A wideband balanced homodyne detector for high speed continuous variable quantum key distribution systems

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In Gauissian-modulated coherent-state quantum key distribution, the measurement of quadratures of coherent states is performed by using homodyne detector. However, the existing detectors usually suffer from narrow band. Here we present a method to design a high-speed shot-noise-limited balanced homodyne detector. A 300 MHz bandwidth detector was experimentally tested and the level of shot noise is 14 dB higher than the electronic noise. The results show that a detector with this method is potential to design a GHz bandwidth detector for continuous variable quantum key distribution at a low level of shot noise to electronic noise ratio.

High-speed detectors in quantum communication, and in particular for continuous variable quantum key distribution (CVQKD) [1–3], play an important role for further experiments [4, 5]. Very recently, 80 km CVQKD has been demonstrated by Paul Jouguet *et al.* in their pioneering experiment [5]. It is noteworthy that their experiment was a one-way implementation working at the repetition rate of 1 MHz which was mainly limited by the bandwidth of homodyne detector, high-speed data acquisition and multidimensional reconciliation scheme.

Conventionally, the researchers reached a consensus that wideband, ultra-low noise, voltage-feedback operational amplifier, such as OPA847, is an optimal choice for a higher bandwidth and lower noise detector[6–10]. Furthermore, charge-sensitive preamplifier, such as A250, is better for audio band quantum signal detector[11–13]. To improve the performance of a practical CVQKD system with realistic detectors, a "dual detectors" method that the legitimate receiver randomly uses either a fast (but noisy) detector or a quiet (but slow) detector to measure the incoming quantum signals was proposed[14]. Nonetheless, the reported best performance of detectors are working at repetition rate of no more than 100 MHz, and typically tested at 20 MHz for best time resolution.

The security of the Gaussian CVQKD protocol with homodyne detection has proved to be against individual [1, 2] and collective [15, 16] Gaussian eavesdropping attacks. In fact, Gaussian collective attack is optimal for all the considered bounds on the key rate [15, 16]. In this study, we are focusing on the parameters of detector that intervene in the equations under collective attack, including the quantum efficiency η, the electronic noise V_{el} (in shot noise units), the maximum operating frequency R. In order to extract the optimal secret key rate at a given reconciliation efficiency and transmission efficiency, the quantum efficiency η of detector should be as large as possible. Limited by the responsivity of InGaAs photodiode, the quantum efficiency cannot be greatly improved with current technology. In fact, the optimization of these parameters for CVQKD is difficult. Because the modulation variance is usually less than 100 in a real system, the gain of detector should be as large as possible so that few-photon coherent states can be accurately measured. However, the level of electronic noise will increasing with the bandwidth of detector. As a result, the maximum operating frequencies of reported detectors were far less than 100 MHz[4, 8–10, 12, 17].

To effectively enhance the bandwidth of detector while still reserving the advantage of shot noise to electronic noise ratio, we employ a new approach to build a balanced homodyne detector (BHD). Experimental results of a wideband detector demonstrate substantial improvements in time-domain. The high performance detector makes it possible to increase the current repetition rate of CVQKD from tens of MHz to 100 MHz.

It is known that high speed operational amplifier is suitable for wideband high sensitivity transimpedance preamplifier. Limited by the slew rate (<1 V/ns) and the Gain-Bandwidth Product (GBP) (<4 GHz), the generalized amplifiers are too difficult to greatly improve the speed in the condition of high gain. In this case, designers must make a trade off between speed and gain in traditional electronic structures. To solve this problem,

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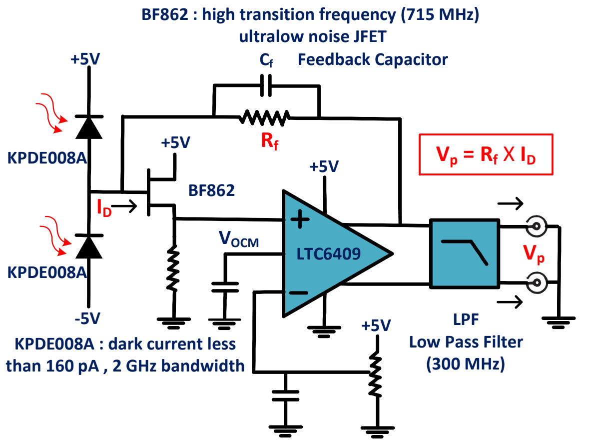

Fig. 1. Simplified electronic circuit of homodyne detector.

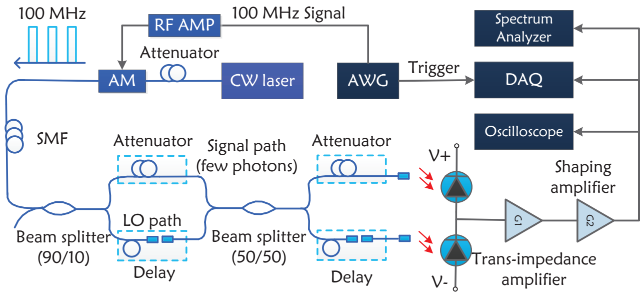

Fig. 2. Diagram of the experiment setup.

we introduce a speed-enhancing structure which gives attention to both indexes of high speed and high gain. We note that high speed fully differential amplifiers are suitable for ultra high speed transimpedance preamplifiers. Furthermore, this series of chips is potential for higher speed homodyne detector in combination with good circuit layout. The fully differential amplifiers can offer unprecedented bandwidth (usually larger than 100 MHz), extremely high slew rate (usually larger than 2 V/ns). And there is another benefit that is worth considering. They can also function well in single-ended feedback applications. We performed and demonstrated that a homodyne detector works well with these amplifiers in our electronic structures.

As shown in Fig. 1., a 10 GHz GBP with 3.3 V/ns differential slew rate amplifier LTC6409 (Linear corporation) is explored. In order to reduce the bipolar input transistor current noise, a high transition frequency (715 MHz) ultra-low noise Junction Field-effect Transistor (JFET) BF862 is selected. Two InGaAs photodiodes KPDE008A (responsivity 1 A/W, quantum efficiency 0.8) from Kyosemi are reversely biased. To dispel high frequency and restrain noises, a fourth-order low-pass filter confines the bandwidth to 300 MHz.

As shown in Fig. 2., The experiment setup is as follows: a 1550nm laser module mainly includes a continuous wave (CW) laser and a 10 GHz amplitude modulator (AM). With a 12 GS/s Tektronix signal source AWG7122B and a 10 GHz RF amplifier, a several nanosecond width pulse optical signal can be generated at a repetition rate of 100 MHz. As the wideband detector is tested at 100 MHz, high-speed data acquisition card (1Gbps AD) is required to be able to sample transient signal in real time. A synchronized FPGA based on PCI bus can transfer the data to the PC host.

To guarantee the detector has been well balanced, we measure the Common Mode Rejection Ratio of detector. As shown in Fig. 3, the red curve is recorded when one photodiode is blocked and the blue curve is recorded when two photodiodes are illuminated. It is clear that the CMRR of our detector reaches as high as 54 dB. To avoid the saturation of InGaAs photodiode (KPDE008A 10 mW), a 100 MHz pulsed laser generated and the intensity of LO power reduced to 42 μW (recorded by a optical power meter). The CMRR can be calculated from the maximum difference of the fundamental harmonic spectral power. In experimenting we find out that the the CMRR is determined by the unbalance factor of beam splitter and the different responsivity of photodiodes at the same time.

Shot noise estimation is one of the important processes in CVQKD. The shot noise measurement has been really tested both in CW laser and pulsed laser. The electronic noise will be tested without light by a 50 GS/s Tektronix oscilloscope DSA72004B in the first place. For CW laser, the AM is blocked and we can attenuate the optical power and record the noise variance directly with high-speed sampling oscilloscope at the same time. while for pulsed laser, the AM should be carefully controlled by AWG and bias setting to make sure that it works in the lowest loss. The effective value can be collected by the oscilloscope and the synchronized FPGA. The noise variance will be calculated from these values.

As shown in Fig. 4., the real time for one point is 200 μs, which is corresponding to 20000 pulses and the setting time could be increased with lower sampling rate,

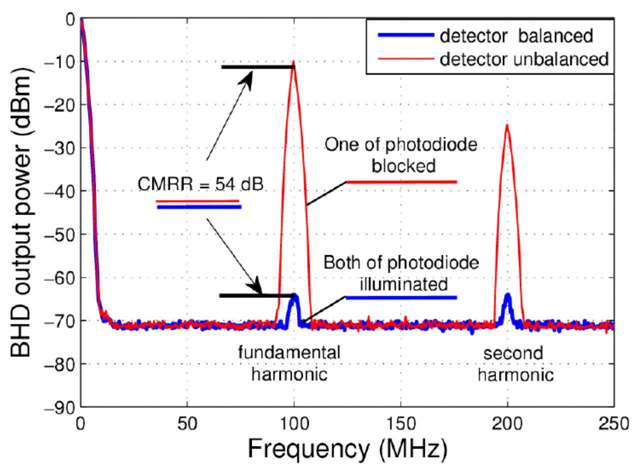

Fig. 3. The CMRR of detector at a 100 MHz pulsed laser.

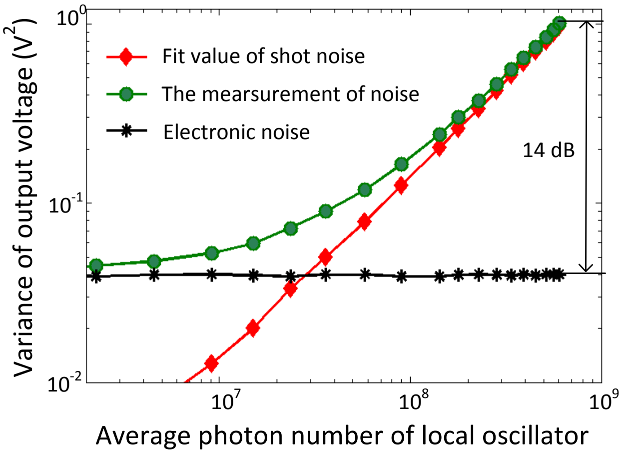

Fig. 4. The variance of output voltage as a function of the average photon number of local oscillator.

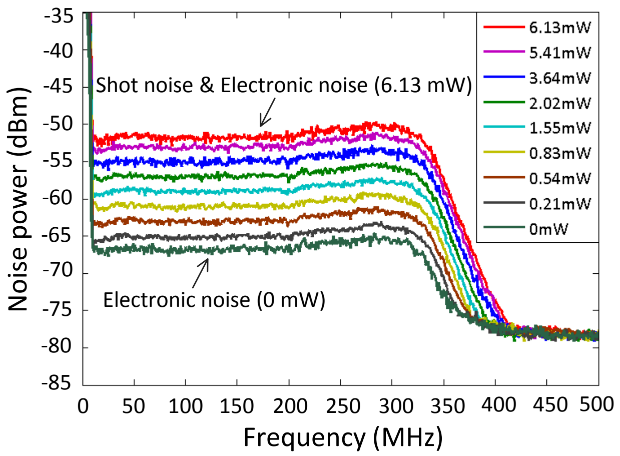

Fig. 5. The noise spectrum of homodyne detector characterization from DC to 500 MHz. With the increasing of LO power, the noise power will arose from DC to 300 MHz and then drop sharply.

while the FPGA is available for an even longer time. The dark green solid circles represent the measurement of noise including shot noise and electronic noise. It is clear that the fit value of shot noise is positively linear correlated with the mean photon number of local oscillator. The achieved maximum noise ratio between shot noise and electronic noise is 14 dB.

In a real system, the LO power is fixed so that the ratio between shot noise and electronic noise will be determined. For this reason, we are focussing on the maximum shot noise to electronic noise ratio in the linearity region. This optimization can be achieved in practical systems by adjusting the intensity of local oscillator power in an appropriate value. On the other hand, the slope of shot noise is determined by the amplifier coefficient and quantum efficiency of detector. To ensure that the

Table 1. A comparison between shot-noise-limited balanced homodyne detectors. (Noise ratio means the ratio between shot noise and electronic noise.)

Detectors	[4]	[12]	[17]	[9]	[10]	[8]	Ours
Wavelength (nm)	1550	790	820	1064	1550	791	1550
Bandwidth (MHz)	1	1	4	250	100	100	300
Noise ratio (dB)	13.4	14	13	7.5	13	13	14

detector has approached the quantum limit in the linear range of photodiodes, the gain of detector ($> 10^3$ at least) should be as large as possible .

In CVQKD, the sender can encode secret key in the quadratures of optical field by using Gaussian modulation, where the secret key rate is proportional to the repetition rate of system. Nevertheless, it is difficult to exceed 100 MHz in traditional ways. As shown in Table 1, the optimal repetition rate is less than several MHz in [4, 12, 17] in the earlier designs. Very recently, a detector [17] with this kind method was applied in quantum optical tomography at a repetition rate of 190 kHz. In order to increase the repetition rate, a new method which has been reported in [8–10] was employed. And the best design was proposed with a 20 ns flat pulse response (50 MHz) in the past year [8]. We can find that the maximum speed can be improved at a low level of noise ratio [9]. Because the gain of the detector in [9] is much lower than the others. And yet for all that, the detectors with these methods are still unable to work at a repetition rate of hundreds of MHz.

As shown in Fig. 5., the bandwidth of our detector is 300 MHz. And it is clear that the shot noise is higher than electronic noise at a LO power of 1.55 mW CW laser (corresponding to 10^8 photons per 10 ns). With the

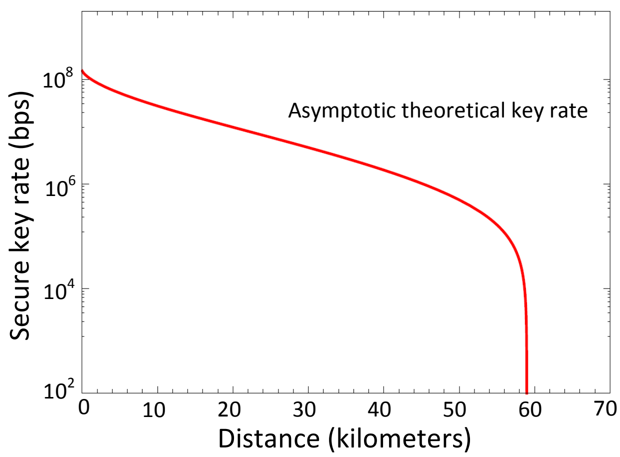

Fig. 6. The secure key rate as a function of the distance at the repetition rate of 100 MHz in our homodyne detector. The simulation parameters $v_{el} = 0.04$ and $\eta = 0.6$ is actual data tested from detector, the other simulation parameters $V_A = 20$ (optimal process), $\varepsilon_A = 0.01$, $\beta = 0.94$ is from [12].

increasing of LO power (from 0.21 mW to 6.13 mW), the output noise power of detector arose. It illustrates that our method is suitable for ultra-high speed shot-noise-limited homodyne detector. The results reveal that a detector with this method is potential to design a GHz bandwidth detector for continuous variable communication at a low level of shot noise to electronic noise ratio.

To comfirm the relationship between the parameters of our homodyne detector and the maximal secret key rete, we simulate the secret key rate of a CVQKD system under collective attack. In Consideration of the excess noise due to overlap between adjacent pulses [10], we can find the optimal pulse repetition rate is about 100 MHz. As can be seen on Fig. 6., the theoretical secure key rate approximately reach 1 Mbps at 50 km (0.2 dB/km). Further implementation of a realistic high-speed CVQKD system is based on high performance homodyne detector and high efficiency error correction.

In summary, we have introduced a approach differing from the methods outlined above for wideband shot-noise-limited homodyne detector. As a demonstration, a 300 MHz bandwidth detector was presented and it reserved the advantage of shot noise to electronic noise ratio. The high performance detector makes it possible to increase the current repetition rate of CVQKD from tens of MHz to 100 MHz, and the high-speed system is being developed in the follow-on work.

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