**Performance of Continuous Variable Quantum Key Distribution System at Different Detector Bandwidth**

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**Abstract**— We evaluate the performance of Gaussian Modulated Coherent State (GMCS) Continuous-Variable Quantum Key Distribution (CV-QKD), in terms of secure key rate, at different detector bandwidths. We illustrate the advantages and limitations of high-speed CV-QKD systems using a general noise model in which we consider various noise sources and their dependence upon detection bandwidth. Experimentally, the feasibility of high speed CV-QKD is demonstrated by using a GHz bandwidth balanced homodyne detector (BHD) established with commercially available components. We provide secure key rates of transmitted and local local oscillator schemes under various clock rates.

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**Introduction**

Quantum key distribution (QKD) has been shown as a promising approach to provide information theoretic secure communication together with classical encryption methods [1][2]. Unlike conventional cryptography, where the security is based on computational and mathematical complexities, the security of QKD relies on the quantum physical properties of light [3][4]. Since its first introduction in 1984 [5], various QKD protocols have been proposed and demonstrated, and these can be categorized into two classes– discrete variable (DV)-QKD and continuous variable (CV)-QKD. DV-QKD utilizes discrete values of the properties of a single photon, such as polarization and phase, to encode secure key information, these being decoded using single photon detection techniques. In CV-QKD, secure key is extracted from correlated data shared between the users. Amplitude and phase modulation of highly attenuated light together with balanced homodyne/heterodyne detection are used to distribute correlated data [6][7].

The phase reference for the detection, called the local oscillator (LO), is either transmitted over the link from the source or generated locally, these being referred to as the Transmitted Local Oscillator (TLO) or the Local Local Oscillator (LLO) schemes [8], respectively. CV-QKD has attracted much research interest in recent years due to its ability to operate in highly noisy environments, its compatibility with integrated photonic chips and its relatively low cost, as it can use components which are also suitable for classical optical communications. Several CV-QKD protocols have been proposed and demonstrated experimentally [9-13]. Among them, the Gaussian modulated coherent state (GMCS) protocol [9] has been thoroughly analyzed and proven to be secure against collective attacks [14] and general attacks [15]. CV-QKD has also been found to allow key distribution at longer transmission distances [16] [17] and network field deployment [18]. Side channel attacks and countermeasures have also been demonstrated experimentally for GMCS CV-QKD [19-22].

However, compared with the recent demonstrations of GHz clock rate DV-QKD systems [23][24], CV-QKD suffers from lower key generation rates. Most practical GMCS CV-QKD systems work at a repetition rate of 1 MHz or below, however higher rate systems have been reported [25][26]. Although the speed of post-processing after detection is one limiting factor [27], this is not a significant issue as it can be mitigated by high-performance hardware. It has been pointed out that the computational complexity can be significantly reduced by modern GPUs which are able to efficiently process large amounts of data in parallel [16][28]. Several demonstrations have been made in the realization of wideband BHDs for high speed CV-QKD [27,29-33]. To our knowledge, the state-of-the-art secure key rate of a complete GMCS CV-QKD system is around 1 Mbps at 25 km with a 50 MHz repetition rate using a 1 GHz bandwidth BHD [26].

In this study, we consider the performance of GMCS CV-QKD systems at different bandwidths. In particular, we conduct a noise analysis of CV-QKD at different clock rates, showing the bandwidth dependence of various noise sources. Previously, various noise sources in CV-QKD have been studied [34], but the influence of system clock rate has not been taken into account. We also experimentally demonstrate shot noise performance of a GHz bandwidth detector in pulsed and continuous regimes and analyze the secure key rate under a collective attack.

This paper is organized as follows. In Section 2, a general description of the GMCS protocol is given and we detail and analyze rate-dependent noise sources in high speed CV-QKD systems. In Section 3, a 1GHz bandwidth BHD for high speed CV-QKD detection is built around modified commercially available components and experimentally tested. Conclusions are drawn in Section 4.

1. **Noise analysis in high speed CV-QKD**

In GMCS CV-QKD, Alice prepares coherent states |*α*> = |*XA* + *iPA*>, where *XA* and *PA* are quadrature values drawn from a set of normally distributed random variables, *N*(0, VA) *,* with variance *VA* and mean zero, and sends the signals to Bob through the quantum channel. At Bob, a BHD is used to randomly measure *X* or *P*quadrature values of each state. The quantum channel is characterized by its transmittance *T* and excess noise *ξ*. Under the Gaussian linear model with additive Gaussian noise, the quadrature variance measured by Bob, *VB*, can be written as

*VB* = *ηTVA* + *Z* (1)

Here, *η* is the efficiency of Bob’s detectors, and *Z* is the Gaussian noise variance added to the measurement. By estimating the parameters *η, T* and *Z*, Alice and Bob can bound Eve’s information and extract the final secure key. Under a collective attack and in reverse reconciliation, it can be written as:

(2)

where is reconciliation efficiency, is the mutual information between Alice and Bob, and is the maximum information available to Eve from Bob and is related to the Holevo bound [35]. In order to evaluate the performance of high bit rate CV-QKD systems, it is essential to study the behaviour of the noise variance *Z* = *N*0 +*ηTξ* +*vele* at higher detection speeds. Here, *N*0 is the shot noise variance, *ξ* is the excess noise at Alice and *vele* is the electronic noise of the homodyne detector. Theoretically, *ξ* is assumed to have originated from eavesdropping. However, in practice, *ξ* can have contributions from a range of experimental parameters. In the following, we investigate and categorize the noise contributions which behave in proportion to the system repetition rate.

1. **Shot noise variance**

The shot noise variance, *N0*, is the fundamental vacuum noise associated with the coherent states. All the parameters of a CV-QKD system are normalized to shot noise variance and expressed in terms of shot noise units (SNU). Therefore, careful and precise calibration of *N0* is required. In practice, *N0* is measured with respect to the LO power at Bob by blocking the signal port of the homodyne detector. To fall within the linear Gaussian model, the BHD is set within the linear regime of the output with respect to the input signal. This is achieved by setting the shot noise sensitivity of the BHD well above the electronic noise with sufficient LO power- typically 108 photons per LO pulse. Hence the detection is said to be shot noise limited.

Assuming a fixed duty cycle for the LO pulses, the LO pulse duration decreases with increasing repetition rate. The requirement for maintaining the linear relationship between the output and input of the BHD requires a corresponding increase in the peak power of the LO pulse. In practice, this cannot happen indefinitely with an increasing repetition rate, being limited by the maximum power available from the LO laser as well as the optical power handling capability of the photodiodes in the BHD. Additionally, at longer transmission distances, the optical loss in the channel imposes a further requirement for increased peak power of the LO pulses in the TLO-CV-QKD scheme. This power constraint is not present in LLO based CV-QKD schemes as the local oscillator power is not affected by channel attenuation, since it is locally generated at Bob.

1. **Imbalance drift in the BHD**

The measured quadratures at Bob follow a Gaussian distribution, *N(0, VB)* with a variance *VB* (Eq. 1) and zero mean . This zero mean of the distribution is set by balancing the homodyne detector. Practically, the BHD output drifts from its balancing condition over time, and hence the measured mean value of each quadrature is not maintained during the key transmission. This can be for multiple reasons, such as temperature fluctuations, drift in data acquisition sampling or its clock, and time variation of the characteristics of the detector electronics. Within the total data sampling interval, typically 108 samples, this fluctuation in the mean value of the distribution is manifested in the signal variance estimation, *VB*, and adds extra noise, *ξbd*, in the CV-QKD system. This can be expressed as:

|  |  |
| --- | --- |
|  | (3) |

where, σ(t) is the time-varying imbalance factor between two different arms of homodyne detection, which is related to the common-mode rejection ratio ( CMRR ) as *σ* =1/2CMRR [27], and Δt is the period of measurement. *Nsig* and *NLO* are the photon numbers per pulse in the signal and LO respectively. Higher imbalance may increase the contribution of RIN (relative intensity noise) from the LO. However, we assume is it contribution to excess noise is negligible.

A typical CV-QKD experiment, as demonstrated in [36], shows that the excess noise due to relative drift in the homodyne output can be negligible for Δt of 100 ms but increases to an observable level of 10-3 *N0* over a period longer than a few hundred seconds. To mitigate this effect, shot noise measurement, parameter estimation and key transmission sessions should in principle be conducted repeatedly at different time slots. However, measurements within each session need to be conducted with over 108 sampling points to reduce the statistical fluctuations [36]. For a system with a 1 MHz repetition rate, only 105 sampling points can be obtained within a session of 100 ms, while measurements can be more precisely conducted with 108 sampling points for a system with a repetition rate of 1GHz. Therefore, the use of high bit rate CV-QKD can better mitigate excess noise due to drift in homodyne balancing and hence improve the system performance.

1. **Phase drift noise**

Among the sources of excess noise, phase noise plays a significant role in the achievable transmission distance as well as secure key rate. Phase noise is the variance of the difference between the estimated and actual phase of signal relative to LO. In the case of the GMCS CV-QKD, the excess noise contributed by phase noise is written as [8][37]:

(4)

In CV-QKD with the TLO scheme, signal and LO pulses propagate through the different optical paths inside Alice and Bob. Thermal fluctuations in the path cause a drift in relative phase between the signal and the LO. Experimentally, the phase noise corresponding to this drift is mitigated by periodically transmitting pilot pulses from Alice to Bob. Bob carries out a relative phase estimation of the pilot pulses with respect to the LO's phase during the reverse reconciliation procedure, whilst Alice compensates the phase drift by phase correcting her transmitted quadrature values. Therefore, the remaining phase noise after the phase correction becomes [8]:

(5)

The term corresponds to the phase measurement accuracy, which is the variance of the difference between the estimated and exact phase values of the pilot pulses. This is inversely proportional to the amplitude of the pulse and is considered to be independent of the repetition rate [8]. However, inspired by the work in [38], the term can be expressed as:

(6)

where is the time dependent phase difference between the pilot and signal pulse when they travel through the transmission channel, is the period of each measurement session. At high repetition rates the phase noise decreases as the relative phase drift experienced within approaches zero.

In CV-QKD with an LLO scheme, the signal and LO are generated from two independent free-running lasers. A phase reference pulse is also generated by Alice with each signal pulse. Signal and reference pulses are transmitted through the same optical path. Therefore, the signal and reference pulses experience the same phase change during their propagation . However, the finite spectral width of the two interfering laser pulses creates a phase estimation uncertainty in the reference pulse. The difference between the estimated phase value of the reference pulse from the exact phase values contribute to a phase noise. The total phase noise in this case can be expressed as:

(7)

The term is the relative phase drift between two free running lasers with spectral linewidths ΔvA and ΔvB, and can be written as a function of repetition rate *frep* [8]:

(8)

This noise limits the achievable transmission distance of the LLO scheme to a few tens of km [37]. With higher repetition rate, the drift *Vdrift* becomes smaller and hence the excess noise can be reduced. This in turn increases the secure key rate and transmission. From the practical point of view, narrow linewidth lasers are normally selected to minimize the phase noise. However, the more commonly available higher linewidth lasers can be used in systems with higher repetition rate. In addition to the conventional LLO-based CV-QKD, an LLO-delay line design has been recently proposed [8]. In this scheme, by employing delay line interferometers, *Vdrift* can be eliminated. However, *Vphase* will then be affected by thenoise variance *Vchannel* , similar to the case of TLO-based CV-QKD.

1. **Quantisation noise**

In practice, excess noise is introduced by imperfect modulation by Alice during the preparation of Gaussian modulation coherent states. Specifically, this happens in digital to analog convertors (DAC) used for the amplitude and phase modulation. During translation from discrete bits into voltage levels, the quantization noise in the DAC affects the state preparation and contributes to excess noise as [34]:

(9)

where, is the gain factor of the amplifier and is the voltage required to achieve a phase rotation of π. At Bob, the quantisation noise will also be introduced by the analogue to digital (ADC) converter at the output of the BHD and TIA, which is used to convert the measured output voltage to the measured quadrature at Bob. This contributes to the excess noise as [34]:

(10)

where *ρ* is the responsivity of the PIN diodes. Similarly, is the voltage noise variance of the ADC due to the limited resolution, *f* represents the optical LO frequency and *PLO*and τ are the peak optical power and pulse duration of the LO pulse train, respectively.

in Equations 9 and 10 is the output voltage variance from the converter which is applied to the modulators. It is affected by the resolution of the digital to analog conversion [39]:

(11)

where, *LSB* is the least significant bit and *VFS* is the full-scale voltage range of the converter. *N* is the resolution of the converter in bits. The voltage variance in both Alice and Bob shows a system speed dependency which comes from the trade-off between the effective number of bits available and the sampling rate of conversions. In ref. [39], it has been shown that approximately one bit of resolution is lost for every doubling of the sampling rate - which does not account for the improvements in the ADC signal to noise ratio over the period. However, we consider the bit resolution of the ADC in our analysis based on commercially available data acquisition boards and we follow the noise estimation according to ref[39].

1. **Electronic noise**

The main source of electronic noise, *vele*, in the BHD is the thermal noise associated with the transimpedance amplifier (TIA) circuit. To detect quantum signals, a homodyne/heterodyne detector must be sensitive enough to distinguish shot noise from electronic noise. Experimentally, shot noise is determined when the BHD output variance linearly scales with the LO's power, and the electronic noise is measured with respect to the shot noise variance as a function of the LO power without sending a quantum signal to the BHD. For reaching the maximum transmission distance and key rate, the electronic noise in SNU should be as low as possible. It is expressed as [34]:

(12)

where *NEP* is the electrical noise equivalent power in A/√Hz, referring to the power at the input of the TIA and *B* is the bandwidth of the detector. According to this equation, the electronic noise in the SNU increases with bandwidth. Lower bandwidth, 10MHz, detectors are reported to have electronic noise 25dB below the shot noise value, equivalent to 0.003*N0*, measured with a local oscillator power equivalent to 108 photons per pulse [36]. The GHz bandwidth detector reported in [26] exhibits shot noise to electronic noise clearance of 6dB, equivalent to 0.25*N0*, with local oscillator power of 107 photons per pulse. In addition, electronic noise is proportional to *NEP* which depends on the circuit components but has been shown to generally increase with the repetition rate for a given electrical bandwidth [40].

Based on the analysis of above noise sources, *Z* in Equation (1) becomes:

(13)

where the term is the system excess noise, i.e. the repetition rate independent excess noise contribution. Each of the above noise terms is estimated at different repetition rates of CV-QKD, as shown in Figure 1. The increase of quantisation noise in the plot is shown as ‘steps’. This is because the calculation uses the approximation stated in [39], that one bit of resolution is lost for every doubling of the sampling rate and the number of quantisation bits is assumed to be an integer. It can be seen that the phase noise and the noise due to imbalance drift decrease with increasing repetition rate and can be considered negligible in a high speed CV-QKD system. On the other hand, the electronic noise and quantitation noise increase with the repetition rate. They are shown as the limiting factors for implementing high speed CV-QKD systems. Fortunately, by carefully selecting commercially available higher bandwidth, lower electronic noise photodiodes and TIAs, it is possible to construct a shot noise limited GHz bandwidth homodyne detector. Below, we evaluate the performance of our homodyne detector built from commercially available components and study the feasibility of a high-speed CV-QKD system.

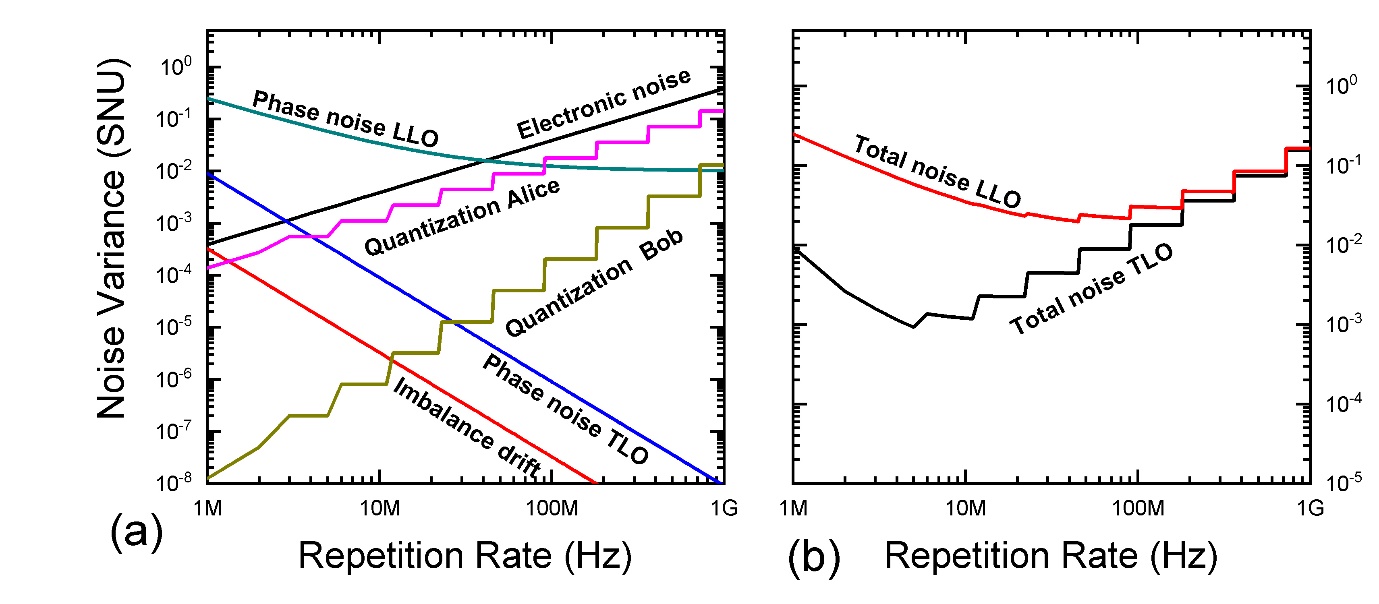


Figure 1(a). Estimation of different noise sources as a function of repetition rate. In the estimations, is fixed as 107 (with a PLO of 3mW and a td of 0.5ns). η is set as 60%, and the VA=10. The time interval of both shot noise drift and phase noise drift is set as the time corresponding to the108 sampling point at different repetition rates. The linewidth of the lasers is assumed to be the state of art value of 1.9kHz [41]. and are assumed to be 5V and 1V, respectively. The gain factor and *g* are fixed at 5 V/V and 50k A/V, respectively. *N* is 16 bits at 1MHz repetition rate and decrease to 8 bits at 250MHz. The bandwidth of detector *B* is assumed to be four times of repetition rate. Figure 1(b). Sum of noise variance from figure 1(a) for TLO and LLO. The steps in the plots are due to quantization noise.

1. **Feasibility of 250MHz CV-QKD system**

In this section, we experimentally study the feasibility of high-speed CV-QKD with a pulse repetition rate of 250MHz using a GHz BHD system. Driving a homodyne detector near to its bandwidth limit causes consecutive electrical pulses to overlap (inter symbol interference) and induces additional noise which can be reduced to some extent by applying deconvolution techniques. However, this noise is negligible at lower repetition rates. In a 1GHz bandwidth homodyne detector operating at a 250MHz repetition rate, excess noise due to pulse overlap is <10−3*N0* and so can be ignored [27]. In addition, we report an efficient method of using equalization for CV-QKD detection to mitigate possible overlapping distortion [42].

The experimental setup is shown in Figure 2. A CW laser source operating at a wavelength of 1550nm is modulated by a 10GHz amplitude modulator driven by an electrical signal to generate 400ps width optical pulses at a repetition rate of 250MHz. A variable attenuator is used to control the LO power launched into the balanced detectors, and the power is monitored by a power meter together via a 99:1 beam splitter. The LO is then coupled into two reverse biased InGaAs PIN detectors. A variable attenuator and an optical delay line are employed to balance the BHD and a CMRR of 51dB is obtained. The output current from the photodiodes is subtracted and then amplified by a modified commercial 1 GHz high-speed TIA. The data acquisition is performed using a 20GS/s real-time oscilloscope.

The voltage fluctuations on the power supply increase the electronic noise of the TIA. This effect can be described by the Power Supply Rejection Ratio (PSRR) ratings which is normally specified by manufacturers for the circuits. To reduce the PSRR of our TIA and hence minimize the electronic noise in our BHD system, we power the TIA using a 12V battery instead of a power supply unit. The reduction of electronic noise is measured to be about 2dB. The linearity of the BHD is investigated by shot noise measurement at different LO powers and the variance of the electronic noise is determined by setting the power of the LO to zero.

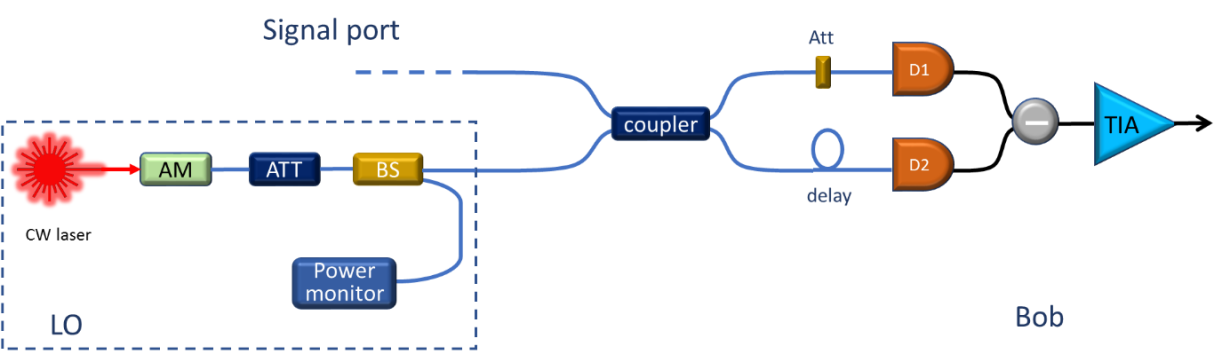


Figure 2. Experimental setup. AM: amplitude modulator; ATT: variable optical attenuator; BS: 99/1 beam splitter; D1 and D2: PIN detectors; TIA: Transimpedance amplifier.

To meet the linear model of the GMCS protocol, the linearity of the BHD has been tested by measuring the output noise variance with respect to various LO powers, from 0 to 1×107 photons per pulse (corresponding to pulse peak power of 3mW). The measurement is shown in the Figure 3 (a). The black trace is the electronic noise obtained at zero LO power. The total output variance is a sum of the shot noise variance and electronic variance. When the LO power is set lower than about 3×106 photons per pulse, the output variance is dominated by the electronic noise, as shown by the black dotted line. The electronic noise in the system is about 0.0004 mV2 and is unaffected by the LO power. As the power of the LO is increased to about 3×106 photons per pulse, the output variance from the BHD starts to be dominated by the shot noise. As shown in the plot, the region between 4×106 to 1×107 photons/pulse could be feasible for detecting CV-QKD signals using the GMCS protocol, which requires a linear relationship between input signal and output of the detector. The shot noise to electronic noise ratio obtained is about 9.5dB, 13.9dB, 16.8dB, corresponding to electronic noise values 0.11, 0.04, and 0.02, at 4.4×106, 6.2×106, 8.7×106 photons per pulse, respectively. We also characterize our BHD system with a continuous wave LO. The frequency response at different LO powers is shown in Figure 3(b). The black trace is the electronic noise obtained when LO is 0mW. Considering the synchronized repetition rate between LO and signal (ie. 250MHz), shot noise to electronic noise ratios of about 13 dB and 10 dB are observed at LO powers of 12mW and 6mW, respectively.

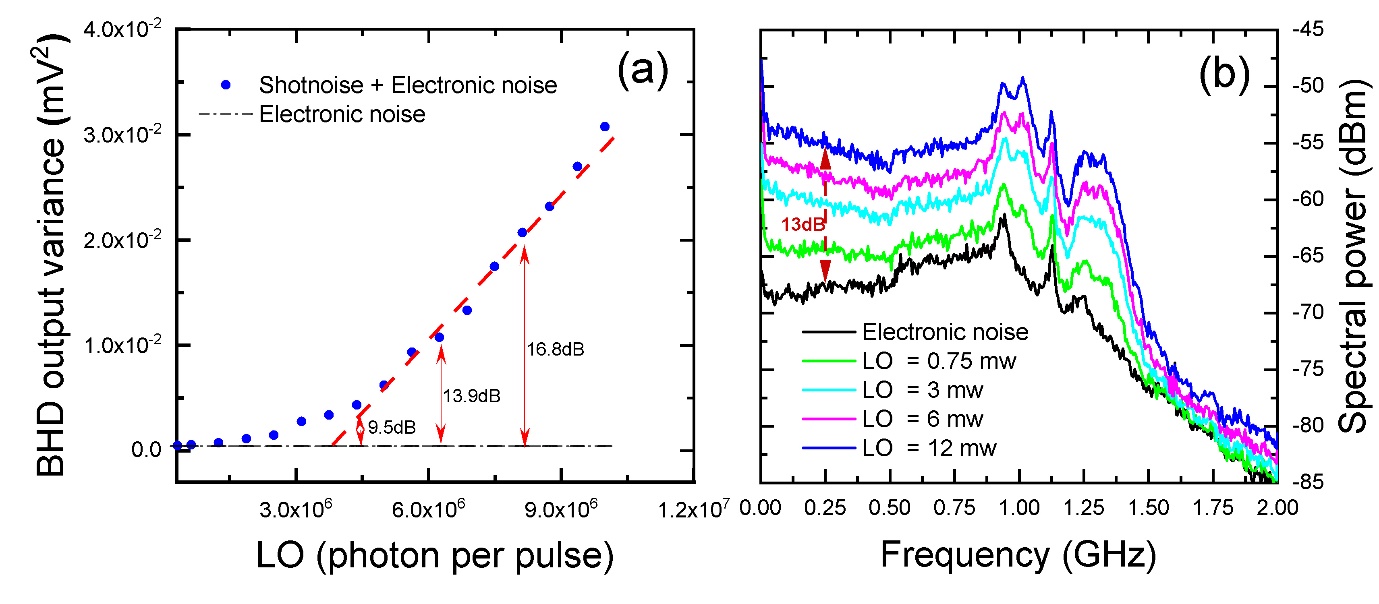


Figure 3. (a) Shot noise variance as a function of LO power. The red dashed line shows the linear region of the shot noise variance increasing with LO power; (b) frequency response of noise measurements with CW LO at different powers.

In a GMCS CV-QKD system, the quantum keys are extracted from the signal quadrature measurements. For the both cases, i.e. using TLO and LLO, the performance of our BHD is predicted by estimating the secure key generation rate under collective attack. Excess noises is estimated as 0.036 SNU and 0.047 SNU at 250MHz for TLO and LLO, respectively. The remaining excess noise which does not change with repetition rate is assumed to be 0.02 N0. The modulation variance VA is 10*N0* and reconciliation efficiency *β* is assumed to be 95%. In our key rate estimation, we consider, for a given clock rate, one third of the data is for parameter estimation, one third is for key generation and rest is for shot noise variance estimation.

In the case of TLO, shown in Figure 4a, about 3 Mbits/s secure key rate can be obtained at a transmission distance of 30 km and the maximum achievable transmission distance is 78km. In our simulation, we consider the experimentally tested 16.8dB (= 0.02N0) shot noise to electronic noise ratio at a LO power of 8.7×106 photon per pulse, corresponding a pulse peak power of about 2.5 mW at the Bob’s end. The maximum power at the output of the LO laser is 51mW at 25oC, and the maximum handling power of the PIN diodes is about 7mW. Therefore, it is feasible to distribute the LO from Alice to Bob over 60km (corresponding to 12dB loss), with an achievable secure key rate of more than 200 kbits/s.

On the other hand, CV-QKD using the LLO, shown in Figure 4b, can achieve tens of Mbits/s secure key rate at transmission distances within a 15km range. The maximum transmission distance is around 65 km at 250MHz clock rate. In the LLO scheme LO power is not limited by the channel attenuation, 16.8dB shot noise to electronic noise ratio is achievable, as long as LO power is lower than the detector saturation level (in our case, 7mW per PIN diode).

For comparison, the performance of TLO and LLO-CV-QKD systems with 100MHz, 500MHz and 1GHz repetition rates are investigated at different distances. The case of the typical repetition rate of 1MHz is also plotted as a reference for comparison. The excess noise and electronic noise are calculated for different clock rates based on the noise analysis given in the section 2.

For TLO-CV-QKD, the secure bits per pulse and the maximum transmission distance are reduced with increasing clock rate due to the increase in excess noise and electronic noise. However, as the repetition rate goes up, a higher secure key rate can be achieved, though over a smaller range. For the case of LLO, comparing with the typical repetition rate 1MHz, 100MHz of repetition rate offers reduced phase noise, hence better performance can be achieved for a given laser linewidth. When the clock rate is increased from 100MHz to 1GHz, the phase noise decreases and becomes less dominant in the total excess noise, and then the excess noise due to modulation errors starts to degrade the system performance. In turn, the maximum distance decreases with an increased repetition rate. Although the maximum key rate is boosted by repetition rate, the transmission distance becomes limited at higher speed.



Figure 4. Secure key rate as a function of distance at clock rate of 1MHz 100MHz , 250MHz 500MHz and 1GHz for (a) TLO CV-QKD (b) LLO CV-QKD



Figure 5. Secure key rate as a function of clock rate. (a) TLO and (b) LLO. The steps in the graph are due to quantization noise at Alice and Bob.

We have also compared the secure key rate to the clock rate, for different transmission distances, and the result is shown in figure 5(a) for TLO and 5(b) for LLO based GMCS CV-QKD system. It is evident from the figure that: for TLO systems, higher bandwidth of homodyne detection does improve the secure key rate however reducing the transmission distance typically due to higher electronic and quantization noise. In the case of LLO based systems, at lower bandwidth phase noise and higher bandwidth quantization noise reduces the secure key rate. The step behavior in the graphs is due to the reduction in bit resolution of data convertors while doubling the data sampling rate [39]. One can consider the figure 5(a) and (b) for optimizing the clock rate in GMCS CV-QKD system.

1. **Conclusion**

In this paper, we have analyzed various noise sources associated with GMCS CV-QKD system and their influence on secure key rate at different bandwidths. We have determined that the balanced homodyne detector bandwidth should be 3 times the clock rate in order to avoid inter symbol interfence noise.We have studied the feasibility of achieving a 250MHz clock GMCS CV-QKD system with a practical BHD receiver. The performance of the BHD is experimentally investigated in terms of the ratio between the shot noise and electronic noise. With the chosen BHD , 16.8dB shot to electronic noise ratio is achieved with linear response at repetition rate of 250MHz, which is a record for high speed CV-QKD systems in terms of both speed and performance. To illustrate the feasibility of this BHD for realizing a high-speed CV-QKD transmission, secure key rates at different transmission distances are simulated for both TLO and LLO based systems. 3 Mbit/s secure key rate is predicted at a distance of 30 km in a CV-QKD system with TLO. The results also predict CV-QKD with LLO can achieve tens of Mbit/s secure key rate at transmission distances within the range of 15km.

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