ISSN:2790-1688 DOI: 10.56028/aetr.1.1.135

A 600 MHz Balanced Homodyne Detector for Quantum Information Processing

Tianxiang Zhang[1], Yundi Huang[1], Xiangyu Wang[1,*], Ziyang Chen[2], Song Yu[1]

[1] State Key Laboratory of Information Photonics and Optical Communications Beijing University of Posts and Telecommunications Beijing, China

[2] State Key Laboratory of Advanced Optical Communication, Systems and Networks, School of Electronics,and Center for Quantum Information Technology Peking University Beijing, China

*e-mail: xywang@bupt.edu.cn

Abstract. Balanced homodyne detector (BHD) has been widely used in quantum information processing. In this paper, we design a wide bandwidth BHD and implement an optical layout to test the performance of our BHD. The test results show that the bandwidth is about 600 MHz, the quantum to classical noise ratio (QCNR) is 15.2 dB and the common mode rejection ratio (CMRR) is 41.16 dB. The performance of BHD shows that it can meet the requirements of high-speed applications in quantum information processing.

Keywords: Balanced homodyne detector; Quantum to classical noise ratio; Bandwidth; Common mode rejection ratio; Quantum information processing.

1. Introduction

Homodyne detection can effectively measure the canonical quadrature of optical field , proposed by Yuen and Chan in 1983 [1], is now widely used in quantum information processing. Such as continuous-variable quantum key distribution (CV-QKD) [2][3], vacuum-state-based quantum random number generator (QRNG) [4] and other quantum information processing. Also, in the time transfer system, which is based on phase modulation, the phase information of the signal can be provided by homodyne detector [5].

Recently, CV-QKD system with local-local-oscillator (LLO) was proposed to resist the hacking of the local-oscillator through quantum channel [6], in which wide bandwidth balanced homodyne detector (BHD) plays an important role, because BHD with wide bandwidth is the basis of realizing high repetition frequency system.

We use a pair of high quantum efficiency photodiodes and a special transimpedance amplifier HMC799 combined with the post stage voltage amplifier to construct our BHD. We design optical experiments to test the performance of BHD. The test results show that the bandwidth is about DC ~ 600 MHz, the quantum to classical noise ratio (QCNR) is 15.2 dB and the common mode rejection ratio (CMRR) is 41.16 dB. Our BHD can meet the requirement for high-speed LLO CV-QKD, and support higher synchronization accuracy of the phase modulated time transfer systems.

2. Design and Performance Analysis

In this section, the schematic diagram of our BHD is introduced, and we implement an optical layout to test the performance of our BHD.

2.1 Schematic Representation

As shown in Fig.1, the whole circuit can be divided into three parts. The first part is photoelectric conversion, which uses a pair of InGaAs photodiodes with reverse bias (HAMAMAYSU, G9801-32, bandwidth: 2 GHz, junction capacitance: 1 pF, sensitivity: 0.95 A/W@1550 nm). The photodiode converts the optical signal into current and enters the second part of transimpedance amplification. In transimpedance amplification part, the current needs to be

ISSN:2790-1688 DOI: 10.56028/aetr.1.1.131
converted into voltage and amplified. We selected ADI's transimpedance amplifier chip HMC799, which is a special transimpedance amplifier. The feedback resistor and other devices are integrated inside the chip to reduce the design complexity and external influence. The third part is the voltage amplification part. To amplify the differential mode signal and improve the common mode rejection ratio, we select the radio frequency (RF) fully differential amplification chip ADL5565. Since HMC799 is powered by a single power supply +5 V, a fixed voltage is given at the negative input to offset the DC bias voltage output by HMC799. After that, a current feedback operational amplifier OPA695 is used to convert the differential signal to single ended signal which is output through a 50 ohm resistance.

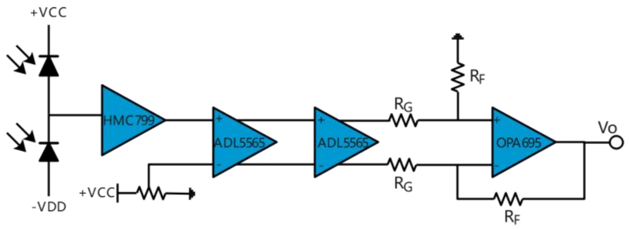

Figure 1. Simplified electronic circuit schematic of the balanced homodyne detector. The "+VCC" symbol represents the positive supply voltage and the "-VDD" symbol represents the negative supply voltage.

The optical experimental layout is shown in the Fig.2. A 1550 nm fiber coupled laser (NKT Basic E15, linewidth 100 Hz) provides continuous light (CW) and the optical power is adjusted to an appropriate value by a variable optical attenuator (VOA1). We use an amplitude modulator (AM) of Photline (MXER-LN-10,1550 nm, 10 GHz) to modulate the pulsed signal generated by arbitrary waveform generator (AWG) into local signal (LO). In the experiment, one input port of the beam splitter (BS) is not connected to provide vacuum state, and LO and vacuum state are connected to BS with a beam splitting ratio of 50:50. After that, VOA2 and VOA3 are used to eliminate the beam splitting ratio error to ensure the output arm of the optical fiber coupler being balanced. At the output of BHD, we use spectrum analyzer (Rigol DSA815) and oscilloscope (Keysight DSOS404A) to analyze the output signal in frequency domain and time domain.

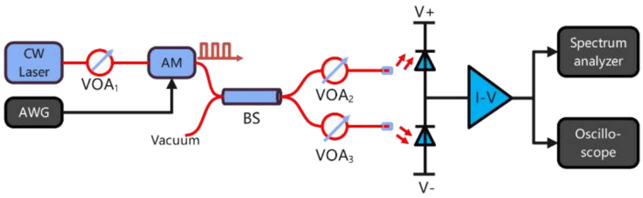

Figure 2. Diagram of the optical layout. The black lines are electrical cables and the red lines are optical paths. CW Laser: 1550 nm continuous wave fiber laser, AWG: Arbitrary waveform generator, BS: Beam splitter, VOA1,2,3: Variable optical attenuators, AM: Amplitude modulator.

ISSN:2790-1688 DOI: 10.56028/aetr.1.1.131

2.2 Bandwidth and QCNR

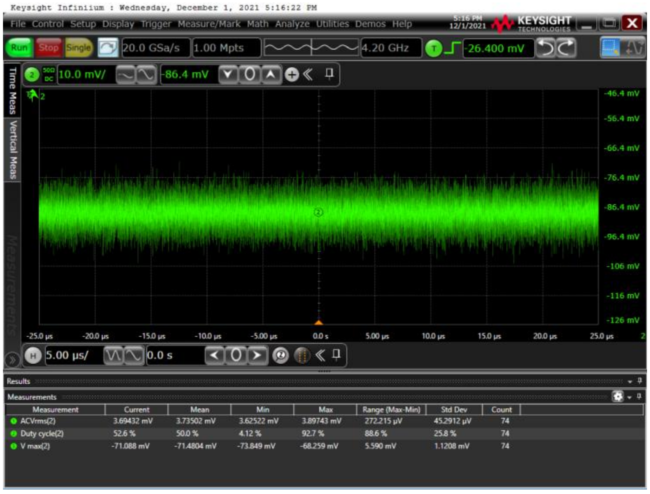

Figure 3. Root mean square (rms) electronic noise of the BHD. The Vrms value is 3.69 mV.

During this test, the optical layout is shown in Fig. 2, except for AM. We use an oscilloscope to record the electrical noise in the time domain. In Fig. 3, the root mean square value of the electrical noise is 3.69 mV. The spectrum analyzer is used in the frequency domain to record the background noise spectrum, the electrical noise spectrum of BHD and the output noise spectrum of BHD under different LO power, as shown in Fig. 4. With the increase of LO power, the output noise power of BHD will increase from kHz to 600MHz and then decrease. In the low frequency region, the 1/f noise and instrument noise are very strong, so the output covers the noise spectrum of BHD [7]. With the increase of frequency, the whole passband is flat until it reaches about 600MHz, which decreases by 3dB, i.e., the cut-off frequency of BHD.

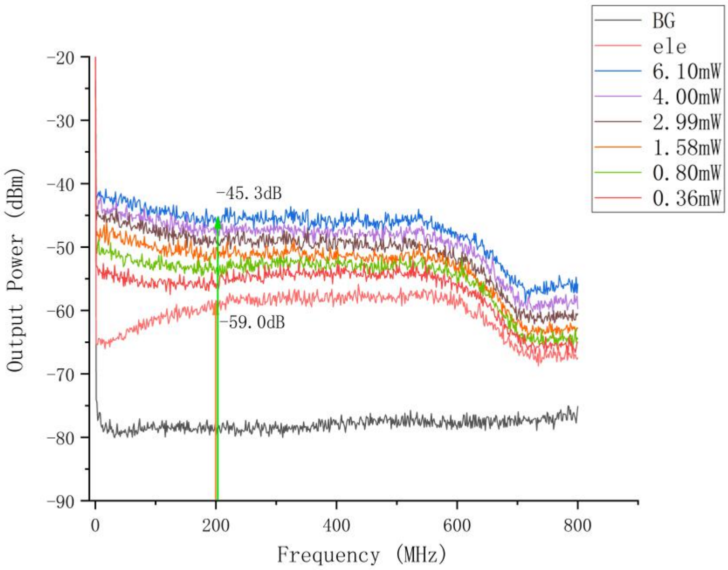

Figure 4. Measured noise power of BHD ranges from kHz to 800 MHz. Spectrum analyzer background noise spectrum (BG), BHD electronic noise spectrum (ele) and BHD noise spectrum at CW LO powers of 0.36, 0.80, 1.58, 2.99, 4.00 and 6.10 mW (from the third lowest to highest curve). Resolution bandwidth: 300 kHz.

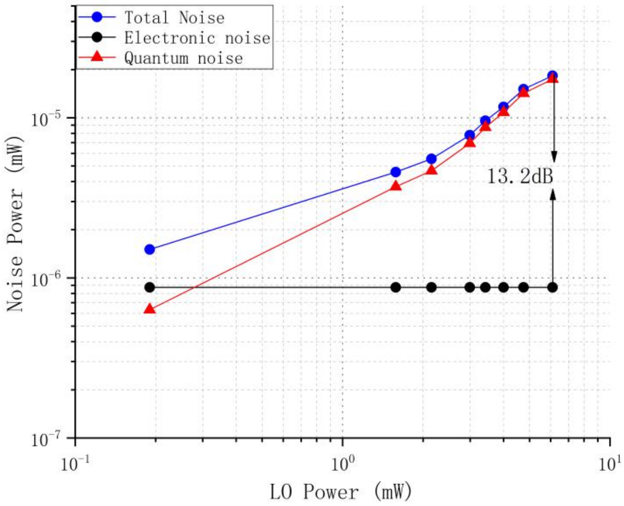

Figure 5. BHD noise power as a function of CW LO in the frequency domain. The quantum noise power to electronic noise power ratio is 13.2 dB at an LO power of 6.1 mW.

To test QCNR, we use the LO of continuous light. Because the electrical noise and quantum noise distribution obey Gaussian distribution, the noise variance is equals to the noise power [7]. The total noise includes electrical noise and quantum noise, so in order to calculate the quantum noise, the electrical noise needs to be subtracted from the total noise. In Fig. 4, we can only see the QCNR at a specific frequency, so we convert it into a more readable form. At low frequency, 1/f noise and instrument induced noise account for a large part [8]. So, we calculate the mean value of quantum noise in the frequency range of 5 MHz ~ 600 MHz. As shown in Fig. 5, when the optical power is 6.1 mW, QCNR is 13.2dB.

Similarly, we use an oscilloscope to repeat the experiment, and record the data in the time domain. The sampling rate is set as 20 GSa / s, and the time base is set to 1 us to ensure that enough data is stored. Under these test conditions, we measured the output noise voltage of BHD under different LO power. We calculate the variance of the electric noise and the variance of total noise. Also, by subtracting the variance of electronic noise from the variance of total noise, we can calculate the variance of quantum noise. As shown in Fig.6, the QCNR is up to 15.2 dB at the LO power of 4.8 mW.

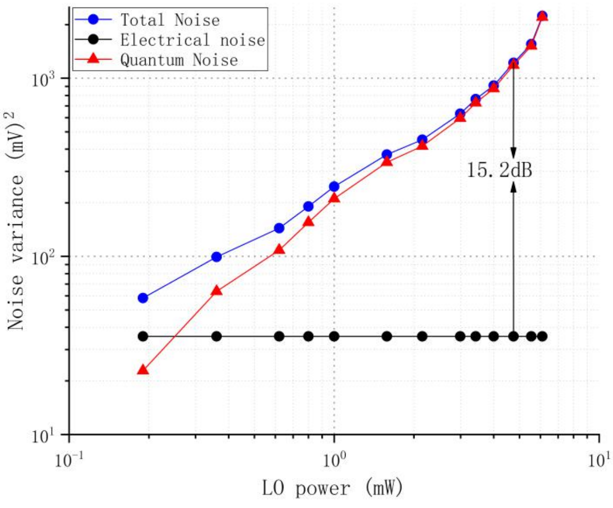

Figure 6. Noise variance as a function of the CW LO power in the time domain. The quantum noise variance to electronic noise variance ratio is 15.2 dB at an LO power of 4.8 mW.

ISSN:2790-1688 DOI: 10.56028/aetr.1.1.131

2.3 CMRR

The common mode rejection ratio (CMRR) is used to represent the ability to amplify differential mode signals, which can be obtained by calculating the difference between the differential mode signal and the common mode signal in the frequency domain [9]. To eliminate the common mode signal as much as possible, VOA2 and VOA3 need to be adjusted to obtain a small residual signal from the output of the BHD.

A square wave signal with 5MHz and 20% duty cycle is loaded on the AM, and the test results in two cases are shown in Fig. 7. When only one PD is illuminated, the differential mode signal is represented by the red curve. When two PDs are illuminated, the common mode signal is represented by the blue curve. The CMRR can be calculated according to the maximum difference of fundamental wave spectrum power, and the CMRR is 41.16 dB.

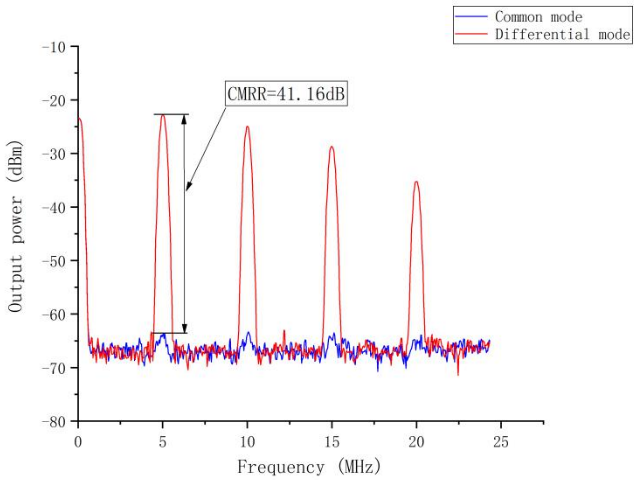

Figure 7. When only one PD is illuminated, the differential mode signal is represented by the red curve. When two PDs are illuminated, the common mode signal is represented by the blue curve. Resolution bandwidth: 300 kHz.

3. Application

In this paper, we design a balanced homodyne detector and build a test environment. The results show that the bandwidth of our design is about 600 MHz. When the local oscillator optical power is about 5 mW, the quantum to classical noise ratio can reach 15.2dB and the common mode rejection ratio is 41.16 dB.

The performance of BHD shows that using our designed BHD for continuous variable quantum key distribution (CV-QKD) is possible to reach a secret key rate of tens of MHz and a random number generation rate of about Gbps for vacuum state based quantum random number generator (QRNG). Also, in the time transfer system, our BHD can support high synchronization accuracy.

Acknowledgments

This work is supported by the Key Program of National Natural Science Foundation of China under Grant No. 61531003, National Natural Science Foundation of China under Grant No. 62001041, China Postdoctoral Science Foundation under Grant No. 2020TQ0016, Sichuan Science and Technology Program under Grant No. 2020YFG0289 and the Fund of State Key Laboratory of Information Photonics and Optical Communications.

ISSN:2790-1688 DOI: 10.56028/aetr.1.1.131

References

[1] H. P. Yuen and V. W. Chan, “Noise in homodyne and heterodyne detection,” Optics Letters. 8, 177–179 (1983)

[2] S. Pirandola, U. L. Andersen, L. Banchi, M. Berta, D. Bunandar, and R. Colbeck, et al, “Advances in quantum cryptography,” Advances in Optics and Photonics. 12, 1012-1236 (2020)

[3] X. Feihu, M. Xiongfeng, Z. Qiang, L. Hoikwong and P. Jianwei, “Secure quantum key distribution with realistic devices,” Reviews of Modern Physics. 92, 025002 (2020)

[4] Z. Ziyong, Z. Yichen, H. Weinan, Y. Song, and G. Hong, “6 Gbps real-time optical quantum random number generator based on vacuum fluctuation,” Review of Scientific Instruments. 90, 043105 (2019)

[5] W. Jialiang, Y. Chaolei, X. Yueli, S. Yanguang, C. Nan, and Y. Fei, et al, "Fiber-optic joint time and frequency transfer with the same wavelength," Optics Letters. 45, 208-211 (2020)

[6] H. Peng, H. Jingzheng, W. Tao, L. Huasheng, H. Duan, and Z. Guihu, “Robust continuous-variable quantum key distribution against practical attacks,” Physical Review A. 95, 052302 (2017)

[7] Z. Xiaoxiong, Z. Yichen, L. Zhengyu, Y. Song, and G. Hong, “1.2-GHz Balanced Homodyne Detector for Continuous-Variable Quantum Information Technology,” IEEE Photonics Journal. 10. 1-10 (2018)

[8] Y. Chi, L. Tian, B. Qi, L. Qian, and H. Lo, High Speed Homodyne Detector for Gaussian-Modulated Coherent-State “Quantum Key Distribution,” Univ. Toronto, Toronto, ON, Canada (2009).

[9] J. Xiaoli, S. Jing, Z. Yaohui, C. Chaoyong, W. Wenzhe, and P. Kunchi, "Balanced homodyne detection with high common mode rejection ratio based on parameter compensation of two arbitrary photodiodes," Optics Express. 23, 23859-23866 (2015)