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Dependence of measured audio-band squeezing level on local oscillator intensity noise

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Abstract: We investigate the dependence of the measured squeezing level on the local oscillator (LO) intensity noise. The theoretical results indicate that it produces a large measurement error with the increase of the LO intensity noise, but the measurement error has immunity to the product *P* of the common mode rejection ratio (CMRR) with the LO intensity noise. According to the investigation results and the LO intensity noise, we employ a detector with the CMRR of 67 dB to detect the quantum noise at audio frequencies, the product *P* of the CMRR with the LO intensity noise is 20 dB below the shot noise limit (SNL), which can induce the measurement error of 0.1 dB for 10 dB of squeezing. Finally, the squeezing level measured at 15.2 kHz is 9.9 ± 0.2 dB. The influence of the intensity noise of the LO, and the electronic noise of the detector is subtracted, the inferred squeezing level is approximately 10.2 ± 0.2 dB. It is extremely important to quantify the requirements of the CMRR of the detector for measuring the squeezing at audio frequency and inferring the real squeezing level.

OCIS codes: (270.0270) Quantum Optics; (270.6570) Squeezed states; (190.4970) Parametric oscillators and amplifiers.

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1. Introduction

Squeezed state light is an important resource in precision measurement [1,2] and quantum information technique [3,4]. For example, quadrature squeezed states are implemented to improve the sensitivity of laser interferometers, and realize quantum teleportation which is a fundamental protocol in quantum information processing. The sensitivity and fidelity of such applications are limited by the measured value of squeezing level. So it is extremely important to directly detect high-level squeezed light [5].

Squeezed states built on the optical parametric oscillator (OPO) are firstly demonstrated by Wu et al in 1986 [6]. The measured squeezing level is usually limited by loss, phase noise, and detection system performance. By lowering the optical loss and improving the stability of the relative phase, high-level squeezed state is experimentally generated [7-10]. Recently, maximum squeezing values of 15 dB is directly detected in the MHz regime [11]. While, many applications, especially high precision measurement, require high-level squeezed state at audio frequency band and below. Jing group demonstrate intensity difference squeezing at audio frequencies by a nondegenerate four-wave-mixing amplifier [12,13]. In the field of the generation of the quadrature squeezed state at audio band, McKenzie et al compare the parametric down-conversion with and without the seed field and confirm that the seed field leads to the degradation of the squeezing at low frequencies due to classical noise coupling [14]. Subsequently, the vacuum seeded OPO becomes the standard of generating low frequency squeezed states [15-17]. After the generation of the squeezed states, another key task is the construction and characterization of a detection system that can accurately measure quantum noise suppression in the audio frequency band [18].

The balanced homodyne detection (BHD) method, in the ideal case, can effectively cancel this classical noise, amplify the measured state, and characterize any general quadrature of the measured state, which represents a well-established technique for drawing upon the features of squeezed light [18-21]. Since the BHD was first proposed by Yuen et al [20], it has been the essential measuring system in quantum noise measurement. However, differencing from the MHz regime, the BHD at low frequencies can be technically challenging. At the MHz regime, the laser intensity noise of the LO is at the SNL, the influence of the intensity noise on the measured squeezing level is small. At audio frequencies and below, the laser intensity noise of the LO is far higher than the SNL [22], an actual detector cannot cancel thoroughly the classical noise of the LO, which masks the measured squeezing level. Qualitatively, the effect of laser intensity noise on the LO can be reduced by suppressing the low frequency classical noise of the laser [23], and increasing the level of CMRR of the detector [24]. However, up to now, there is no quantitative analysis of the dependence of the measured squeezing level on the LO intensity noise, CMRR of the detector, and the real squeezing level.

Here, motivated by the requirement to measure the squeezed noise at audio frequencies, we investigate the dependence of the measured squeezing level on the LO intensity noise. The analysis results indicate that the measurement error depends on the LO intensity noise, but have immunity to the product P of the CMRR with the LO intensity noise. According to the investigation results and the LO intensity noise, we employ a detector with the CMRR of 67 dB to detect the quantum noise at audio frequencies, the product *P* of the CMRR with the LO intensity noise is 20 dB below the SNL, which can induce the measurement error of 0.1 dB for 10 dB of squeezing. Finally, the squeezing level measured at 15.2 kHz is 9.9 ± 0.2 dB. Taking the influence of LO intensity noise and electronic noise into account, the inferred squeezing level is approximately 10.2 ± 0.2 dB. The consequences may quantify the requirements of the CMRR for detector at audio frequencies, guide the design of the detector, and infer the real squeezing level from the measured squeezing level.

2. Background of balanced homodyne detection

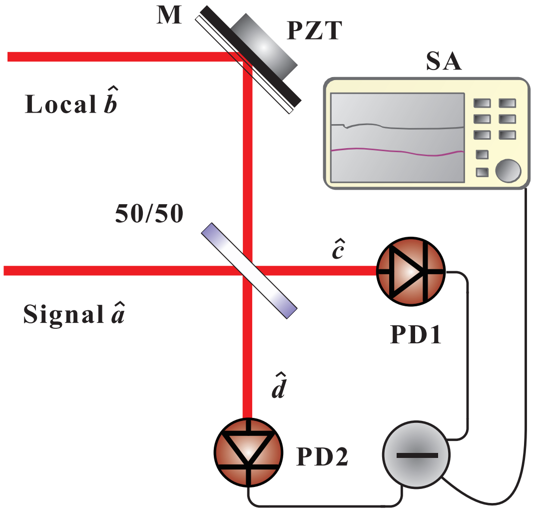

Fig. 1. Schematic of the balanced homodyne detection scheme.

The BHD, shown in Fig. 1, the weak signal field, whose noise properties one wish to measure, and a bright LO, used to amplify and probe the signal field, interference on a beamsplitter of power ratio of 50/50. We label the signal field as $(\hat{a} = \alpha + \delta\hat{a})$ and the LO field as $\left(\hat{b} = \beta + \delta\hat{b}\right)$. The beamsplitter output fields $\hat{c}$ and $\hat{d}$ are received with two photodiodes (PDs) installed in the balanced homodyne detector. The two PDs have the different quantum efficiencies η_1, η_2. Therefore, the output fields of beamsplitter incident on the two PDs, written as:

$$\hat{c} = \sqrt{\eta_1} \cdot \frac{1}{\sqrt{2}} \left(\hat{a} - \hat{b}e^{i\theta}\right) \tag{1}$$

$$\hat{d} = \sqrt{\eta_2} \cdot \frac{1}{\sqrt{2}} \left(\hat{a} + \hat{b}e^{i\theta}\right) \tag{2}$$

Where θ is the relative phase-difference between the signal beam and the LO, and actively controlled by movable mirror M on the piezoelectric transducer (PZT) drive. The photocurrent on PD1 is then proportional to $\hat{c}^+\hat{c}$ and similarly for the photocurrent on PD2. Also, assuming $\beta \gg \alpha$. The two photocurrents Eq. can be simplified as:

$$\begin{aligned} \hat{i}_c &= \frac{\eta_1}{2} \left(\beta \left(\delta\hat{a}^+ \exp(i\theta) + \delta\hat{a} \exp(-i\theta)\right) + \beta \left(\delta\hat{b} + \delta\hat{b}^+\right) + \beta^2\right) && (3) \\ &= \frac{\eta_1}{2} \left(\beta\delta\hat{X}_a(\theta) + \beta\delta\hat{X}_b(\theta)\right) + \frac{\eta_1}{2}\beta^2 && (4) \end{aligned}$$

$$\begin{aligned} \hat{i}_d &= \frac{\eta_2}{2} \left(-\beta \left(\delta\hat{a}^+ \exp(i\theta) + \delta\hat{a} \exp(-i\theta)\right) + \beta \left(\delta\hat{b} + \delta\hat{b}^+\right) + \beta^2\right) && (5) \\ &= \frac{\eta_2}{2} \left(-\beta\delta\hat{X}_a(\theta) + \beta\delta\hat{X}_b(\theta)\right) + \frac{\eta_2}{2}\beta^2 && (6) \end{aligned}$$

Where the $\delta\hat{X}_a(\theta)$ term is the quadrature fluctuation operators for the field fluctuation term $\delta\hat{a}$ at relative phase θ and similarly for $\delta\hat{X}_b$. In an actual BHD, the two photodetectors have differing gain factors, in addition to the discrepancy of quantum efficiencies, as well as electronic components, which are expressed by the CMRR of the detector. The imbalance term induced from the discrepancy of electronics components is expressed as η_{imb}. The imbalance term, η_{imb}, is added to one arm of the balanced homodyne detector to simulate the imbalance of other electronic components of the photodetector in addition to photodiodes. Therefore, the difference of the two photocurrents ($\hat{i}_c$ and $\hat{i}_d$) is expressed by:

$$I_- = \frac{\beta\eta_1}{2} \left(\left(1+G\right)\delta\hat{X}_a(\theta) + \left(1-G\right)\delta\hat{X}_b + \beta(1+G)\right) \tag{7}$$

Here $G = \eta_2\eta_{imb}/\eta_1$ represents all imbalanced elements of BHD. By taking the square of the current I_-, the variances V can be calculated

$$V(I_-) = \frac{\beta^2\eta_1^2}{4} \left(V\left(\hat{X}_a(\theta)\right)(1+G)^2 + V\left(\hat{X}_b\right)(1-G)^2\right) \tag{8}$$

When the signal field is blocked, the signal field corresponds to a vacuum state, the variances $V\left(\hat{X}_a(\theta)\right)$ is SNL. When the signal field is injected into the BHD, the measured value of squeezing level can be expressed by

$$S_m = 10\lg \frac{(1+G)^2 + V\left(\hat{X}_b\right)(1-G)^2}{V\left(\hat{X}_a(\theta)\right)(1+G)^2 + V\left(\hat{X}_b\right)(1-G)^2} \tag{9}$$

If the imbalance factor equals to 1, and the intensity noise of the LO reaches the SNL, the Eq. (7) can be simplified as

$$S_m = S_{real} = -10\lg\left(V\left(\hat{X}_a(\theta)\right)\right) \tag{10}$$

Then the measured value of squeezing level equals to that of the real value. Otherwise, the measured value deviates from the real value. The deviation E depends on the CMRR, and the intensity noise of the LO, which is given by

$$E = -10\lg\left(V\left(\hat{X}_a(\theta)\right)\right) - 10\lg\frac{(1+G)^2 + V\left(\hat{X}_b\right)(1-G)^2}{V\left(\hat{X}_a(\theta)\right)(1+G)^2 + V\left(\hat{X}_b\right)(1-G)^2} \tag{11}$$

According to the definition of CMRR, the amount of signal subtraction from both photodiodes can be characterized by the CMRR, which is defined as the ratio of the power P_{com} measured on one photodiode when the other is blocked by the power $\Delta \times P_{com}$ measured when both photodiodes are illuminated. It can be expressed as:

$$CMRR = 10\lg\frac{P_{com}}{\Delta \times P_{com}} = 20\lg\frac{I_{com}}{\Delta \times I_{com}} = 20\lg\frac{1+G}{2\left|1-G\right|} \tag{12}$$

Where I_{com}, $\Delta \times I_{com}$ are the single PD current and differential current of the two PDs, respectively. The Eq. (10) can be transferred into:

$$G = \frac{2 \times 10^{\frac{CMRR}{20}} - 1}{2 \times 10^{\frac{CMRR}{20}} + 1} \tag{13}$$

According to the Eq. (9) and Eq. (11), we can calculate the dependence of the measured squeezing level on the LO intensity noise, CMRR of the detector and the real squeezing level. In addition, the measured value of the SNL deviates from the real quantum noise limit, affected by the intensity noise of the LO, which depends on the BHD and the laser intensity noise. The deviation E_{SNL} can be expressed by

$$E_{SNL} = 10\lg\frac{(1+G)^2 + V\left(\hat{X}_b\right)(1-G)^2}{(1+G)^2 + (1-G)^2} \tag{14}$$

For our experimental system, with the CMRR of 67 dB, the laser intensity noise is 47 dB above the SNL, the E_{SNL} is only 0.01 dB, which can be neglected in the downstream experiment.

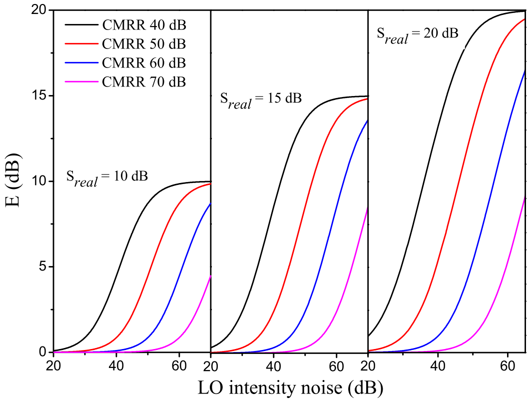

Fig. 2. Detection deviation E dependence on the CMRR, the LO intensity noise, and the real squeezing level ($E : S_{real} - S_m$). Left-hand chart indicates the deviation of measured value and real value at the real squeezing value 10 dB. Middle chart indicates the deviation of measured value and real value at the real squeezing value 15 dB. Right-hand chart indicates the deviation of measured value and real value at the real squeezing value 20 dB.

3. Theoretical results

Figure. 2 shows the deviation between the measured and real squeezing degree depends on the LO intensity noise under the conditions of different CMRR. We know, from Fig. 2, that the deviation grows with the increase of the LO intensity noise, and the CMRR of the detector can deliver immunity to LO intensity noise dependent of the level of the CMRR. Under the same conditions, the increase of the CMRR can decrease the measurement error. So we should improve the CMRR of the detector as far as possible for the detection of the squeezed state at audio frequencies. For the same CMRR and LO intensity noise, the above the real squeezing level is, the farther the deviation is. When the real squeezing level is more than the product P of the CMRR with the LO intensity noise, it produces a large accretion of the measurement error. Therefore, the detection of high-level squeezed light requires that the BHD has high CMRR to reduce the measurement error. For our experiment parameter with the real quantum noise reduction of 10 dB, and the LO intensity noise of 47 dB above the SNL, when the CMRR of the detector is 30 dB, 40 dB, 50 dB, and 60 dB, the measurement error is 8.3 dB, 3.4 dB, 0.55 dB, and 0.1 dB, respectively. The results demonstrate that the deviation is quickly enlarged with the CMRR value below the LO intensity noise.

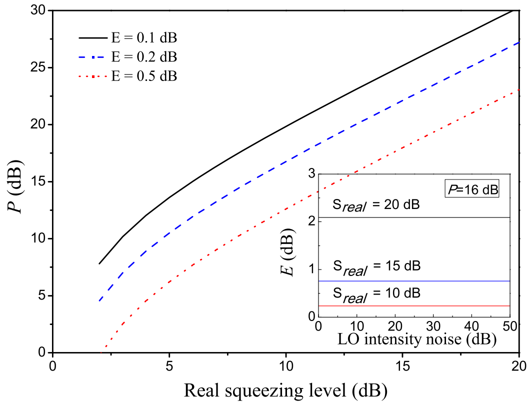

Fig. 3. Product P of the CMRR with the LO intensity noise dependence on the real squeezing level under the different measurement error. Detection deviation as a function of the LO intensity noise when the product P of the CMRR with the LO intensity noise is constant ($E : S_{real} - S_m$).

The inset of the Fig. 3 shows the measurement error depends on the LO intensity noise at real squeezing level of 10 dB, 15 dB, and 20 dB, when the product P of the CMRR with the LO intensity noise is constant. The results indicate that the measurement error depends on the LO intensity noise, but have immunity to the product P of the CMRR with the LO intensity noise. So there needs to be an increase the CMRR to compensate the influence of the LO intensity noise on the measurement error, when the LO intensity noise is above the SNL. Figure. 3 shows that the product P of the CMRR with the LO intensity noise depends on the real squeezing level of the measurement error of 0.1 dB, 0.2 dB, and 0.5 dB. For the same measurement error, the product P of the CMRR with the LO intensity noise should increase with the increase of the real squeezing level. For a squeezed state with the real quantum noise reduction of 10 dB, there requires that the product P of the CMRR with the LO intensity noise is 12.5 dB, 17 dB, and 20 dB, when the allowable measurement error is 0.5 dB, 0.2 dB, and 0.1 dB, respectively.

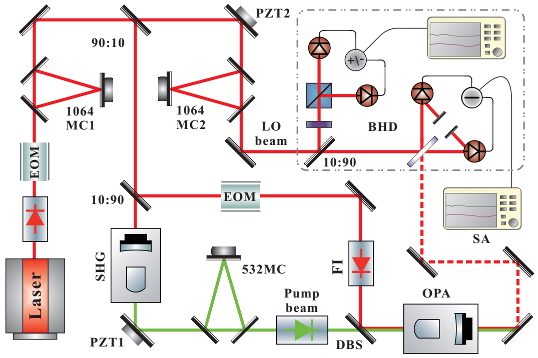

Fig. 4. Schematic of the experimental setup for measuring the LO intensity noise and generating the squeezed state. SHG: Second harmonic generation; EOM: electro-optical modulator; MC: mode cleaner; DBS: dichroic beam splitter; OPA: optical parametric amplifier; FI: Faraday isolator; PZT: piezoelectric transducer; BHD: balanced homodyne detection; SA: spectrum analyzer.

4. Experimental setup and results

A schematic of our experimental setup is illustrated in Fig. 4. The laser source of our experiment is a home-made Nd:YVO$_4$ ring laser with 2.5 W continuous-wave single-frequency output power at 1064 nm. The laser transmits through a mode cleaner (MC) that provides spatial-temporal filtering and polarization purifying for the downstream experiment. Approximately 30 mW of the transmitted light are reserved to be used as the LO for BHD. The remaining light is used for second harmonic generation (SHG) to provide the pump field at 532 nm for our OPA. Another mode cleaner (MC2) is placed in the beam paths of the LO to improve the mode matching efficiency between the LO and signal fields. All of these MCs are locked on resonance with the laser frequency by using Pound-Drever-Hall technique with low residual amplitude modulation [25]. After the MC2, we employ a BHD to quantify the laser intensity noise of the LO. The subtraction of two photocurrents corresponds to the SNL, the sum of two photocurrents is the LO intensity noise. The measurement results are shown in Fig. 5, which indicates that the LO intensity noise is approximately 47 dB above the SNL at audio frequencies. In the downstream experiment, we should reduce the influence of the LO intensity noise on the measured squeezing noise as small as possible based on the above analysis results. Our OPA is a semi-monolithic cavity consisting of a piezo-actuated concave mirror and a PPKTP crystal with the dimensions 10 mm × 2 mm × 1 mm. The crystal end face with a radius of curvature of 12 mm is coated as high reflectivity (HR) for the fundamental field and high transmission for the pump field, thus serving as the cavity end mirror. The plane front face of crystal is coated as anti-reflectivity (AR) for both wavelengths. An air gap of 27 mm length is realized between the AR coated side of the crystal and the coupling mirror. The concave mirror with a radius of curvature of 30 mm has a transmissivity of 12 % for 1064 nm and HR for 532 nm, which is used as the output coupler. A peltier element beneath the crystal is used to keep the phase matching temperature at around 35 centigrade.

The squeezed states emit out from the concave mirror, separated from the pump light by a dichroic beam splitter (DBS) and directed towards a BHD to detect the noise level. The BHD is constructed from a pair of p-i-n photodiodes (from Laser Components) with quantum efficiency of more than 99 %. To recycle the residual reflection from photodiodes surface, two concave mirrors with the curvature radius of 50 mm are used as retroreflectors. By operating an auxiliary cavity technique [26], we achieve a fringe visibility of 99.8 % between the signal beam and the LO on the 50/50 beam splitter.

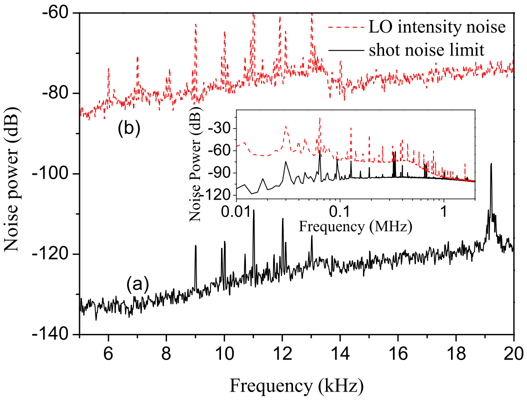

Fig. 5. LO intensity noise as a function of measurement frequency. Trace (a) corresponds to the SNL from the subtraction of two photocurrents. Trace (b) corresponds to the LO intensity noise from the sum of two photocurrents.

According to the analysis results in section 3, the audio frequencies measurements of squeezing level are impeded by the LO intensity noise. The BHD delivers immunity to LO intensity noise to the level of the CMRR. With the increase of the CMRR, the measurement error decreases. In our experiment, the CMRR is quantitatively measured by taking the transfer function from the amplitude modulator to the homodyne output, then normalizing this by the transfer function from the amplitude modulator to a single photodetector. The measurement results are recorded by the Network Analyzer (HP 4395A), shown in Fig. 6, with the CMRR of approximately 67 dB from 15 kHz-50 kHz. When the analysis frequency is less than 15 kHz, the CMRR deteriorate, which may be limited by the electronic noise of the photodetector. Therefore, the analysis frequency is set to 15.2 kHz to measure the squeezing level in the downstream experiment. When the pump power is 175 mW, the parametric gain of approximately 100 is observed. During the measurement process, the seed field is blocked to produce vacuum squeezing, which eliminate the noise coupling of the seed field at audio frequencies. Therefore, no cavity length control signal can be obtained, the squeezed light source cavity is manually tuned on resonance with the laser wavelength. The measured squeezed degree at the analysis frequency of 15.2 kHz, as shown in Fig. 7, are recorded with a Spectrum Analyzer (R&S FSW)

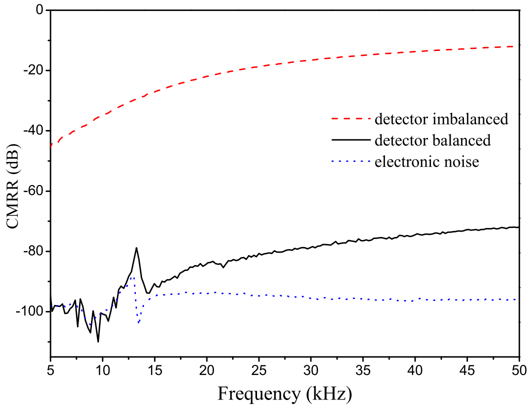

Fig. 6. CMRR of the homodyne detector as a function of measurement frequency via a transfer function method, with an intermediate frequency bandwidth of 10 Hz.

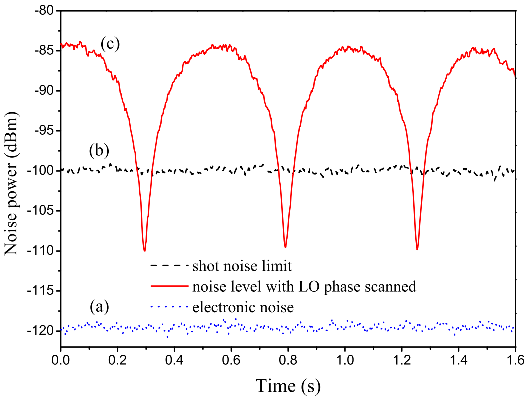

Fig. 7. Balance homodyne measurements of the quadrature noise variances. The measurement is recorded at a Fourier frequency of 15.2 kHz, with a RBW of 500 Hz, and a VBW of 5 Hz. The data still include electronic noise, and represent direct observations.

with a resolution bandwidth (RBW) of 500 Hz, and a video bandwidth (VBW) of 5 Hz. The measurement uncertainty of the Spectrum Analyzer is 0.2 dB. Trace (a) corresponds to the electronic noise of the BHD and is recorded with the signal and LO input blocked. The SNL is recorded with only the LO port of the balanced beam splitter open. In this configuration no photons entered through the signal port such that the measured noise directly represents the vacuum noise reference level. When the LO power is 1.4 mW, the corresponding SNL is shown with Trace (b). Trace (c) records the variance of the noise level with the LO phase scanned. The observed squeezing level is 9.9 ± 0.2 dB and the antisqueezing level is 15.5 ± 0.2 dB above the SNL. The electronic noise of the homodyne detector is 21 dB below the SNL. Taking the measurement deviation from the LO intensity noise, this corresponds to a maximum squeezing level of 10.0 ± 0.2 dB. The contribution of the electronic noise is further subtracted, corresponding to a maximum squeezing level of 10.2 ± 0.2 dB at 15.2 kHz.

5. Conclusion

We investigate the dependence of the measured squeezing level on the LO intensity noise, CMRR of the detector and the real squeezing level. The results indicate that the measurement error depends on the LO intensity noise, but has immunity to the product P of the CMRR with the LO intensity noise. So there need to increase the CMRR to compensate the influence of the LO intensity noise on the measurement error, when the LO intensity noise is above the SNL. Based on the BHD technique, LO intensity noise is measured, which is approximately 47 dB above the SNL at audio frequencies. In order to reduce the deviation between the measured and real squeezing level originating from the LO intensity noise, we employ a detector with the CMRR of 67 dB to detect the quantum noise at audio frequencies, the product P of the CMRR with the LO intensity noise is 20 dB below the SNL, which can induce the measurement error of 0.1 dB for 10 dB of squeezing. Finally, the squeezing level measured at 15.2 kHz is 9.9 ± 0.2 dB. Taking the influence of the intensity noise of the LO, and the electronic noise of the detector into account, the inferred squeezing level is approximately 10.2 ± 0.2 dB. With the decrease of the analysis frequency, increases of the measurement time , the fluctuations of the control loop are responsible for the degradation of the squeezing strengths at Fourier frequencies above 1 kHz. At below 1 kHz, there could be more factors in affecting the squeezing strengths, such as the remnant parasitic interferences, and the high electronic noise of the photodetector [15]. The theoretical results are very important to detect the squeezing level at audio frequencies, guide the design of the detector, and infer the real squeezing level from the measured squeezing level. If one hope to measure the squeezed light with higher squeezing level, the CMRR of the detector should be improved to reduce the measurement error.

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