

Balanced homodyne detection with high common mode rejection ratio based on parameter compensation of two arbitrary photodiodes

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Abstract: A balanced homodyne detector, with a maximum common mode rejection ratio and clearance of 75.2 dB and 37 dB, is experimentally obtained with two arbitrary photodiodes of the same model. On the basis of self-subtraction photodetector scheme, we divide the influence of photodiodes on the common mode rejection ratio into two parts, including magnitude and phase of output signal. The discrepancy of quantum efficiency and dark current affects magnitude of output signal of photodiodes, which is compensated by adjusting the splitter ratio. The difference of the equivalent capacitance and resistance affects the phase of output signal of photodiodes, which is compensated by the differential fine tuning circuit and adjustable bias voltage circuit. With these designs, the developed homodyne detector can be used for measuring accurately the squeezed state.

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OCIS codes: (040.5160) Photodetectors; (040.5570) Quantum detectors; (270.5570) Quantum detectors; (270.5585) Quantum information and processing; (270.6570) Squeezed states.

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1. Introduction

Squeezed state of light is an important resource for quantum information processing for continuous variables [1]. For example, quadrature squeezed vacuum states are applied to realize quantum teleportation which is a fundamental protocol in quantum information processing [2–4]. The fidelity of such protocols is limited by the measured value of squeezing level. So it is very important not only to generate highly squeezed light [5] but also to measure accurately the highly squeezed light. A typical method to generate highly squeezed light is utilization of sub-threshold optical parametric oscillator (OPO). By improving the stability of phase locking and reducing the system loss, the factor of 9 dB at 860 nm [6] and the factor of 12.3 dB at 1550 nm [7] quantum noises squeezing of a laser field were observed, respectively.

At the same time, many dedicated researches have been developed in order to explore an effective detection method and a high-performance photodetector for measuring accurately quantum noise suppression [8]. Measuring the quantum noise requires that all classical noise terms, such as laser intensity noise and electronic noise, are reduced to a level well below the noise level of interest [9]. Balanced homodyne detection (BHD) method 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 [9, 10].

Electronic noise and gain of the photodetector set a strong limit to the measurement of quantum noise. In order to reduce the influence of the electronic noise on the measured value, the photodetector should be designed to make the clearance between shot noise and electronic noise much higher than the amount of squeezing one wishes to measure. The condition can be achieved by boosting the detector gain and reducing the electronic noise. For this purpose, our group has designed a low-noise, high-gain photodetector based on the bootstrap structure with a clearance of 21 dB for 410 μ W injected power [11]. Subsequently, by adopting a junction field-effect transistor (JFET) buffering input, we suppress further the electronic noise of the photodetector, extend the dynamic range to 11.22 mW with a clearance of 36 dB [12]. However, these works described above do only improve the performance of single photodetector, not consider how to compensate the combined effect of different photodiodes and electronic components of twin photodetectors. By choosing matching photodiodes and electronic components, 28 dB of common mode rejection ratio (CMRR) was obtained.

A high CMRR, the measurement of the ability of the balanced homodyne to reject signals common to both photodetectors, is necessary to eliminate the influence of classical noise from the local oscillator and measure accurately the highly squeezed light [9]. In order to improve the CMRR, a single electronic board design [9, 13, 14] is usually adopted, where the photocurrents of both photodiodes are directly subtracted from each other before any further electronic

signal processing. However, according to the equivalent circuit of photodiode, its parameters include quantum efficiency (QE), equivalent capacitance and equivalent resistance etc, which are very difficult to compensate completely the discrepancy, or expensive for selecting a pair of photodiodes from a larger purchased batch [13]. Thus, there should be an effective method of compensating these parameters and obtaining conveniently higher CMRR by using two arbitrary photodiodes with the same model.

In this paper, we analyze theoretically the influence of unequal equivalent capacitance and resistance of two photodiodes on the CMRR. By adding the differential fine tuning circuit (DFTC) between two photodiodes and setting adjustable bias voltage (ABV) on each photodiode, phase discrepancy of output current signal of both photodiodes induced from unequal equivalent resistance and capacitance in the case of self-subtraction photodetector scheme is compensated. Combined with low-noise, high-gain design in the former works [11, 12], a balanced homodyne detector, with the feature of low-noise, high-gain, and high CMRR, is experimentally obtained. We fix two arbitrary photodiodes (ETX500) in the photodetector, a maximum CMRR of 75.2 dB is obtained, which shows that the DFTC and ABV are effective methods of compensating the difference of photodiodes.

2. Compensation model and circuit

In the BHD, the weak signal field, whose noise properties one wishes to measure, and a bright local oscillator, used to amplify and probe the signal field, interfere on a beam splitter. In order to suppress completely the classical noise of the local oscillator, balancing the current signal of two ports is crucial to the performance of the balanced homodyne detection, that is, a high CMRR. A self-subtraction photodetector scheme, shown in Fig. 1, is widely adopted, which can eliminate effectively the influence of electronic components tolerance. However, choosing two photodiodes with same parameter faces the challenge. The process of increasing the CMRR, is a combination of means, including optical method and electronic method on the premise of no additional loss, whose purpose is to compensate the mismatch in two photodiodes.

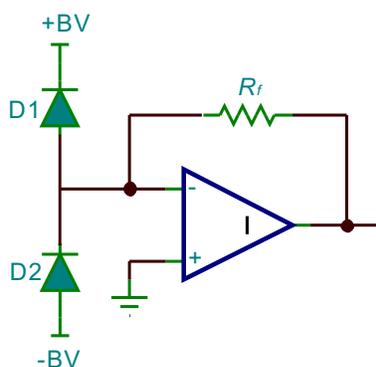


Fig. 1. The self-subtraction photodetector scheme.

According to the photodiode theory [15], a photodiode can be represented by current source in parallel with an ideal diode. The current source represents the current generated by the incident radiation. The diode represents the p-n junction, which is equivalent to a junction capacitance and a shunt resistance in parallel with the other components, as well as a series resistance in series with all components. Thus, a photodiode has the equivalent circuit shown in Fig. 2. The current I_s is dependent upon the optical power and QE, whose capability is to convert the number of the incident photons to the number of electrons or holes. For the same optical power,

unequal QE can induce on the different current, which decreases the CMRR of BHD with the increase of discrepancy. The signal current is superposed with the discrepancy of the dark current I_d , which will aggravate further the CMRR. The discrepancy of QE and dark current can be compensated by adjusting finely the splitter ratio of beam splitter.

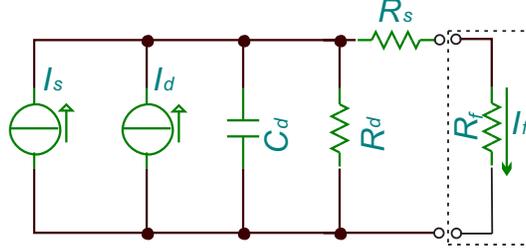


Fig. 2. The equivalent circuit of a photodiode. I_d : dark current that is current when no light is present; I_s : signal current; C_d : junction capacitance; R_d : shunt resistance; R_s : series resistance; R_f : load resistance.

According to the equivalent circuit of the photodiode, the effective output current I_f flowing through load resistance can be calculated as:

$$I_f = (I_s + I_d) \frac{R_d (R_d + R_s + R_f) - jR_d^2 (R_s + R_f) \omega C_d}{(R_d + R_s + R_f)^2 + R_d^2 (R_s + R_f)^2 \omega^2 C_d^2} \quad (1)$$

Where $\omega = 2\pi f$ is analysis frequency. The phase of output current signal can then be expressed below,

$$\varphi_f = -\arctan \frac{R_d (R_s + R_f) \omega C_d}{R_d + R_s + R_f} \quad (2)$$

In expression (2), the value of the shunt resistance R_d is usually high (2E8 Ohms), the series resistance R_s (several ohms) and the load resistance R_f (kilo ohms) are comparably very low. So the formula can be simplified as:

$$\varphi_f = -\arctan[(R_s + R_f) \omega C_d] \quad (3)$$

It can be seen, from expression (3), that the phase of output current signal depends on the equivalent capacitance, series resistance and load resistance. The load resistance is common to two photodiodes, which does not affect the final phase discrepancy. So the phase discrepancy is only induced from the unequal equivalent capacitance and series resistance between two photodiodes for self-subtraction photodetector scheme. According to the definition of CMRR and expression (3), if we want to obtain a CMRR of 73 dB at $R_f = 100 \text{ k}\Omega$ and $f = 2 \text{ MHz}$, the tolerance of the equivalent capacitance of two photodiodes is only 0.01 pF at 43 pF under the condition of the same series resistance. It is very difficult to meet the requirements by choosing suitable photodiodes.

According to the theoretical background about the the relationship between equivalent capacitance and bias voltage [16], the equivalent capacitance C_d can be expressed by:

$$C_d = \frac{\epsilon_0 \epsilon A}{d} = \frac{\epsilon_0 \epsilon A}{\sqrt[2]{2\epsilon_0 \epsilon \mu \rho (V + V_{in})}} \quad (4)$$

Where ϵ_0 is the permittivity of free space, ϵ is the material dielectric constant, A is the diffused junction area, d is the depletion layer depth, μ is the mobility of the electrons at 300

K , ρ is the resistance of the material, V_{in} is the built-in voltage of photodiode. The capacitance C_d is dependent on the depletion layer depth d and hence bias voltage V , so the difference of the equivalent capacitance can be compensated by changing bias voltage imposed on each photodiode, which are supplied by two stable sources (named as ABV) with the adjustable range of $3 \sim 15$ V and $-15 \sim -3$ V, respectively. It can be seen, from expression (4), that the variation of the equivalent capacitance ranges approximately from C_d to $5C_d/11$ with the adjustable bias voltage range of $3 \sim 15$ V. When the ratio of the equivalent capacitance of two photodiodes is more than $5/11$, our scheme can compensate effectively the difference.

In order to eliminate the discrepancy of the series resistance, we design a DFTC, and then add the circuit between two photodiodes, the scheme is shown in Fig. 3. In the DFTC, Fixed resistors R_5 , R_7 are used to compensate coarsely the series resistance, make the resistance approximately same above and below joint Z, lack of the adjustable resistor P_1 . The function of the adjustable resistor P_1 is to finely tune the resistance, as a result, the series resistance above and below joint Z are strictly equal. On the basis of the above analysis, the phase discrepancy can be finely compensated by the ABV and DFTC.

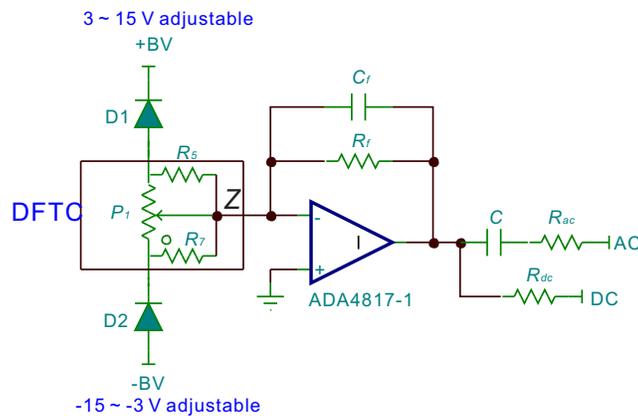


Fig. 3. The schematic of photodetector with the DFTC and ABV.

3. Experimental setup and regulation procedure

We design and build the photodetector with focus on fine balancing of the photocurrents from the electronic aspects in Fig. 3. The scheme, shown in Fig. 4, is constructed to test the performance of the photodetector. A single-frequency Nd:YVO₄ laser at 1064 nm with coherent output is applied as light source. The intensity of the output laser is precisely adjusted with power adjustment system consisting of a half-wave plate (HWP1) and a polarization beam splitter (PBS1). The combination of HWP2 and PBS2 is used to generate an optical input linearly polarized at 45° injected to electro-optic amplitude modulator (EOAM), so as to measure the CMRR of the balanced homodyne detector, the EOAM is modulated by a signal generator connected with its RF input connector. The most important optical aspect of the detector is based on a 50/50 beam splitter consisting of HWP3 and PBS3, which can be used to finely tune the splitting ratio by rotating the HWP3. Output beams from optical beam splitter are injected into two photodiodes after being focused with Lenses L1 and L2. The DC (direct current) output of photodetector is connected with a digitizing oscilloscope (OSC) to verify whether the light is thoroughly received by each photodiode, The AC (alternating current) is connected with a spectrum analyzer (N9320A, Agilent) to read the balanced state, respectively. In our photodetector, two InGaAs photodiodes (JDSU ETX500) are used as optical receiver. One of the photodiodes

D1 has the parameters of $I_d = 0.429$ nA, $C_d = 43.578$ pF, $R_d = 205.25$ M Ω , $R_s = 1.3$ Ω , QE = 83.6%. The other photodiode D2 has the parameters of $I_d = 0.242$ nA, $C_d = 48.957$ pF, $R_d = 177.07$ M Ω , $R_s = 1.6$ Ω , QE = 86.3%. All these parameters above show the large discrepancy of two photodiodes. According to the definition of CMRR and expression (3), we calculate that the CMRR is only 18 dB at $R_f = 100$ k Ω and $f = 2$ MHz. We can not obtain high CMRR by using self-subtraction scheme.

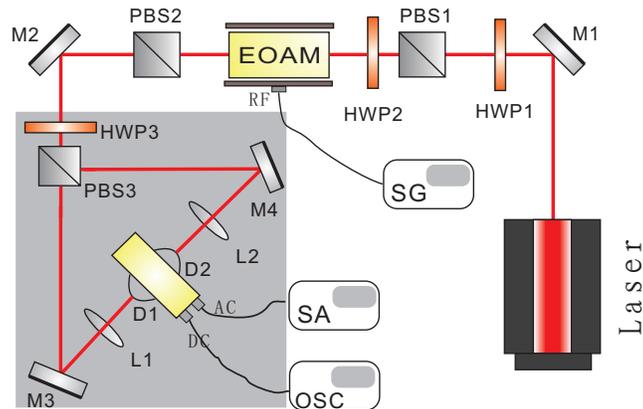


Fig. 4. Experimental setup for regulation procedure. HPW: half-wave plate; PBS: polarization beam splitter; EOAM: electro-optic amplitude modulator; D: ETX500 InGaAs photodiode; SA: spectrum analyzer; OSC: digitizing oscilloscope; SG: signal generator.

In our photodetector, by adding the ABV and DFTC, the discrepancy between the two photodiodes can be effectively compensated. The regulation procedure is shown below. Firstly, we read the differential mode signal from spectrum analyzer, and tune finely the splitting ratio at the same time. When the differential mode signal reaches minimum value, the discrepancy of QE and dark current is compensated by the splitter ratio. Secondly, balancing further the photodetector is performed by setting different bias voltage on photodiodes. The success of the balancing process is confirmed at the spectrum analyzer by monitoring the differential mode signal to further reduce the value. At last, we continue to balance the photodetector by changing the parameter of DFTC. On the basis of the equivalent series resistance, balancing roughly the equivalent resistance is achieved by choosing fixed resistors $R_5 = 3.3$ Ω and $R_7 = 3$ Ω , respectively. Balancing finely the equivalent resistance is achieved by adjusting adjustable resistor P_1 (with the tunable range of $0 \sim 10$ Ω). The tolerance of series resistance ranges from 0 to 2.48 Ω . Considering the mutual-influence of bias voltage, resistance and dark current, we repeat the three steps above at least three times to reach eventually the optimal CMRR.

4. Experimental results

A typical result of the balancing process at the spectrum analyzer is shown in Fig. 5. Curve a, corresponding to common mode signal, indicates the noise spectrum of the unbalanced detector (one photodiode blocked, the other photodiode illuminated at the power of 500 μ W) with a total power of 1 mW. The peak is visible that correspond to the modulation frequency (2 MHz) of loading on the EOAM. Curve b, corresponding to differential mode signal, shows the noise spectrum of the balanced detector (two photodiode illuminated at the power of 500 μ W, respectively). Curve c is the electronic noise spectrum of the balanced homodyne detector without any light signal. Curve d is the internal noise of spectrum analyzer. The amount of signal subtraction from both photodiodes can be characterized by the CMRR, which is defined

as the ratio of the power measured on one detector when the other is blocked by the power measured when both photodiodes are illuminated. We can see, from Fig. 5, that the CMRR is 75.2 dB at 2 MHz. Such high CMRR can reduce effectively the deviation between the measured value and real value. However, the measured CMRR is only 20 dB, when the above-mentioned photodiodes are used in conventional self-subtraction scheme.

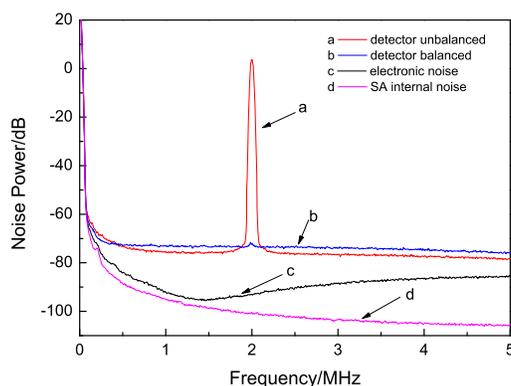


Fig. 5. The typical result of the balancing process. Curve a, the spectrum of the unbalanced detector (one photodiode blocked, one photodiode illuminated); curve b, the spectrum of the balanced detector (two photodiodes illuminated); curve c, the electronic noise spectrum (two photodiodes blocked); curve d, the spectrum analyzer internal noise.

In addition, we checked the linearity of the balanced homodyne detector by measuring the shot-noise levels versus local oscillator powers, the results are shown in Fig. 6. With the local oscillator power double increased, a clearance of 3 dB at 2 MHz could be obtained from the clearance of 20 dB for 1 mW to the clearance of 35 dB for 32 mW. The maximum clearance of 37 dB at 2 MHz is obtained at a saturation power of up to 54 mW. The results show that the photodetector can operate linearly in larger power range, and have a larger clearance to mitigate the influence of dark noise.

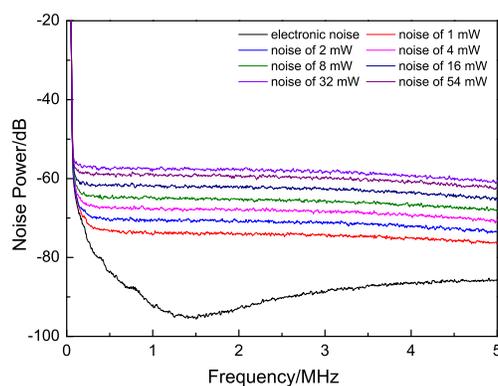


Fig. 6. Linearity and clearance of the balanced homodyne detection system.

5. Conclusion

In conclusion, a balanced homodyne detector, with the feature of low-noise, high-gain, and high CMRR, is experimentally obtained with two arbitrary photodiodes of the same model, with a maximum CMRR and clearance of 75.2 dB and 37 dB, respectively. In addition, the photodetector can operate linearly in large power range. Based on bootstrap structure and junction field-effect transistor (JFET) buffering input proposed in our former works [11, 12], larger clearance (depend on the gain and electronic noise) is achieved. According to the equivalent circuit of photodiode, these parameters, including mainly quantum efficiency, dark current, equivalent capacitance and resistance of two photodiodes, affect the CMRR on the self-subtraction photodetector scheme. The discrepancy of quantum efficiency and dark current affects the magnitude of output signal of photodiodes, which is compensated by adjusting the splitter ratio of beam splitter. We design the ABV circuit and DFTC to compensate the unequal equivalent capacitance and resistance, respectively. The difference of the equivalent capacitance can be compensated by changing bias voltage imposed on each photodiode. In the DFTC, Fixed resistors R_5 , R_7 are used to compensate coarsely the series resistance, the adjustable resistor P_1 is the fine adjustment element, as a result, the resistance above and below joint Z is strictly equal. In comparison to the self-subtraction detector without the DFTC and ABV, the CMRR is largely extended from original 20 dB up to 75.2 dB. With these parameters, the developed homodyne detector can be used for measuring accurately the squeezed state.

Acknowledgments

This research is supported in part by the National Natural Science Foundation of China (Grant No. 61575114, 61405107, 11504220), in part by the Program for Outstanding Innovative Teams of Higher Learning Institutions of Shanxi, and in part by the Natural Science Foundation of Shanxi Province, China (Grant No. 2015021022, 2014021011-3).