$ is the heterodyne frequency.

$$\varepsilon_{bl}^{(+)}(t) = (\varepsilon_1 e^{-i\omega_1 t + i\theta_1} + \varepsilon_2 e^{-i\omega_2 t + i\theta_2})/\sqrt{2}, \tag{1}$$

in which the amplitudes $\varepsilon_{1,2}$, the phases $\theta_{1,2}$, and the angular frequencies $\omega_{1,2}$ ($\omega_1 > \omega_2$) are real numbers for both frequency components.

A two-mode squeezed state to be measured is assumed to be of the form [10]

$$\hat{E}_s(t) = \hat{a}_+ e^{-i(\omega_+ t - \phi_+)} + \hat{a}_- e^{-i(\omega_- t - \phi_-)}, \tag{2}$$

wherein $\hat{a}_\pm$ are the photon annihilation operators for the two modes; $\omega_\pm$ ($\omega_+ > \omega_-$) and $\phi_\pm$ are the corresponding optical frequencies and phases, respectively. Because it is impossible to distinguish between the positive and negative frequency beat-note signals when detecting the heterodyne signal, it is necessary to include frequencies that symmetrically appear on either side of the local oscillator. Consequently, the state of light that is measured is not the two-mode squeezed state given by Eq. (2); instead, it takes the form [10]

$$\begin{aligned}\hat{E}_s(t) = {}& \hat{a}_+ e^{-i(\omega_+ t - \phi_+)} + \hat{a}_{v+} e^{-i(\omega_{v+} t - \phi_{v+})} \\ & + \hat{a}_- e^{-i(\omega_- t - \phi_-)} + \hat{a}_{v-} e^{-i(\omega_{v-} t - \phi_{v-})},\end{aligned} \tag{3}$$

in which $\hat{a}_{v\pm}$ are the image band modes.

Under the approximations that the image bands are within the squeezing spectrum, $\varepsilon_1 = \varepsilon_2 \equiv \varepsilon$, $\Omega_0 \ll |\omega_+ - \omega_-|$, and that the BLO intensity is much greater than the intensity of the measured signal, the variance of the differential heterodyne signal reads [please refer to Eq. (13) in [10] for details]

$$\langle(\Delta\hat{J}_-)^2\rangle = 2|\varepsilon|^2[(e^{2s} + e^{2s_v})\cos^2\theta_b + (e^{-2s} + e^{-2s_v})\sin^2\theta_b],$$

where s and s_v refer to the squeezing parameter at the frequency of the carrier and image band modes, respectively, and $\theta_b = (\theta_1 + \theta_2 - \phi_+ - \phi_- - \theta)/2$ with θ the squeezing angle.

Let us further assume that $\Omega_0 \ll \Gamma$, where Γ stands for the bandwidth of the squeezing spectrum, such that the squeezing parameters of the carrier and image band modes are the same, i.e., $s = s_v$. Then one arrives at

$$\langle(\Delta\hat{J}_-)^2\rangle = 4|\varepsilon|^2(e^{2s}\cos^2\theta_b + e^{-2s}\sin^2\theta_b), \tag{4}$$

from which it follows that the image band modes contribute an extra 3 dB noise at the output of the PS heterodyne detector, whose quantum noise floor is twice of that of a MLO heterodyne detector. To make this statement clearer, let us consider PS heterodyne detection of the same signal light in a two-mode squeezed state, with a MLO of the form

$$\varepsilon_{ml}^{(+)}(t) = \varepsilon e^{-i\omega_l t + i\theta_l}, \tag{5}$$

in which $\omega_l = (\omega_+ + \omega_-)/2$. This oscillator has the same optical power as the BLO, but there are no extra image band modes in the MLO detection scheme, since the two squeezed modes mirror each other with respect to the MLO [Fig. 1(b)]. It is not difficult to show that the variance of the differential heterodyne signal reads [see Eq. (8) in [10] for details]

$$\langle(\Delta\hat{J}_-)^2\rangle = 2|\varepsilon|^2(e^{2s}\cos^2\theta_m + e^{-2s}\sin^2\theta_m), \tag{6}$$

in which $\theta_m = (\theta_l - \phi_+ - \phi_- - \theta)/2$. Equation (6) in comparison with Eq. (4) proves that the PS heterodyne detector in the BLO case has a quantum noise floor that is 3 dB higher than that of a MLO heterodyne detector.

B. Model 2

In what follows, let us summarize a second theoretical model for the PS heterodyne detector with a BLO. This model adopts a quantum field of light having a continuum of frequency modes as the input signal to the detector [13]:

$$\hat{E}_s^{(+)}(\mathbf{r},t)=\frac{i}{\sqrt{V}}\sum_{\mathbf{k}}\left(\frac{1}{2}\hbar\omega_{\mathbf{k}}\right)^{\frac{1}{2}}\hat{a}_{\mathbf{k}}e^{i(\mathbf{k}\cdot\mathbf{r}-\omega_{\mathbf{k}}t)}, \tag{7}$$

in which V is the quantization volume, $\mathbf{k}$ represents the set of plane-wave modes, and $\omega_{\mathbf{k}}$ the corresponding optical frequency of each mode. The amplitude operator $\hat{a}_{\mathbf{k}}$ is the photon annihilation operator for mode $\mathbf{k}$ and remains constant when there is no free electrical charge in the space [21]. The noise performance of the detector is quantitatively described by the average power spectral density of the photocurrent fluctuations as a Fourier transform of a certain two-time autocorrelation function [13]:

$$\chi(\omega)=\frac{1}{T}\int_0^T \mathrm{d}t\int_{-\infty}^{+\infty}\mathrm{d}\tau e^{i\omega\tau}\langle\Delta J_-(t)\Delta J_-(t+\tau)\rangle_s, \tag{8}$$

where $\langle\Delta J_-(t)\Delta J_-(t+\tau)\rangle_s$ is the auto-correlation function of the differenced-photocurrent fluctuations. Under the assumptions that the average photocurrent is stationary over the period of measurement time $T\sim\Omega_r^{-1}$ (Ω_r is the resolution bandwidth of the spectral analyzer in use), the spectral density of the photocurrent fluctuations is calculated as [13]

$$\begin{aligned}\chi(\omega)=\varepsilon^2|K(\omega)|^2 & \\ &\times\{1+(1/4)[\Phi_{11}(\omega+\Omega)+\Phi_{11}(\omega-\Omega)](1+\cos 2\bar{\phi})\\ &+(1/4)[\Phi_{22}(\omega+\Omega)+\Phi_{22}(\omega-\Omega)](1-\cos 2\bar{\phi})\\ &+(1/4)[\Phi_{12}(\omega+\Omega)+\Phi_{21}(\omega+\Omega)+\Phi_{12}(\omega-\Omega)\\ &+\Phi_{21}(\omega-\Omega)]\sin 2\bar{\phi}\},\end{aligned} \tag{9}$$

wherein $K(\omega)$ is the frequency response of the detector, $\Omega=(\omega_1-\omega_2)/2$ stands for the BLO frequency, and $\Phi_{mn}(\omega)$ is the Fourier transform of the correlation functions $\Gamma_{mn}(\tau)$:

$$\Phi_{mn}(\omega)=\int_{-\infty}^{+\infty}\mathrm{d}\tau\Gamma_{mn}(\tau)e^{i\omega\tau}(m,n=1,2). \tag{10}$$

Here, $\Gamma_{mn}(\tau)\equiv\langle T{:}\Delta\hat{E}_m(t)\Delta\hat{E}_n(t+\tau){:}\rangle$, and $\hat{E}_{1,2}(t)$ are the quadrature operators defined as

$$\hat{E}_1(t)=\hat{E}_s^{(+)}(t)e^{i(\omega_0 t-\beta)}+\hat{E}_s^{(-)}(t)e^{-i(\omega_0 t-\beta)},$$
$$\hat{E}_2(t)=\hat{E}_s^{(+)}(t)e^{i(\omega_0 t-\beta-\pi/2)}+\hat{E}_s^{(-)}(t)e^{-i(\omega_0 t-\beta-\pi/2)}.$$

Here, $\omega_0=(\omega_+ +\omega_-)/2$, and β is an arbitrary phase associated with the field quadratures. $\bar{\phi}\equiv(\phi_1+\phi_2)/2-\beta$ in Eq. (9).

To evaluate the noise performance of the BLO heterodyne detector as delineated by Eq. (9), one needs the spectral density of the photocurrent fluctuations for a MLO detector, which is calculated as [13,22,23]

$$\begin{aligned}\chi'(\omega)=\varepsilon^2|K(\omega)|^2\{1+(1/2) & \\ &\times[\Phi_{11}(\omega)(1+\cos 2\bar{\phi}')+\Phi_{22}(\omega)(1-\cos 2\bar{\phi}')\\ &+(\Phi_{12}(\omega)+\Phi_{21}(\omega))\sin 2\bar{\phi}']\},\end{aligned} \tag{11}$$

in which $\bar{\phi}'=\theta_l-\beta$. It turns out that Eq. (11) for the MLO detector can be derived from Eq. (9) by setting $\Omega=0$, from which it is reasonable to believe that the noise performance of the BLO heterodyne detector can be similar to that of the MLO detector. To prove this, let us consider a two-mode squeezed light field with a squeezing spectrum of the form

$$\Phi_{11}(\omega)=-\frac{\epsilon\gamma}{(\gamma/2+\epsilon)^2+(\omega-\Omega')^2}-\frac{\epsilon\gamma}{(\gamma/2+\epsilon)^2+(\omega+\Omega')^2}, \tag{12}$$

where $\Omega'=|\omega_+-\omega_-|/2$ represents half the frequency separation between the two modes, ϵ is a measure of the effective pump intensity in the generation of the squeezed light, $\gamma=2\pi\Gamma$, and $\gamma/2\epsilon$ is a crucial parameter that determines the spectrum of squeezing.

For the BLO heterodyne detector, when the relative phase is controlled such that $\bar{\phi}=k\pi$, the normalized spectral density $\chi_n(\omega)\equiv\chi(\omega)/[\varepsilon^2|K(\omega)|^2]$ reads

$$\begin{aligned}\chi_n(\omega)=1&-\frac{\epsilon\gamma/2}{(\gamma/2+\epsilon)^2+(\omega-\Omega'+\Omega)^2}\\ &-\frac{\epsilon\gamma/2}{(\gamma/2+\epsilon)^2+(\omega+\Omega'+\Omega)^2}\\ &-\frac{\epsilon\gamma/2}{(\gamma/2+\epsilon)^2+(\omega-\Omega'-\Omega)^2}\\ &-\frac{\epsilon\gamma/2}{(\gamma/2+\epsilon)^2+(\omega+\Omega'-\Omega)^2}.\end{aligned} \tag{13}$$

Meanwhile, for the MLO detector, when the relative phase is controlled such that $\bar{\phi}'=k\pi$, the normalized spectral density $\chi'_n(\omega)\equiv\chi'(\omega)/[\varepsilon^2|K(\omega)|^2]$ is

$$\chi'_n(\omega)=1-\frac{\epsilon\gamma}{(\gamma/2+\epsilon)^2+(\omega-\Omega')^2}-\frac{\epsilon\gamma}{(\gamma/2+\epsilon)^2+(\omega+\Omega')^2}. \tag{14}$$

To make a quantitative comparison between the two spectral densities [Eqs. (13) and (14)], the squeezing bandwidth Γ must be large compared to the mode separation Ω' [13], i.e., $\Gamma\gg\Omega'$. Under this condition, simulation results based on Eqs. (13) and (14) are shown in Fig. 2, from which it follows

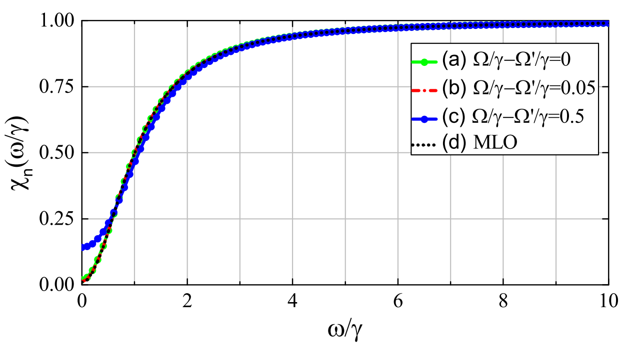

Fig. 2. Normalized noise power spectral density in PS heterodyne detection of two-mode squeezed light. $\gamma/2\epsilon=1$ and $\Omega'/\gamma=0.1$ are assumed for simplicity. (a)–(c) Detection with a BLO. (d) Detection with a MLO.

that the PS heterodyne detector with a BLO has a noise floor level similar to that of the MLO detector, in contrast to the results of model 1.

3. EXPERIMENT AND RESULTS

Because the two theoretical models do not completely share the same assumptions on which they are established, the experiment must be carefully designed such that the chosen values of all the experimental parameters comply with the hypotheses of both models. Table 1 provides a list for the key assumptions in the two models, from which it follows that, if $\Gamma \gg \Omega' \gg \Omega_0$ is satisfied, the two models can be put under test in one experiment. In our design, the heterodyne frequency Ω_0 is less than 1 MHz, the mode separation Ω' is 2–10 MHz, and the squeezing bandwidth Γ is greater than 50 MHz.

The experiment (Fig. 3) utilizes as the light source a laser (Mephisto, Innolight GmbH) emitting a continuous-wave single-frequency coherent light beam (spectral linewidth <1 kHz for 0.1 s measurement time, $\lambda = 1064$ nm). The squeezed light is produced by using a 10-mm-long periodically poled $KTiOPO_4$ (PPKTP) crystal (Raicol Inc.) in a subthreshold optical parametric oscillator (OPO). The OPO cavity is 12 mm long and has two coupling mirrors, each with a radius of curvature of 50 mm. The reflectivities are 99.95% at 1064 nm and 80% at 532 nm for the input coupler, and 92% at 1064 nm and 99.95% at 532 nm for the output coupler. The crystal is maintained at 34°C to optimize the parametric downconversion. When pumped at frequency ω_0 and operated below threshold, which is about 120 mW in our experiment, the OPO correlates the upper and lower sidebands of a vacuum field entering the OPO around the center frequency ω_0. The correlation of the optical sidebands appears as a squeezed vacuum field.

Given the above parameters for the OPO, the squeezing bandwidth of the output light from the OPO cavity is $\Gamma \approx 190$ MHz. To produce two-mode squeezed light, the parametric device is fed with a seed light that is frequency-shifted by $\Omega' = +2.12$ MHz relative to the degenerate frequency ω_0 through acousto-optic modulators (AOMs). The output light from the OPO cavity is detected by a PS heterodyne detector (ETX-500 photodiodes, JDS Uniphase) with a total quantum efficiency of 60%. The BLO is prepared through frequency

Table 1. Key Assumptions on Which the Two Theoretical Modes Are Based

Model 1	Model 2
Strong LO	Strong LO
$\varepsilon_1 = \varepsilon_2$	$\varepsilon_1 = \varepsilon_2$
$\bar{\phi} = k\pi$	$\bar{\phi}' = k\pi$
$\Omega_0 \ll \Gamma$	–
$\Omega_0 \ll \Omega'$	–
–	$\Omega' \ll \Gamma$

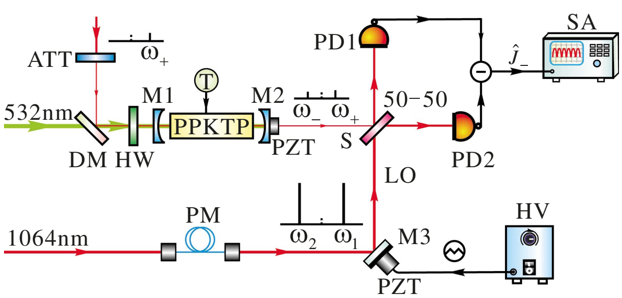

Fig. 3. Experimental schematics for PS heterodyne detection of two-mode squeezed light. ATT, light attenuator; DM, dichroic mirror; HW, $\lambda/2$ plate; M1, input mirror; M2, output mirror; T, temperature controller; PPKTP, PPKTP crystal, antireflection-coated; PZT, piezoelectric transducer; S, optical signal in two-mode squeezed states; 50–50, 50–50 beam splitter; PD, photodetector (5 k Ω feedback resistance); SA, spectrum analyzer; LO, local oscillator; PM, polarization-maintaining single-mode fiber, used as a spatial mode cleaner; M3, reflection mirror; HV, high-voltage driver for PZT.

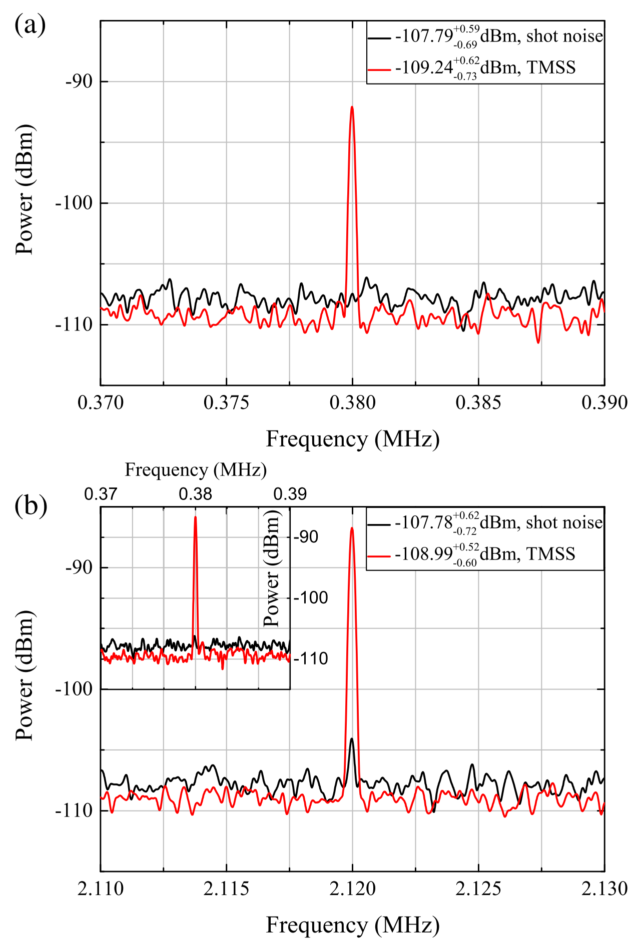

Fig. 4. Noise power spectra of the photoelectric signals from PS heterodyne detectors measuring two-mode squeezed light. (a) BLO detector, $2\Omega' = 4.24$ MHz and $2\Omega = 5$ MHz. (b) MLO detector, $2\Omega' = 4.24$ MHz. The inset shows the noise power spectra produced by the same MLO detector when $2\Omega' = 0.76$ MHz. In both the BLO and MLO cases, the theoretically expected shot noise level is −107.84 dBm, in good agreement with the data, and the dark noise of the detector is about 10 dB below the shot noise. The BLO detector produces two photoelectric signals at 0.38 MHz (as shown in the data) and 4.62 MHz (not shown), respectively. This explains the difference in signal power between the BLO and MLO cases. RBW = 200 Hz and the time of average was 6 s. TMSS: two-mode squeezed state.

synthesis [19] and the optical power is about 4 mW, equally distributed between the two frequency components. The heterodyne frequency is $\Omega_0 = 0.38$ MHz, thereby $\Gamma \gg \Omega' \gg \Omega_0$ is well satisfied. The relative phases between the squeezed light and the local oscillator are controlled for observation of optical squeezing. The photoelectric signals are fed into a spectrum analyzer (R & S, FSW-8) for data acquisition.

Figure 4(a) shows the noise power spectra of the photoelectric signals generated by the BLO heterodyne detector measuring the two-mode squeezed light from the OPO. The same two-mode squeezed light is also measured by a MLO detector [Fig. 4(b)]. The local oscillators for the two detectors have the same optical power. The degree of squeezing measured by the BLO detector is $1.45^{+1.29}_{-0.99}$ dB, and $1.21^{+1.18}_{-0.93}$ dB by the MLO detector. No significant difference in the noise power level is observed between the BLO detector and the MLO one in detection of two-mode squeezed states.

4. DISCUSSION

The traditional theory for optical heterodyne detectors has been developed on the concept of the image band mode, and a connection has been established between the quantum noise in heterodyne detection and the image sideband vacuum mode [7–9]. There is no doubt that the concept of image band mode plays a critical role in understanding of the quantum noise origin in the traditional theory. When this theory was first applied to a PS heterodyne detector with a BLO, a 3 dB noise penalty was expected due to the existence of the image band modes [10], as shown by Eqs. (4) and (6).

That the 3 dB difference in the quantum noise floor level between the BLO and MLO detectors escaped detection in experiment should have a significant impact on the study of the quantum nature of optical detectors. The experimental results agree with Model 2, which is established on the concept of the light field. In this model, the measured light field, a continuum of an infinite number of frequency modes, is a whole entity, and it is the fluctuations of this field that give rise to the quantum noise in optical detection. As for the image band modes, they are parts of the light field at the detector's input and do not contribute extra noise, in good agreement with experiment.

Understanding of the quantum behavior of the BLO heterodyne detector is also of great importance for its potential application in audio band GW signal detection beyond the shot-noise limit. Use of this detector may enhance the sensitivity in the detection of audio band GW signals by the aid of broadband squeezed light and eliminate the need to create low-frequency squeezed light. However, if the detector suffers 3 dB noise penalty, the measurement sensitivity will be degraded by the extra noise. The reported experimental results prove that the BLO heterodyne detector is noise free and should be a very useful tool in audio band GW signal detection.

5. CONCLUSIONS

In conclusion, we have studied the quantum noise performance of a PS heterodyne detector with a BLO that is exposed to light in two-mode squeezed states. Two theoretical models are introduced with different predictions about the quantum noise floor of the BLO heterodyne detector. The first model is established on the concept of image band mode and predicts 3 dB extra quantum noise for the studied detector due to the existence of an image band vacuum. The other model is developed on the concept of the light field and forecasts that the studied detector is noise free. We have carried out an experimental test on the two models, and the results prefer the second model since no difference in the quantum noise floor level has been observed between a BLO heterodyne detector and a MLO one. This work should be of importance in understanding the noise origin in optical detection and of great interest in practical application for audio band GW signal searching.

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