High-speed Balanced Homodyne Detector for Quantum Information Applications

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Abstract. We have developed a balanced homodyne detector capable of working with femtosecond pulsed light at a 76MHz repetition rate and 800nm wavelength. It exhibits a common mode rejection ratio of 55dB, and can achieve the shot-noise limit. Provided with good performance, our detector can be used in high speed quantum information applications.

1. Introduction
With the powerful ability of demonstrating complete characterization of a quantum light state, high-speed balanced homodyne detection is essential for foundational analysis of quantum optics on many areas, such as quantum process tomography, quantum key distribution and quantum precision measurement. By measuring the quadrature operators of the input signal state, the balanced homodyne detector can then obtain the quasi probability distribution or in other words, the Wigner function after kinds of quantum state tomography [1]. The first experiment determining the quantum state of light field was proposed by Smithy, Beck, Cooper, Raymer, et al in 1993 [1,2]. Nowadays, the quantum state tomography with balanced homodyne detector has become a standard method in quantum information field.

Over the past decades, remarkable effort has been made to make a balanced homodyne detector with satisfactory performance applying to various applications [3]. Conventionally, researchers use a circuit with a dual-stage amplifier to gain higher magnification and stability, but this design will bring extra noise as well. In our experiments, a single-stage simple-construct amplifier homodyne detector was also found able to satisfy the performance requirements of homodyne detectors: (a) low enough electrical noise competent to beat the shot-noise limit which is the key requirement to make a quantum measurement; (b) high enough bandwidth to distinguish 76 MHz repetition rate femtosecond optical pulse; (c) high common mode rejection ratio (CMRR) to make a balance between the two photodiodes [1].

2. Theoretical analysis
Depicted in the Fig. 1 is a simple layout of balanced homodyne detector. The signal $\hat{\rho}_s$ and the much more powerful local oscillator $|\alpha\rangle_L$ are combined on the 50:50 beam splitter, resulting in two output lights $\hat{b}_1$ and $\hat{b}_2$ which are collected by two photodiodes respectively. The photocurrent from D1 and D2 are subtracted finally to get a difference current $\hat{I}$ which will collected by our circuit and oscilloscope.
Figure 1. Principle diagram of the balanced homodyne detector.

We use the annihilation operators of the input and output field here for convenience. The transformation over a 50:50 beam splitter follows the rule:

\[
\hat{b}_1 = \frac{1}{\sqrt{2}} (\hat{a}_1 + \hat{a}_2),
\]

\[
\hat{b}_2 = \frac{1}{\sqrt{2}} (\hat{a}_1 - \hat{a}_2);
\]

According to the rules in equation (2.1) and (2.2), we can derive the difference photocurrent operator \( \hat{I} \):

\[
\hat{I} = \hat{b}_1^\dagger \hat{b}_1 - \hat{b}_2^\dagger \hat{b}_2
\]

\[
\hat{I} = \hat{a}_1^\dagger \hat{a}_2 + \hat{a}_2^\dagger \hat{a}_1
\]

Considering the local oscillator \( \hat{a}_1 \) is a strong coherent state \( |\alpha\rangle_{LO} \) which has the eigenvalue relations with the annihilation representation:

\[
\hat{a} |\alpha\rangle = \alpha |\alpha\rangle, \quad \langle \alpha |\hat{a}^\dagger = \langle \alpha |\alpha^*;
\]

where \( \alpha = |\alpha|e^{i\theta} \), and \( \theta \) is the local oscillator phase relative to the signal, we can infer the expected photocurrent difference \( \langle \hat{I} \rangle \):

\[
\langle \hat{I} \rangle = |\alpha|((\hat{a}_2^\dagger + \hat{a}_2)cos\theta + (\hat{a}_2^\dagger - \hat{a}_2)sin\theta)
\]

Replacing the annihilation operators with the quadrature operators defined by equation (2.7) and equation (2.8), we have another representation of \( \langle \hat{I} \rangle \) in equation (2.9),

\[
\hat{X} = \frac{1}{2}(\hat{a}_2^\dagger + \hat{a}_2)
\]

\[
\hat{Y} = \frac{1}{2}(\hat{a}_2^\dagger - \hat{a}_2)
\]

\[
\langle \hat{I} \rangle = 2|\alpha|(\hat{X}cos\theta + \hat{Y}sin\theta)
\]

From equation (2.9), we can get the phase space information of signal mode \( \rho_s \) in a phase \( \theta \), and by scanning the local oscillator through \( 2\pi \), the complete information about the signal quadrature distribution is confirmed from which the quasi probability distribution can be inferred[1].

3. Experiment Design
The schematic of detector circuit is shown in figure 1(a), two p-i-n photodiodes (Hamamatsu S3883) are wired in series to gain the difference current which is then sent to the high-bandwidth, low-noise operational amplifier (Texas Instruments OPA847) to gain a desirable amplification. Then, the voltage output is collected by oscilloscope (Agilent MSO-X 3034A) through a 50 Ohm coax. The choice of the two photodiodes are extremely strict to reach perfect subtraction, the photodiodes should exhibit similar temporal response characteristics and quantum efficiency.

![Figure 1a](image1.png)

**Figure 1.** (a) Schematic of detector circuit which shows the main component only. (b) Optical setup of balanced homodyne detector. We use a 78MHz repetition rate, 830nm wavelength, mode-lock Ti:Sapphire laser from Coherent.

The optical setup is shown in figure 1(b), half-wave plate 1 (HWP1), HWP2 and polarization beam splitter 1 (PBS1) control the local oscillator (LO) power, while HWP1, HWP3 and PBS1 control signal power. The LO and signal are sent into PBS2 separately, care was taken to ensure both temporal and spatial mode of LO and signal should be overlapped. So, we use a travel stage as illuminated in figure to control temporal overlap and use a fiber coupler (not shown here) to control spatial overlap. The combination of HWP4 and PBS3 is used to make up a 50:50 beam splitter, HWP4 is nominally set at 22.5° to the horizontal. Finally, the two beams splt by PBS3 go into the two photodiodes respectively. To achieve a perfect balance, the route paths after PBS3 should be equal and the spot size focused on the photodiodes should be equal too.

Among the ten photodiodes (S3883) at our disposal, we have to pick the two matching best, which indicates how well the common mode component is being cancelled. There are two most important factors we took into consider: the quantum efficiency and the pulse delay. We measured the output of the detector with each photodiode on one socket while the other socket in idle and pick the two photodiodes whose output are the most similar.

### 4. Performance and Characterization

The most critical requirement of the homodyne detector is shot-noise limit performance which shows the ability of detecting quantum field of light instead of the classical field [3]. From Eq. (2.5), we can calculate the variance of the output current as shown in equation (4.1), where \( \hat{X}_\theta = \hat{X}_{\cos \theta} + \hat{Y}_{\sin \theta} \):

\[
var[I] = 4P_{LO}var[\hat{X}_\theta]
\]  

(4.1)

In the non-ideal condition, there is also some constant noise from the circuit itself \( var[e] \), so the final variance is:

\[
var[I] = 4P_{LO}var[\hat{X}_\theta] + var[e]
\]

(4.2)
Figure 3. Plot of detector output variance as a function of the LO power. A balanced homodyne detector which is set in the linear range will work well in quantum field detection [3].

It’s clear that in a well worked balanced homodyne detector the output variance should be proportional to the local oscillator power. With the signal route blocked, we get the output variance on different LO powers, one thing notable here is that the output variance is variance of the integral of detector output over the laser pulse duration. Shown in Fig.3 is the shot-noise limit performance of our detector, apparently, it has a long enough linear range to detect quantum field light.

Figure 4. Inset figure is the time domain of the output of each photodiode and the final output after balancing. The main figure is the frequency spectrum of balanced output (red line) and unbalanced output (blue line).

The CMRR is another parameter we must pay attention to, it represents the ability of efficiently performing the difference between the amplitude fluctuations of the beams impinging on the two photodiodes. The time-domain outputs of balanced and unbalanced (one of the photodiodes is blocked) condition is plotted in small figure of the Fig. 4, and we plot the frequency domain in the larger figure,
the value at 76MHz of unbalanced output is -10.72dBm and the balanced output is -65.76dBm. According to its definition in Eq. (4.3), the CMRR is the difference of output power between the balanced and the unbalanced frequency spectrums value [5], thus is 55.04dB.

\[
CMRR_{dB} = 20 \log_{10} \frac{V_{\text{unbalanced}}}{V_{\text{balanced}}}
\]  

(4.3)

We compare the performance of our detector with the others, it can be seen that our detector achieves both the high speed and high CMRR. Shown in table.1 is the performance comparison between some other high-speed homodyne detectors.

|                  | Ours  | [4]   | [5]   | [6]   |
|------------------|-------|-------|-------|-------|
| Wavelength (nm)  | 800   | 1550  | 780   | 786   |
| Repetition rate (MHz) | 76    | 32    | 76    | 82    |
| CMRR (dB)        | 55    | 46.0  | 52.4  | 42    |

5. Summary
In conclusion, we demonstrate a simpler single-stage balanced homodyne detector, all of whose components are usual and easy to get. We present most of the key details essential for the detector building and some parameters we attach importance to. With a CMRR of 55dB and long enough linear area in its shot-noise limit figure, our detector is capable of quantum field detection.

6. Acknowledgment
This work is supported by the National Natural Science Foundation of China (Grant No. 11404040, No. 91536113 and No. 11474159).

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