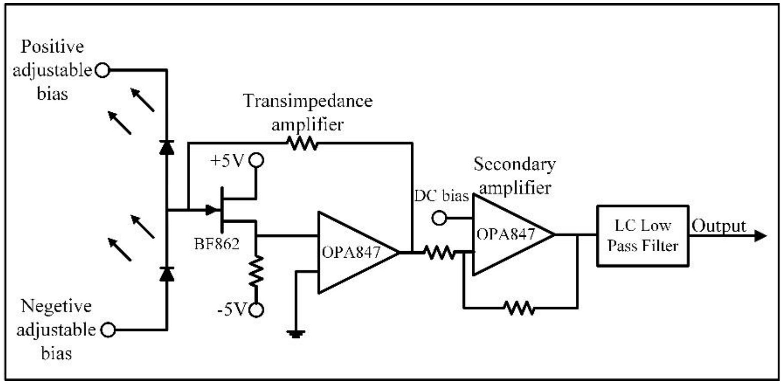
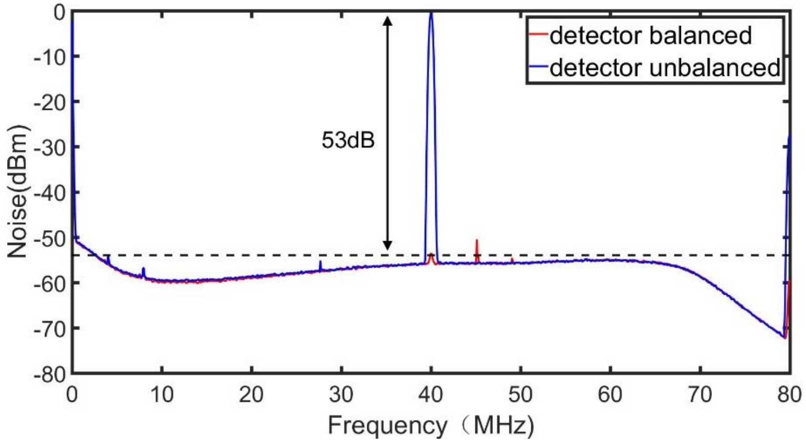
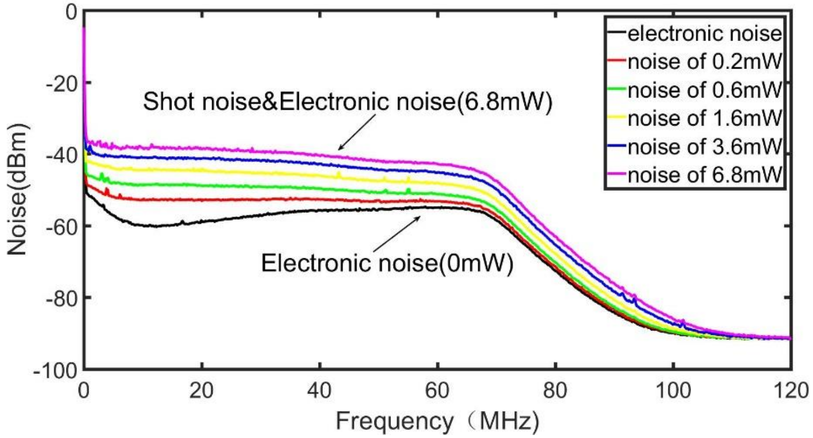
# An Ultra-Sensitive Balanced Detector with Low-Noise for Continuous Variable QKD





| Transimpedance | 8K |
|---|---|
| Total Gain | 3.2E5 V/W |
| Bandwidth | 70MHz |
| Noise | ~6mV |
| CMRR | 53dB |
| NEP | 2.2pW/rtHz |



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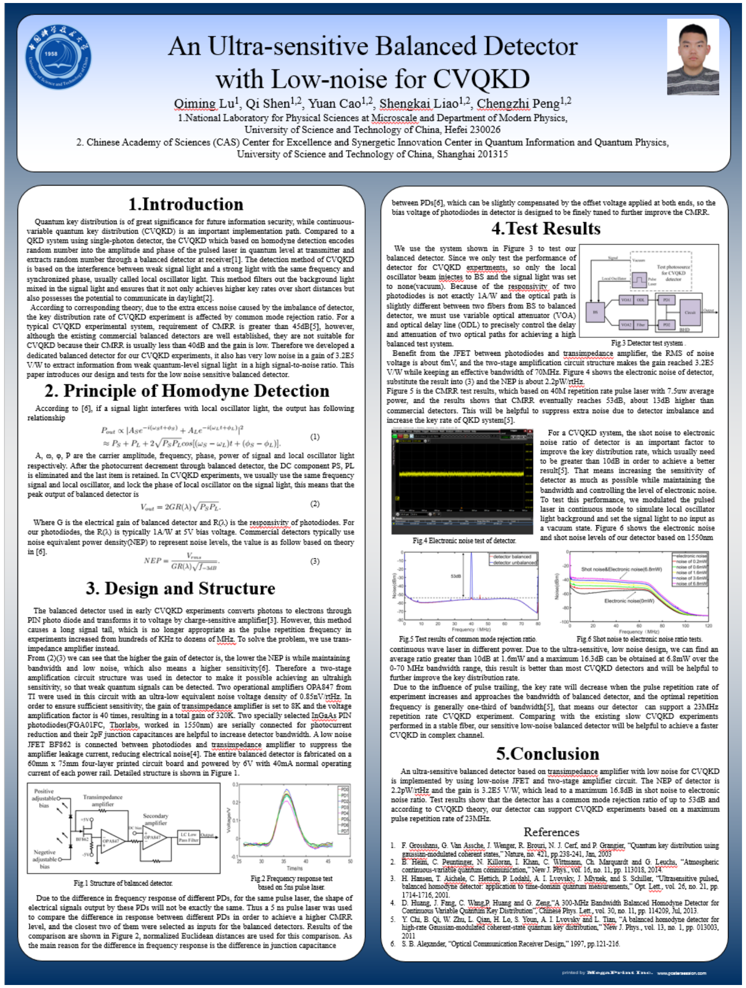
# Poster

Introduction

Principle

Design



## An Ultra-sensitive Balanced Detector with Low-noise for CVQKD

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### 1.Introduction

Quantum key distribution is of great significance for future information security, while continuous-variable quantum key distribution (CVQKD) is an important implementation path. Compared to a QKD system using single-photon detector, the CVQKD which based on homodyne detection encodes random number into the amplitude and phase of the pulsed laser in quantum level at transmitter and extracts random number through a balanced detector at receiver[1]. The detection method of CVQKD is based on the interference between weak signal light and a strong light with the same frequency and synchronized phase, usually called local oscillator light. This method filters out the background light mixed in the signal light and ensures that it not only achieves higher key rates over short distances but also possesses the potential to communicate in daylight[2].

According to corresponding theory, due to the extra excess noise caused by the imbalance of detector, the key distribution rate of CVQKD experiment is affected by common mode rejection ratio. For a typical CVQKD experimental system, requirement of CMRR is greater than 45dB[5], however, although the existing commercial balanced detectors are well established, they are not suitable for CVQKD because their CMRR is usually less than 40dB and the gain is low. Therefore we developed a dedicated balanced detector for our CVQKD experiments, it also has very low noise in a gain of 3.2E5 V/W to extract information from weak quantum-level signal light in a high signal-to-noise ratio. This paper introduces our design and tests for the low noise sensitive balanced detector.

### 2. Principle of Homodyne Detection

According to [6], if a signal light interferes with local oscillator light, the output has following relationship

$$\begin{aligned} P_{out} &\propto |A_S e^{-i(\omega_S t+\phi_S)} + A_L e^{-i(\omega_L t+\phi_L)}|^2 \\ &\approx P_S + P_L + 2\sqrt{P_S P_L} cos[(\omega_S - \omega_L)t + (\phi_S - \phi_L)]. \end{aligned} \quad (1)$$

A, ω, φ, P are the carrier amplitude, frequency, phase, power of signal and local oscillator light respectively. After the photocurrent decrement through balanced detector, the DC component PS, PL is eliminated and the last item is retained. In CVQKD experiments, we usually use the same frequency signal and local oscillator, and lock the phase of local oscillator on the signal light, this means that the peak output of balanced detector is

$$V_{out} = 2GR(\lambda)\sqrt{P_S P_L}. \quad (2)$$

Where G is the electrical gain of balanced detector and R(λ) is the responsivity of photodiodes. For our photodiodes, the R(λ) is typically 1A/W at 5V bias voltage. Commercial detectors typically use noise equivalent power density(NEP) to represent noise levels, the value is as follow based on theory in [6].

$$NEP = \frac{V_{rms}}{GR(\lambda)\sqrt{f_{-3dB}}}. \quad (3)$$

### 3. Design and Structure

The balanced detector used in early CVQKD experiments converts photons to electrons through PIN photo diode and transforms it to voltage by charge-sensitive amplifier[3]. However, this method causes a long signal tail, which is no longer appropriate as the pulse repetition frequency in experiments increased from hundreds of KHz to dozens of MHz. To solve the problem, we use trans-impedance amplifier instead.

From (2)(3) we can see that the higher the gain of detector is, the lower the NEP is while maintaining bandwidth and low noise, which also means a higher sensitivity[6]. Therefore a two-stage amplification circuit structure was used in detector to make it possible achieving an ultrahigh sensitivity, so that weak quantum signals can be detected. Two operational amplifiers OPA847 from TI were used in this circuit with an ultra-low equivalent noise voltage density of 0.85nV/rtHz. In order to ensure sufficient sensitivity, the gain of transimpedance amplifier is set to 8K and the voltage amplification factor is 40 times, resulting in a total gain of 320K. Two specially selected InGaAs PIN photodiodes(FGA01FC, Thorlabs, worked in 1550nm) are serially connected for photocurrent reduction and their 2pF junction capacitances are helpful to increase detector bandwidth. A low noise JFET BF862 is connected between photodiodes and transimpedance amplifier to suppress the amplifier leakage current, reducing electrical noise[4]. The entire balanced detector is fabricated on a 60mm x 75mm four-layer printed circuit board and powered by 6V with 40mA normal operating current of each power rail. Detailed structure is shown in Figure 1.

Fig.1 Structure of balanced detector.

Fig.2 Frequency response test based on 5ns pulse laser.

Due to the difference in frequency response of different PDs, for the same pulse laser, the shape of electrical signals output by these PDs will not be exactly the same. Thus a 5 ns pulse laser was used to compare the difference in response between different PDs in order to achieve a higher CMRR level, and the closest two of them were selected as inputs for the balanced detectors. Results of the comparison are shown in Figure 2, normalized Euclidean distances are used for this comparison. As the main reason for the difference in frequency response is the difference in junction capacitance between PDs[6], which can be slightly compensated by the offset voltage applied at both ends, so the bias voltage of photodiodes in detector is designed to be finely tuned to further improve the CMRR.

### 4.Test Results

We use the system shown in Figure 3 to test our balanced detector. Since we only test the performance of detector for CVQKD expertments, so only the local oscillator beam injectes to BS and the signal light was set to none(vacuum). Because of the responsivity of two photodiodes is not exactly 1A/W and the optical path is slightly different between two fibers from BS to balanced detector, we must use variable optical attenuator (VOA) and optical delay line (ODL) to precisely control the delay and attenuation of two optical paths for achieving a high balanced test system.

Fig.3 Detector test system .

Benefit from the JFET between photodiodes and transimpedance amplifier, the RMS of noise voltage is about 6mV, and the two-stage amplification circuit structure makes the gain reached 3.2E5 V/W while keeping an effective bandwidth of 70MHz. Figure 4 shows the electronic noise of detector, substitute the result into (3) and the NEP is about 2.2pW/rtHz.

Figure 5 is the CMRR test results, which based on 40M repetition rate pulse laser with 7.5uw average power, and the results shows that CMRR eventually reaches 53dB, about 13dB higher than commercial detectors. This will be helpful to suppress extra noise due to detector imbalance and increase the key rate of QKD system[5].

Fig.4 Electronic noise test of detector.

For a CVQKD system, the shot noise to electronic noise ratio of detector is an important factor to improve the key distribution rate, which usually need to be greater than 10dB in order to achieve a better result[5]. That means increasing the sensitivity of detector as much as possible while maintaining the bandwidth and controlling the level of electronic noise. To test this performance, we modulated the pulsed laser in continuous mode to simulate local oscillator light background and set the signal light to no input as a vacuum state. Figure 6 shows the electronic noise and shot noise levels of our detector based on 1550nm continuous wave laser in different power. Due to the ultra-sensitive, low noise design, we can find an average ratio greater than 10dB at 1.6mW and a maximum 16.3dB can be obtained at 6.8mW over the 0-70 MHz bandwidth range, this result is better than most CVQKD detectors and will be helpful to further improve the key distribution rate.

Fig.5 Test results of common mode rejection ratio.

Fig.6 Shot noise to electronic noise ratio tests.

Due to the influence of pulse trailing, the key rate will decrease when the pulse repetition rate of experiment increases and approaches the bandwidth of balanced detector, and the optimal repetition frequency is generally one-third of bandwidth[5], that means our detector can support a 23MHz repetition rate CVQKD experiment. Comparing with the existing slow CVQKD experiments performed in a stable fiber, our sensitive low-noise balanced detector will be helpful to achieve a faster CVQKD in complex channel.

### 5.Conclusion

An ultra-sensitive balanced detector based on transimpedance amplifier with low noise for CVQKD is implemented by using low-noise JFET and two-stage amplifier circuit. The NEP of detector is 2.2pW/rtHz and the gain is 3.2E5 V/W, which lead to a maximum 16.8dB in shot noise to electronic noise ratio. Test results show that the detector has a common mode rejection ratio of up to 53dB and according to CVQKD theory, our detector can support CVQKD experiments based on a maximum pulse repetition rate of 23MHz.

### References

1. F. Grosshans, G. Van Assche, J. Wenger, R. Brouri, N. J. Cerf, and P. Grangier, "Quantum key distribution using gaussian-modulated coherent states," Nature, no. 421, pp.238-241, Jan, 2003
2. B. Heim, C. Peuntinger, N. Killoran, I. Khan, C. Wittmann, Ch. Marquardt and G. Leuchs, "Atmospheric continuous-variable quantum communication," New J. Phys., vol. 16, no. 11, pp. 113018, 2014.
3. H. Hansen, T. Aichele, C. Hettich, P. Lodahl, A. I. Lvovsky, J. Mlynek, and S. Schiller, "Ultrasensitive pulsed, balanced homodyne detector: application to time-domain quantum measurements," Opt. Lett., vol. 26, no. 21, pp. 1714-1716, 2001.
4. D. Huang, J. Fang, C. Wang,P. Huang and G. Zeng,"A 300-MHz Bandwidth Balanced Homodyne Detector for Continuous Variable Quantum Key Distribution", Chinese Phys. Lett., vol. 30, no. 11, pp. 114209, Jul, 2013.
5. Y. Chi, B. Qi, W. Zhu, L. Qian, H. Lo, S. Youn, A. I. Lvovsky and L. Tian, "A balanced homodyne detector for high-rate Gaussian-modulated coherent-state quantum key distribution," New J. Phys., vol. 13, no. 1, pp. 013003, 2011
6. S. B. Alexander, "Optical Communication Receiver Design," 1997, pp.121-216.

Experimental and results

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