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Ultrastable Fiber-Based Time-Domain Balanced Homodyne Detector for Quantum Communication *

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We present an ultrastable fiber-based time-domain balanced homodyne detector which can be used for precise characterization of pulsed quantum light fields. A variable optical attenuator based on bending the fiber is utilized to compensate for the different quantum efficiencies of the photodiodes precisely, and a common mode rejection ratio of above 76 dB is achieved. The detector has a gain of 3.2 μV per photon and a signal-to-noise ratio above 20 dB. Optical pulses with repetition rates up to 2 MHz can be measured with a detection efficiency of 66%. The stability of the detector is analyzed via an Allan variance measurement and the detector exhibits superior stability which enables a 100-s window for measurement without calibration.

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Time-domain shot noise limited balanced homodyne detectors (BHD) can give the field quadrature values of pulsed quantum light fields directly and play an important role in quantum communication[1−4] and quantum tomography,[5−8] etc. With the rapid progress in quantum information science, the time-domain BHDs have attracted more attention. For example, in all-fiber continuous variable quantum key distribution systems, where the receiver Bob needs to measure the quadratures of the signal field in which random numbers are encoded, fiber-based BHDs with high stability, low electronic dark noise, high common mode rejection ratio (CMRR) are required.

The time-domain BHDs can be divided into two types according to the different ways of integrating the difference photon-current produced by the two photodiodes, one is based on charge sensitive preamplifier (CSP),[5,9−11] and the other is based on a transimpendance preamplifier (TP) or voltage preamplifier (VP).[12−16] For the CSP BHDs, the photon-current is integrated on the feedback capacitor of the CSP and the peak value of the BHD output pulse is linearly proportional to the quadrature value of the signal field. The first time-domain shot noise limited BHD was based on CSP, it has a subkilohertz repetition rate and a shot noise to electronic noise ratio of 9 dB.[5] Hansen *et al.*[9] also built a BHD of this type working at a repetition rate of 204 kHz with a shot noise to electronic noise ratio of 14 dB.

For TP or VP BHDs, when the pulse duration of the incident light is much longer than the response time of the photodiode,[12] and the field quadrature value is proportional to the area under each output electric pulse, one has to collect plenty of data points for each pulse and sum the sample points together to acquire a single value of the signal field quadrature. Although this kind of BHD allows a repetition rate above tens of MHz, high speed data acquisition which should be much higher than the pulse repetition rate and post-processing are necessary. This is quite different from that of a CSP BHD where only the peak value of the output electric pulse is measured and the system cost and complexity can be decreased significantly. For TP or VP BHDs, there also exists another kind of situation where the pulse duration of the input light is shorter than the response time of the photodiode.[13−16] In such a situation, the photodiode's junction capacitance will integrate the difference photon-current and the peak value of output electric pulse is proportional to the signal field's quadrature value. It is known that good linearity is necessary to ensure that the BHD output is proportional to the signal field quadrature. However, when very short optical pulses are incident on the photodiodes, the high peak power will saturate the photodiodes easily and also lead to poor matching of the photodiode responses.[12]

In this Letter, we present an ultrastable fiber-based time-domain CSP BHD, which can be applied in continuous variable quantum communication. The detector exhibits a gain of 3.2 μV per photon, common mode rejection ratio of above 76 dB, and signal-to-noise ratio above 20 dB. Optical pulses with repetition rates up to 2 MHz can be measured with a detection

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efficiency of 66%. The stability of the detector in various time scales is studied by using Allan variance, and the superior stability of the detector enables a 100-s window for measurement without calibration.

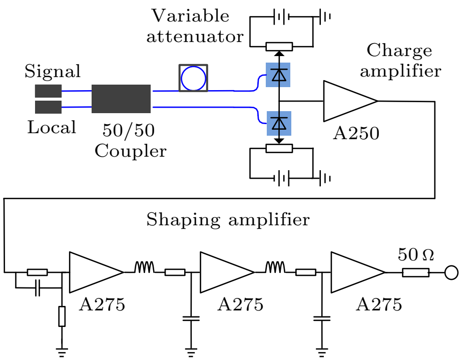

Fig. 1. The schematic diagram of the fiber-based time-domain BHD.

The schematic diagram of the CSP BHD is shown in Fig. 1. The signal and local oscillator (LO) pulses interfere at a 50/50 fiber splitter. For a shot-noise-limited BHD, high CMRR is critical and this means that the optical power of the two output pulses of the fiber splitter should be precisely balanced. In our experiment, a high balanced 50/50 fiber splitter with two equal-length output fiber pigtails was adopted. To compensate for the slight imbalance of the beam splitter and that of the photodiodes quantum efficiency, a variable optical attenuator (VOA) based on bending the fiber was utilized,[11,17] where the variable attenuation was achieved by changing the radius of the bending fiber. Furthermore, to balance the slightly different arrival times of the incident optical pulses, the photodiodes response can be precisely tuned by adjusting their bias voltage. Due to the junction capacitance of the photodiode, there exists a delay between the incident optical signal and the converted electric signal. By varying the applied bias voltage, the junction capacitance can be easily tuned and this will further modify the delay. The techniques adopted above do not need excess optical components which will introduce more losses and instability, and have the merits of high precision and superior stability.

In order to decrease the electronic noises from the power supply, we used batteries to provide the bias voltages to the InGaAs photodiodes (Thorlabs, FGA04). To minimize the parasitic capacitance the pins of the photodiodes should be cut as short as possible and close to the CSP. Due to the low dark current (below 1 nA), the common terminals of the photodiodes were connected directly to the input of the charge amplifier (Amptek A250) to achieve a lower electronic noise instead of connecting through a capacitance.[9] When a capacitance is employed, the bias voltages of the photodiodes are not only determined by the battery voltage, but also affected by the capacitor. The bias voltage will drift during the charging and discharging of the capacitor; such effect will induce instability of the detector. The difference current from the photodiodes was integrated by the CSP and an electrical pulse was generated. The electrical pulse was further transformed to a Gaussian shaped pulse by a shaping network (Amptek A275). To achieve a good output pulse shape, the photodiodes were carefully selected with almost identical response functions which are also important for a high CMRR. The output terminal terminated with a 50 Ω resistor. To avoid electromagnetic interference from the environment, the detector was enclosed in a shielding metal box.

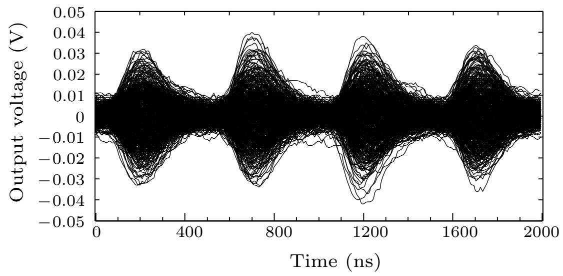

Fig. 2. Time traces of the homodyne detector output at a repetition rate of 2 MHz (The LO power is 5.7×10^6 photons per pulse).

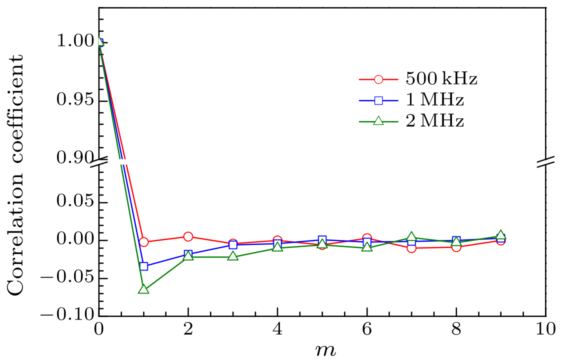

Fig. 3. Correlation coefficient at different repetition rates for vacuum field input.

To evaluate the BHD's performance, a 1550 nm single frequency pulsed laser was employed. Figure 2 shows typical time-traces of the detector for vacuum state input. The input optical field has a pulse width of 100 ns and a repetition rate of 2 MHz. The full width of the output electrical pulse is about 500 ns. From Fig. 2 we can see that the mean value of the output electric pulse is zero. If the output pulses of the fiber splitter are not balanced, the mean value will depart from zero. This zero-point drift can be solved using the VOA. If the arrival times of the incident optical pulses are not consistent, the upper part and lower part of the traces in Fig. 2 will separate along the time axis and it can be recovered by adjusting the bias voltage. The peak value of each electrical pulse gives a quadrature measurement for the signal field with a gain of 3.2 μV per photon. The total detection efficiency and CMRR of the detector are measured to be 66% and 76 dB, respectively.

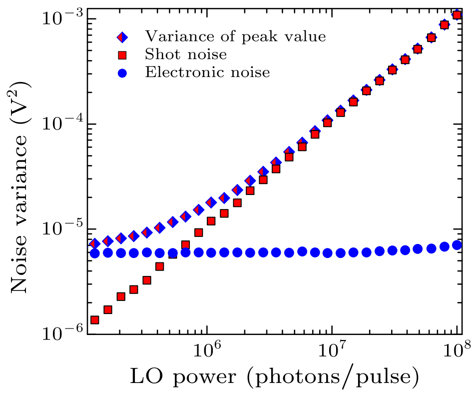

Fig. 4. The output peak value variance of the detector versus the LO power for vacuum field input.

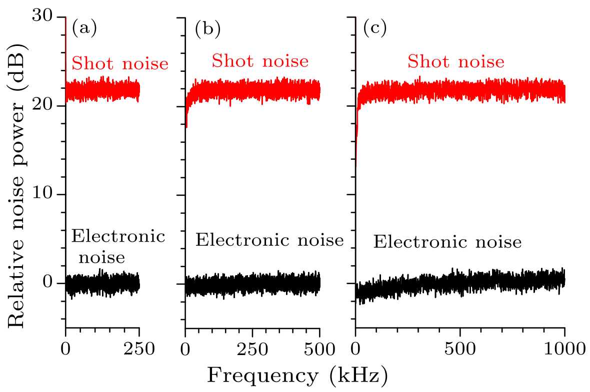

Fig. 5. The frequency spectra of the detector at different repetition rates with an LO power of 5×10^7 photons per pulse: (a) 500 kHz, (b) 1 MHz, (c) 2 MHz.

To check the time resolving power of the detector, the correlation coefficient (CC) between adjacent pulses was calculated.[12] The quadratures of 5009 vacuum field pulses were recorded with the measured values $N(j)$ ($j = 1, 2, \ldots, 5009$), and the CC is defined as

$$\mathrm{CC}(m) = \frac{E(X(k)Y(k)) - E(X(k))E(Y(k))}{\sqrt{E(X(k)^2) - E^2(X(k))}\sqrt{E(Y(k)^2) - E^2(Y(k))}}, \qquad (1)$$

where $X(k) = N(k)$ and $Y(k) = N(k+m)$ ($k = 1, 2, \ldots, 5000$; $m = 0, 1, \ldots, 9$). Figure 3 depicts the CC at different repetition rates (the shot noise to electronic noise ratio is 10 dB). It can be seen that there is a negative CC when the repetition rate is higher than 500 kHz, e.g., the CC between consecutive pulses ($m = 1$) is -0.065 at repetition rate of 2 MHz. For the repetition rate of 500 kHz, the CC decreases down to the order of ± 0.01. In this situation, it is observed that the small correlation between two adjacent pulses is random and it is attributed to the statistical fluctuations due to the limited number of samples and the electronic noise correlation of the detector.

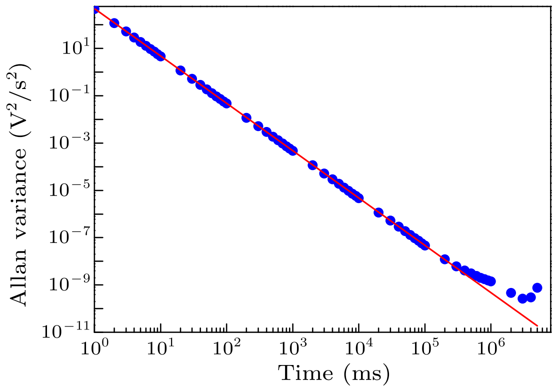

Fig. 6. Allan variance of the peak value of the detector output pulse.

The output peak value variance as a function of the LO power for vacuum signal input is shown in Fig. 4, where each data point was calculated from 50000 pulses. It is clear that the peak value variance scales with the LO power after subtraction of the electrical noise background. For a wide range of LO power spanning more than 2 orders of magnitude, the detector can work well in the linear region up to 10^8 photons per pulse and the shot noise to electronic noise ratio can reach above 20 dB. Figure 5 shows the noise spectra of the BHD at laser repetition rates of 500 kHz, 1 MHz, and 2 MHz. For a laser repetition rate of 500 kHz, the observed noise spectrum is flat in the frequency range from DC to half the repetition rate which indicates the noise observed is frequency independent (white). The dips in the low frequency part of the spectrum for the 1 MHz and 2 MHz repetition rates are due to the correlations of the adjacent electrical pulses. The test results given above confirm that our BHD is shot noise limited.

The BHD's long term stability is essential to determine how long the detector can work accurately without calibrating the low-frequency drift of the detector balance. The stability of the detector in various time scales is analyzed by using Allan variance defined by

$$\sigma^2(n\tau_0, N) = \frac{1}{2n^2\tau_0^2(N-2n)} \sum_{i=0}^{N-2n-1} \cdot (x_{i+2n} - 2x_{i+n} + x_i)^2, \qquad (2)$$

where x_i is the measured quadrature value, τ_0 is the time interval between the adjacent sampling points, and N is the total number of samples. This technique is called the overlapped estimator, it has been accepted as the preferred Allan variance estimator.[18] We acquired the data at a rate of 1 kHz for about three hours. Then different n is used to calculate the Allan variance in different time scales, as shown in Fig. 6.

The solid line is a linear fit using the data points for time less than 10 s, and we can see that the BHD has a 100 s window for accurate measurement without calibration. The departure due to the low-frequency drift of the detector balance begins at the time of around 200 s which is several orders higher than the results reported before.[15,16]

In summary, we have demonstrated a fiber-based time-domain shot noise limited balanced homodyne detector. The detector exhibits a common mode rejection ratio above 76 dB, signal-to-noise ratio above 20 dB. Optical pulses with repetition rates up to 2 MHz, which is to date the highest repetition rate for the CSP BHD, can be measured with shot noise limited sensitivity. The superior stability of the detector enables a 100-s window for measurement without calibration. The detector presented will find useful applications in precision measurement of pulsed quantum light fields and in all-fiber continuous variable quantum information processing including quantum communication, etc.

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