Balanced Homodyne Detector With Independent Phase Control and Noise Detection Branches

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ABSTRACT Squeezed state light is a fundamental resource for many quantum optics experiments. Important applications like quantum-enhanced magnetometer and quantum key distribution, require the squeezing level as high as possible. In balanced homodyne detection, the detector output is directly proportional to the noise of the squeezed beam. The detected quadrature is dependent on the relative phase between the squeezed beam and local oscillator. Here, we present a balanced homodyne detector (BHD) with independent phase control and noise detection branches. The independence between the phase control and noise detection branches is experimentally verified, the two branches are independently optimized according to the practical requirements. With the BHD, a bright squeezed light at 1550 nm with quantum noise reduction of 10.3 dB is directly detected. After stabilizing the relative phase between the squeezed states and local oscillator by the phase locking branch of the BHD, the fluctuation of the noise suppression is ±0.2 dB by 1-h testing time.

INDEX TERMS Photodetectors, phase control, measurement, transimpedance, squeezed states.

I. INTRODUCTION

Squeezed states have less fluctuations in one quadrature component than a coherent state at the expense of increased fluctuations in the other quadrature one [1]. In terms of its ultra-low fluctuations, such states offer intriguing possibilities. They can increase the sensitivity of a Gravitational wave detector by injecting squeezed states into the dark port of the interferometer [2]–[4]. Squeezed states can be also used to transmit information in the quadrature component that has fluctuations below quantum noise limit, which contributes to increasing the channel capacity, reducing error rate [5], [6]. The performance improvement of these applications is determined by the measured value of squeezing level.

In theory, an infinite squeezing level can be detected at the threshold. However, the measured squeezing level is usually limited by optical loss and phase noise during the process of squeezed states generation, propagation and detection. This loss reduces the squeezing factor by introducing

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vacuum noise into the squeezed states. Phase noise limits the measured value of squeezing level by coupling the anti-squeezing quadrature into the squeezing quadrature at the time of the measurement. There have been a number of key advances made in the reduction of loss and phase fluctuation during squeezed states generation, propagation, and detection, aiming to increase the squeezing factor [7]–[12]. The particular focus of this paper is the construction of a balanced homodyne detector (BHD) that can effectively draw upon the features of squeezed states.

In balanced homodyne detection, a squeezed beam is overlapped at a 50/50 beam splitter with a strong local oscillator (LO) shown in Fig. 1. Both beam splitter outputs are detected with a pair of photodiodes (PDs) and subtracted from each other. The output is directly proportional to the noise of the squeezed beam, the detected quadrature is dependent of the relative phase θ between squeezed beam and LO. Such measurement imposes a stringent requirement on the relative phase θ stability to detect the desired quadrature [13], [14]. The fragility of the squeezed states for loss warns us that it is not a good idea of tapping off a portion of squeezed
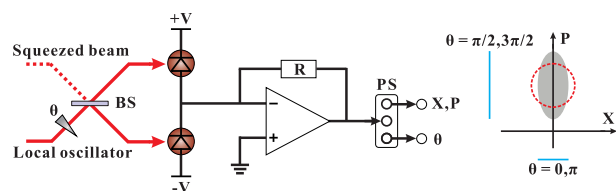
FIGURE 1. Popular schematic of balanced homodyne detection. The photo detector output is divided into two parts by a power splitter: One for the amplitude X and phase P quadratures detection, another for the phase θ stability. The amplitude X (phase P) quadrature is detected at the relative phase $\theta = 0, \pi$ ($\pi/2, 3\pi/2$) . The coherent state is visualized by the red dashed circle. BS: Beam splitter; PS: Power splitter.

light for phase locking [7], [8], [15]. So BHD should have sufficiently good performance of not only the noise detection, but also the error signal extraction for phase locking. The previous works focus on reducing the electronic noise, boosting the detector gain, and improving the common mode rejection ratio (CMRR) to detect effectively quantum noise [11], [16], [17], but there are not specifically mentioned about the extraction of error signal for phase stability. A popular method is the separation of the BHD output by a power splitter: one for noise detection, another for phase stability [13], [14], [18]–[20]. In this case, both the noise detection and phase stability share a common amplifier that cannot be independently optimized on the basis of their specific requirements. In fact, each specific application makes different demands on the detector parameters, the parameter optimization for multi-function detector faces challenge. Especially for the generation of squeezed state at 1550 nm, it becomes more urgent to achieve good performance of phase locking due to large phase noise of the fiber laser.

In this paper, we present a BHD with independent amplifier units for noise detection and phase locking. The amplifier unit for noise detection is constructed based on the self-subtraction and transimpedance amplifier (TIA) photodetector scheme [11], [16], [17], [21]–[27]. The signal for phase locking is extracted from sample resistances placed between the PDs and bias power supplies. By adjusting the parameters of one of amplifier units, we experimentally confirm that the performances of two amplifier units are mutually independent of each other. The detector has a maximum clearance of 37 dB at 2.2 MHz when 8 mW laser is illuminated. In order to verify the performance of phase locking branch, the BHD is applied to the generation of bright squeezed light at 1550 nm, demonstrating the stable control at 1 hour testing time.

II. PHOTODETECTOR DESIGN
The balanced homodyne detection can amplify the squeezed light field, allow for precisely choosing the measured quadrature of squeezed states, it is a well-proven workhorse for quantum optics experiments. The electronic noise of the detector sets a strong limitation to the measurement of quantum noise. In order to measure accurately quantum noise, the clearance between shot noise and electronic noise is far larger than the generated value of squeezing factor.

So we should reduce the electronic noise of the detector as much as possible to meet the requirements for noise detection.

TIA offering the potential of lower noise and larger bandwidth than a termination resistor and a voltage amplifier, is widely applied to convert the shot noise current to an AC voltage [16]. In addition, the shot noise current from the subtraction signal is rather weak, which puts more stringent requirements upon the detector design. As we mention in the introduction, the BHD should have low electronic noise for quantum noise detection, but also feature of phase locking. Usually, the modulation frequency for phase locking should be far away from the analysis frequency of quantum noise detection to reduce the crosstalk as much as possible. So the detector for phase locking should have broad bandwidth. The two differentiated requirements compel us to use two amplifier units that are independently optimized [24]–[26]. A simple method is that the subtraction signal can be directly divided into two branches. Subsequently, the two branches are amplified, respectively. However, the branch for phase locking will degrade the electronic noise of noise detection branch in this approach.

Here, we design and build BHD with independent phase locking and noise detection branches on the basis of former works [11], [16], [17], shown in Fig. 2. The noise detection branch, shown by solid box, follows our previous designs, with the feature of low-noise, high-gain and high-CMRR in the former works. The particular focus of this paper is the independent signal extraction for phase locking under the premise of not affecting the noise detection branch. The extraction scheme is shown by dashed box in Fig. 2, the signal for phase locking is collected from sample resistance R4 placed between the PD1 and positive bias power supply, then amplified independently by the differential amplifier. According to the PD theory, a PD can be represented by current source in parallel with an ideal diode. The magnitude of the generated current is solely determined by the laser power illuminated onto the PD, independent of the external circuit. If the sample resistance R4 in series with the equivalent current source is placed between the PD and noise detection branch, the load variation of phase locking branch induces the current variation of noise detection branch. When the sample resistance R4 is placed between the PD1 and positive bias power supply, the dependence disappears. The two branches are mutually independent of each other.

Two voltage followers are adopted to isolate further the disturbance of two sections, the front and the back, due to its high input and low output impedances. After isolation, a differential amplifier is employed to amplify the signal for phase locking. The parameters of the differential amplifier can be independently optimized, including the selection of operational amplifier, the amplification factor. Similarly, we collect the phase locking signal from another sample resistance R21 by using the same differential amplifier. The outputs of two differential amplifiers are mixed through a subtracter, the design can amplify phase locking signal to the fullest extent [14].
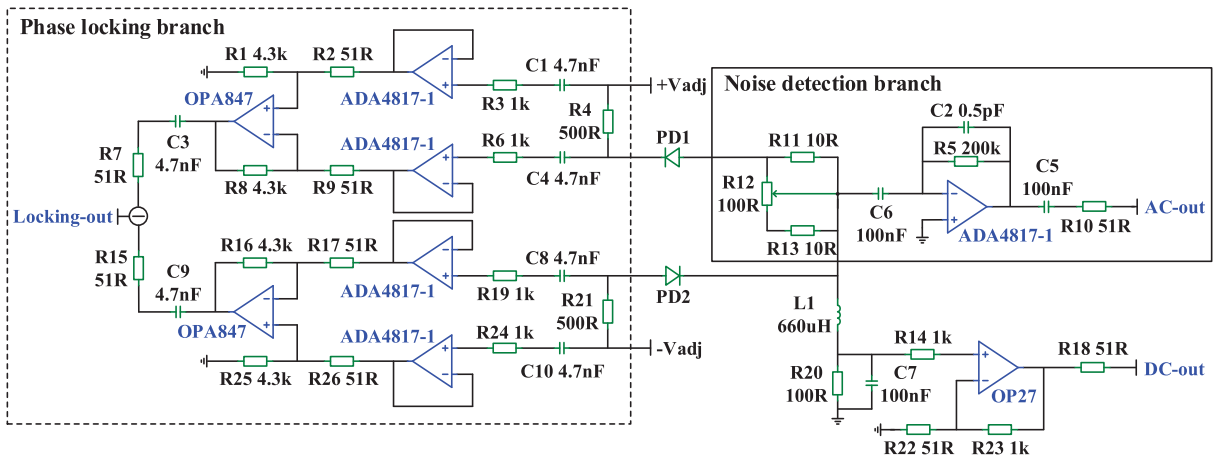
FIGURE 2. Circuit diagram of the detector with independent phase locking and noise detection branches.

To make the noise detection branch with the lowest electronic noise, we select the ADA4817-1 as operational amplifier of the noise detection branch in terms of its low input voltage noise and input capacitance. In addition, the ADA4817-1 with junction field-effect transistor input is more preferred in the high transimpedance gain circuit, which meets the requirement for the noise detection branch [16], [28]. At the same time, the ADA4817-1 is unity-gain stable, ultra-high speed voltage feedback amplifier with very high input impedance, which is ideal for voltage follower application. For the application of the differential amplifier, the OPA847 has high gain-bandwidth product, which is ideal for broadband voltage-feedback amplification [28]. Thus, it is benefit of adopting the locking signal with higher frequency to reduce the crosstalk with the noise detection.

III. EXPERIMENTAL RESULTS AND ANALYSIS

A schematic of our experimental setup is illustrated in Fig. 3. The laser source of our experiment is a fiber laser with 2 W continuous-wave single-frequency output power at 1550 nm, its output power can be conveniently adjusted with power adjustment system consisting of a half-wave plate (HWP1) and a polarization beam splitter (PBS1). The output beam of PBS1 is injected into the electro-optic amplitude modulator (EOAM), which is modulated by a RF signal connected with its RF input connector. The PBS2 in combination with the EOAM serves as amplitude modulation. The RF signal can be conveniently switched from a network analyzer to a signal generator according to the measurement requirement. The most important optical component is a 50/50 beam splitter consisting of HWP2 and PBS3, which can be used to finely tune the splitting ratio by rotating the HWP2. Output beams from PBS3 are injected into two PDs after being focused with lens L1 and L2. The DC output of photodetector is connected with a digitizing oscilloscope (OSC) to verify whether the light is thoroughly received by each PD and meanwhile make sure the power of light injected into each PD is equal.
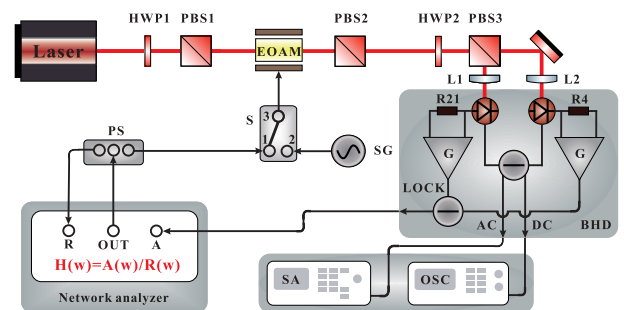

FIGURE 3. Experimental setup for measuring the performance of the photodetector. HPW: Half-wave plate; PBS: Polarization beam splitter; EOAM: Electro-optic amplitude modulator; S: Switch; SG: Signal generator; PS: Power splitter; SA: Spectrum analyzer; OSC: Digitizing oscilloscope.

The AC output is connected with a spectrum analyzer (FSW-8) to read the noise power. The performance of noise detection branch is evaluated by the clearance between the shot noise and electronic noise (signal to noise ratio). The EOAM is driven by an internal reference signal R(w) from a network analyzer (Agilent 4395A). The modulation frequency can be continuously tuned at the predefined range. This amplitude modulated laser beam is sensed by locking output of BHD and then fed into the network analyzer. The network analyzer performs a normalized measurement by calculating the ratio between the locking output A(w) and internal reference signal R(w), the measurement result is a transfer function H(w). The transfer function is used to characterize the performance of the phase locking branch. In our photodetector, two PDs with the same performance parameters are used as optical receivers to improve the CMRR of BHD. During the process of measuring the CMRR, the EOAM is driven by a signal generator instead of the network analyzer.

With the setup described above, the independence between the phase locking and noise detection branches is verified by measuring the performance change of one of the branches with another branch parameters. Firstly, we measure the
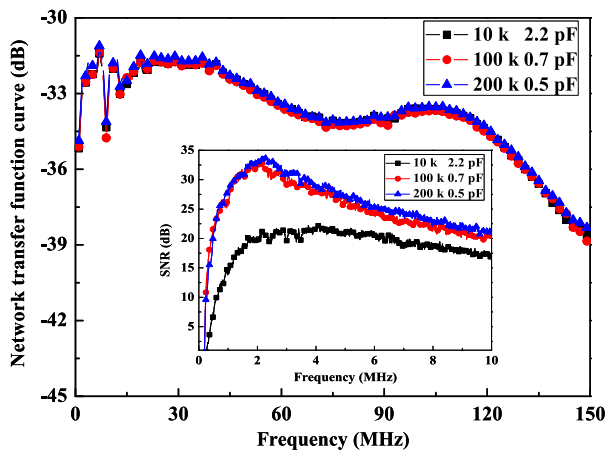
FIGURE 4. Transfer function of the phase locking branch at different combinations of feedback resistance and compensation capacitance of the noise detection branch, independent of the noise detection branch. So the noise detection branch can be independently optimized, the inset shows the clearance of the noise detection branch at different feedback parameters. The input laser power is 4 mW. SNR: Signal to noise ratio.
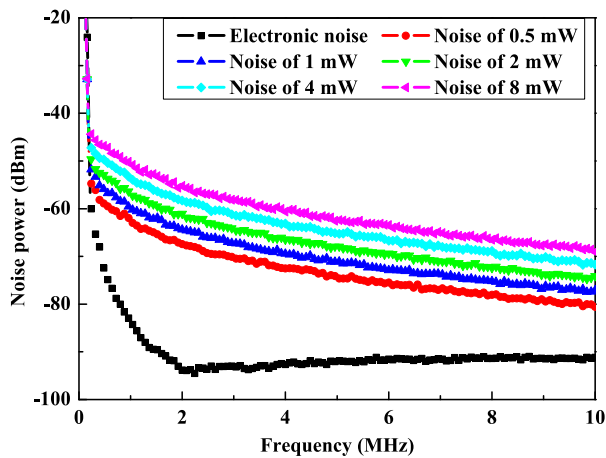

FIGURE 5. Linearity and clearance of the noise detection branch.

FIGURE 6. Clearance of the noise detection branch at different gain factors of the phase locking branch, independent of the phase locking branch. So the phase locking branch can be independently optimized based on the requirement of locking loop.

FIGURE 7. Common mode rejection ratio of the noise detection branch at different amplification factors of the phase locking branch.

transfer function of the phase locking branch at different combinations of feedback resistance $R5$ and compensation capacitance $C2$ of the noise detection branch, shown in Fig. 4. We know, from Fig. 4, that the transfer function has nothing to do with the value $R5$ and $C2$ of the noise detection branch. So the noise detection branch can be independently optimized under the premise of maintaining the transfer function unchanged. The clearance of the noise detection branch is optimal at $R5 = 200 \ k\Omega$, $C2 = 0.5$ pF, corresponding to maximum clearance of 34 dB at 2.2 MHz when the input laser power is 4 mW. At optimal conditions, we check the linearity of the noise detection branch of the BHD by measuring the shot noise levels versus local oscillator powers, the results are shown in Fig. 5. With the local oscillator power double increased, a clearance of 3 dB in the range of between 1 MHz to 10 MHz can be obtained. The clearance is enough to meet the requirement for squeezed states with 20 dB quantum noise reduction.
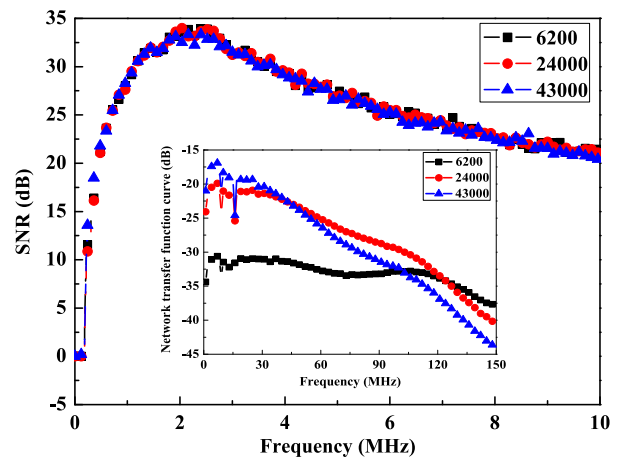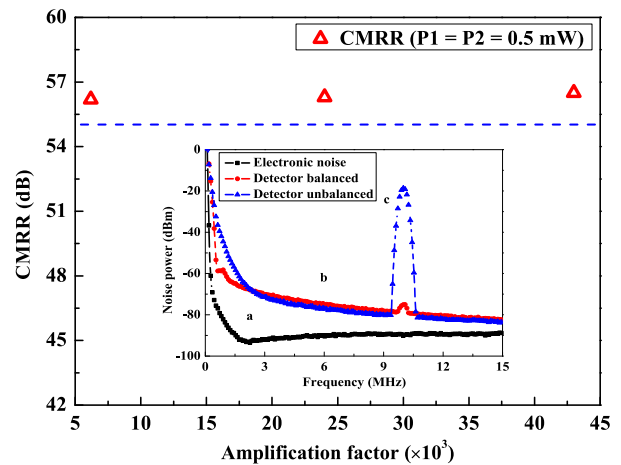
Secondly, we measure the clearance of the noise detection branch in the range from DC to 10 MHz when the amplification factor (changing these values $R1$, $R8$, $R16$, $R25$) of the phase locking branch is changed, the results are shown in Fig. 6. The bandwidth of the phase locking branch is dependent of its gain, which can be adjusted according to the actual requirement. Here, the maximum bandwidth is about 150 MHz. The clearance of the noise detection branch is independent of the amplification factor of the phase locking branch. So the phase locking branch can be independently optimized based on the requirement of locking loop without getting into the performance of the noise detection branch. At three different amplification factors of the phase locking branch, we measure the CMRR of the noise detection branch at 10 MHz, shown in Fig. 7. Three separation points are the measured results at the amplification factor of 6200, 24000, 43000. The inset of Fig. 7 is a typical result of the balancing process at the amplification factor of 43000.
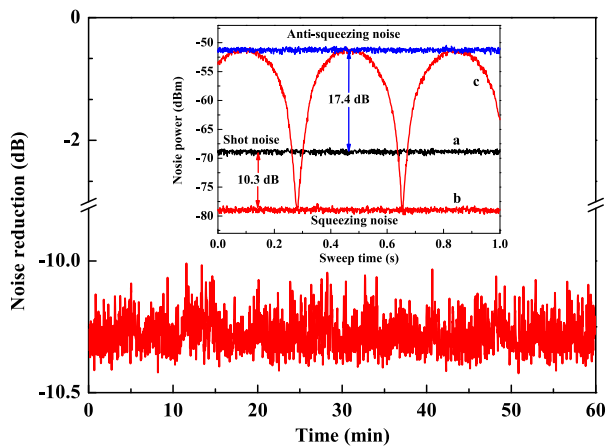
FIGURE 8. Long-term stability of the bright squeezed light recorded continuously for 1 hour, the inset is balanced homodyne measurements of the quadrature noise variances.

The measurement process is in accordance with [11]. The results show the CMRR is immune to the amplification factor of the phase locking branch, more than 55 dB at different amplification factors.

Finally, we adopt the same scheme with [9], except for the laser source, to evaluate the BHD performance at an actual system of squeezed states generation. Here, we use a single-frequency fiber laser at 1550 nm instead of solid laser at 1064 nm as laser source. Due to large phase noise of fiber laser, the phase stability faces challenge. On the basis of the BHD with independent phase locking and noise detection branches, we achieve high-stability phase locking between the squeezed light and local oscillator by optimizing independently the phase locking branch, stably bright squeezed light at 1550 nm is experimentally obtained. Fig. 8 is the detected results about the stability and squeezed degree, the directly observed squeezing level is 10.3 dB. We record the long-term stability of noise suppression of bright squeezed light by 1 hour testing time, the fluctuation of the noise suppression is ±0.2 dB. The results confirm that the BHD scheme can achieve simultaneously the phase locking and noise detection by independent optimization, which is helpful to the generation of squeezed states with long-term stability, especially for these pump sources with large phase noise.

IV. CONCLUSION

In conclusion, we have demonstrated a BHD with independent phase control and noise detection branches. In our scheme, the signal for phase locking is collected from sample resistances placed between the PDs and bias power supplies. According to the equivalent circuit and working principle of the PD, we verify in principle the independence between the phase locking and noise detection branches. Furthermore, the signals from two sample resistances are mixed through a subtracter to amplify phase locking signal to the fullest extent. Subsequently, the independence between the phase locking and noise detection branches is experimentally verified

by measuring the performance change of one of the branches with another branch parameters. The performance of the phase locking branch is characterized by its transfer function, and the noise detection branch is indicated by the clearance between the shot noise and electronic noise (SNR). Finally, we employ the BHD to perform the noise detection and phase locking in the case of squeezed state generation at 1550 nm. Since the fiber laser has large phase noise, there put forward higher request for the detector during the process of squeezed state generation at 1550 nm, which is why we choose the wavelength to evaluate the detector performance. With the BHD, a bright squeezed light at 1550 nm with quantum noise reduction of 10.3 dB at a Fourier frequency of 10MHz is directly detected. When the relative phase between the squeezed states and local oscillator is stabilized by the phase locking branch of the BHD, the fluctuation of the noise suppression is ±0.2 dB by 1 hour testing time, which confirms the good performance of our designed BHD.

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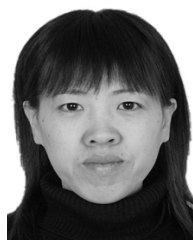
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