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Reference-frame-independent quantum key distribution of wavelength division multiplexing with multiple quantum channels*

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Reference-frame-independent quantum key distribution (RFI-QKD) can allow a quantum key distribution system to obtain the ideal key rate and transmission distance without reference system calibration, which has attracted much attention. Here, we propose an RFI-QKD protocol based on wavelength division multiplexing (WDM) considering finite-key analysis and crosstalk. The finite-key bound for RFI-QKD with decoy states is derived under the crosstalk of WDM. The resulting secret key rate of RFI-QKD, which is more rigorous, is obtained. Simulation results reveal that the secret key rate of RFI-QKD based on WDM is affected by the multiplexing channel number, as well as crosstalk between adjacent channels.

Keywords: quantum key distribution, wavelength division multiplexing, secret key rate

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1. Introduction

Unlike classical cryptography, security of quantum cryptography does not depend on mathematical complexity, but rather, is based on the fundamental principles of quantum physics.[1–5] However, during the implementation of a quantum key distribution (QKD) system, equipment defects lead to vulnerability of the security vulnerability of the QKD protocol.[6,7] To improve the security of a QKD system, many QKD protocols have been proposed.[8–12] In general, existing QKD protocols must perform real-time reference frame calibration between Alice and Bob on both sides of communication to ensure stable operation of the QKD system. However, this operation is very complex and reduces the secret key rate of the QKD system. To avoid complex real-time reference frame calibration, Laing *et al.* proposed a reference-frame-independent quantum key distribution (RFI-QKD) protocol.[13] This protocol not only simplifies the operation of existing devices, but can also be applied to new scenarios, such as earth-to-satellite links and integrated photonic waveguides, which have recently attracted significant attention.[14–17]

In a QKD system, the communication distance may increase to 100 km or more. If the signals are transmitted through separate channels in different fibres, the efficiency of the fibres will be reduced, which will lead to temporal deviation between different signals. If long-distance QKD is performed, the key rate may not meet the requirements of actual communication. Wavelength division multiplexing (WDM) technology solves this problem effectively.[18] The transmission of multiple wavelength signals in a single fibre can effectively increase the number of channels and greatly improve the secret key rate. At present, WDM technology is widely used in classical channels and plays an increasingly important role in the construction of a QKD network. WDM technology can integrate the classical communication channel into the quantum channel of a QKD system, which provides a feasible scheme for combination of the QKD system and the existing fiber communication network. Therefore, the application of WDM technology can greatly improve practicability and compatibility of a QKD system. In addition, WDM technology can be used to merge two QKD systems to increase the secret key rate between two nodes.

The combination of WDM technology and an optical fibre QKD system has attracted widespread attention. In 1997, Townsend proposed and implemented the combination of an optical fibre system and classical optical fibre network.[19] In the experiment, a WDM module was used to input the quantum signal carrying the key into a 1.2-GB/s standard commercial optical fibre and the transmission was performed over 28 km in London, which demonstrated the possibility of implementing QKD using a classical optical fibre network. In 2005, the Telecommunications Science Laboratory in Maryland further verified the feasibility of transmitting classical optical signals and quantum signals in a single fibre.[20] In 2008, the research team of NEC and NICT in Japan built a WDM QKD system with clock signals and conducted field tests, with the actual transmission distance exceeding 97 km.[21] In 2013,

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these two institutions improved on the basis of the previous system by adding stability modules such as temperature control and conducted a QKD test over 30 d over a transmission distance of 22 km with a bit error rate as low as 1.7% and an estimated secret key rate as high as 112.4 kB/s.[22] In 2010, the Gisin team at the University of Geneva combined the quantum channel with the classical channel to realise real-time key transmission and data encryption.[23] In 2014, the Toshiba Europe Cambridge Research Center studied the use of the DWDM multiplexing quantum channel, clock channel and classical channel. The experimental results revealed that the maximum number of classical communication channels that can be supported over 50 km is greater than 10, which can support classical channels of more than 100 Gb/s.[24] Under this circumstance, the QKD secret key rate can still reach 342 kB/s.[25] In 2018, the feasibility of combining QKD with classical data transmission in existing backbone fibre networks was proposed. The experimental demonstrated show that the real-time secret key rate of quantum signals transmitted in the same and reverse directions with classical signals can reach 4.5 kB/s and 5.1 kB/s,[26] respectively. In 2019, the feasibility of the joint transmission of QKD and multi-channel WDM coherent data was experimentally verified. The experiment demonstrated that the continuous-variable QKD could successfully generate the key within 24 h and classical data transmission rate could reach 18.3 Tb/s.[27]

The aforementioned studies demonstrate that it is feasible to combine an existing communication network with a QKD network by WDM technology and that WDM is an effective means of improving the secret key rate, which plays a crucial role in the construction of a QKD network. However, the aforementioned schemes did not consider crosstalk between adjacent channels. In this paper, we propose an RFI-QKD scheme, based on WDM technology, considering the crosstalk between adjacent channels. In this scheme, Alice sends multiple signals of different wavelengths at the legitimate transmitting end and combines optical signals of different wavelengths through an optical multiplexer for long-distance transmission in the optical fibre. After reaching the receiving end for Bob, these optical signals are separated by an optical demultiplexer and are then measured separately in multiple channels. The feasibility of the proposed RFI-QKD protocol based on WDM technology is analyzed through numerical simulation.

2. Protocol

In RFI-QKD based on WDM, Alice sends signals with different wavelengths to Bob. All signals that are modulated by Alice are integrated into a fibre by WDM and sent to Bob. When Bob receives the pulse, an optical demultiplexer is used to decompose the optical pulse and Bob then performs independent interference measurement for each wavelength pair and announces the results. This approach employs the following steps:

(a) One of four states $|\phi_{0Z}\rangle$, $|\phi_{1Z}\rangle$, $|\phi_{0X}\rangle$, and $|\phi_{0Y}\rangle$ is emitted and prepared by Alice with equal probability. Here, $|\phi_{j\alpha}\rangle$ denotes Alice's state with bit j in the α basis. In addition, the intensity of each laser pulse is modulated equiprobably for three different intensity values, μ_1, μ_2, μ_3 ($\mu_1 > \mu_2 > 0$, $\mu_3 = 0$), representing the signal, decoy and vacuum state, respectively.

(b) Thereafter, Bob measures the received pulses with a probability of 50% in the Z basis and 25% in the X and Y bases. An optical demultiplexer is used to demultiplex the optical pulse.

(c) Alice and Bob announce their basis and intensity choices over an authenticated public channel and compute the statistical result, which is denoted by $N_{s\beta j\alpha,k}$, where $k \in \{\mu_1,\mu_2,\mu_3\}$, $s,j \in \{0,1\}$, and $\alpha,\beta \in \{X,Y,Z\}$, indicate the number of events when Alice sends with $|\phi_{j\alpha}\rangle$ in k intensity while Bob receives $|s\beta\rangle$. It should be noted that $|s\beta\rangle$ represents the state with bit s in the β basis in the following description.

(d) According to the results of the parameter estimation, Alice and Bob obtain the final secret key by performing error correction and security amplification. Alice and Bob consume at most λ_{EC} bits to perform the error correction and ensure that they share a pair of identical keys. Alice and Bob share the secure keys via the Z basis encoded by the time-bin because it is easy to maintain stability in a fibre-based channel. The calculation method of λ_{EC} is given by $\lambda_{\mathrm{EC}} = f_{\mathrm{EC}} N_{ZZ} h(E_{ZZ})$. Here, f_{EC} is the error correction coefficient and $h(x)$ is the binary entropy function. N_{ZZ} represents the sum of the detection counts, where both preparation and measurement are operated in the Z basis, whereas the corresponding bit error rate is denoted by E_{ZZ}. According to the above process, the final key rate is given by

$$R = s^{\mathrm{L}}_{ZZ,1}\left(1 - I^{\mathrm{U}}_{\mathrm{E}}\right) - \lambda_{\mathrm{EC}}. \tag{1}$$

Here, $s^{\mathrm{L}}_{ZZ,1}$ denotes the lower bound of single-photon events when both Alice and Bob use the Z basis, whereas $I^{\mathrm{U}}_{\mathrm{E}}$ denotes the upper bound of the leakage information. Superscripts U and L denote the upper and lower bounds, respectively.

The specific experimental model is shown in Fig. 1. The proposed scheme is based on WDM technology. Therefore, the choice of the signal wavelength has an important effect on the QKD system. In the C-band, the relationship between the specific wavelength λ_n and attenuation coefficient η_n is as follows:

$$\eta_n = 0.2119 - \frac{0.2119 - 0.2102}{1565 - 1525}(\lambda_n - 1525).$$

Moreover, due to an unavoidable phase drift. Alice (Bob) encodes quantum states in three orthogonal bases Z, X and Y. Alice randomly sends signals under Z_{A}, X_{A} and Y_{A} bases to

Bob, and the Z basis is assumed to be aligned, i.e., $Z_{\rm A} = Z_{\rm B}$. If the phase drift is represented by ω, the X and Y bases can be related as follows:

$$\begin{aligned} X_{\rm B} &= \cos\omega X_{\rm A} + \sin\omega Y_{\rm A}, \\ Y_{\rm B} &= \cos\omega Y_{\rm A} - \sin\omega X_{\rm A}. \end{aligned} \tag{2}$$

The secret key is generated using the information in the Z basis, and the quantum bit error rate is defined as

$$E_{ZZ} = \frac{1 - \langle Z_{\rm A} Z_{\rm B}\rangle}{2}. \tag{3}$$

In an RFI-QKD system, E_{ZZ} is typically less than 15.9%.[13] The amount of information that can be eavesdropped by Eve in a decoy-state RFI-QKD system is

$$I_{\rm E}^{\rm U} = \left(1 - E_{ZZ}^{\rm U}\right) h\left(\frac{1+v_{\max}}{2}\right) - E_{ZZ}^{\rm U} h\left(\frac{1+f(v_{\max})}{2}\right), \tag{4}$$

where

$$\begin{aligned} v_{\max} &= \min\left(\frac{1}{1-E_{ZZ}^{\rm U}}\sqrt{\frac{C^{\rm L}}{2}},\ 1\right), \\ f(v_{\max}) &= \frac{\sqrt{\frac{C^{\rm L}}{2} - \left(1-E_{ZZ}^{\rm U}\right)^2 v_{\max}^2}}{E_{ZZ}^{\rm U}}. \end{aligned} \tag{5}$$

$H(x) = -x\log_2 x - (1-x)\log_2(1-x)$ is the two-dimensional Shannon entropy function. Parameter C, which is independent of the relative angle, performs a crucial role in the RFI-QKD protocol,

$$\begin{aligned} C &= \langle X_{\rm A} X_{\rm B}\rangle^2 + \langle X_{\rm A} Y_{\rm B}\rangle^2 + \langle Y_{\rm A} X_{\rm B}\rangle^2 + \langle Y_{\rm A} Y_{\rm B}\rangle^2 \\ &= \sum_{\alpha,\beta\in\{X,Y\}} \left(1 - 2E_{\alpha\beta}^2\right), \end{aligned} \tag{6}$$

where $E_{\alpha\beta}(\alpha,\beta \in \{X,Y\})$ is the phase error rate in the QKD process.

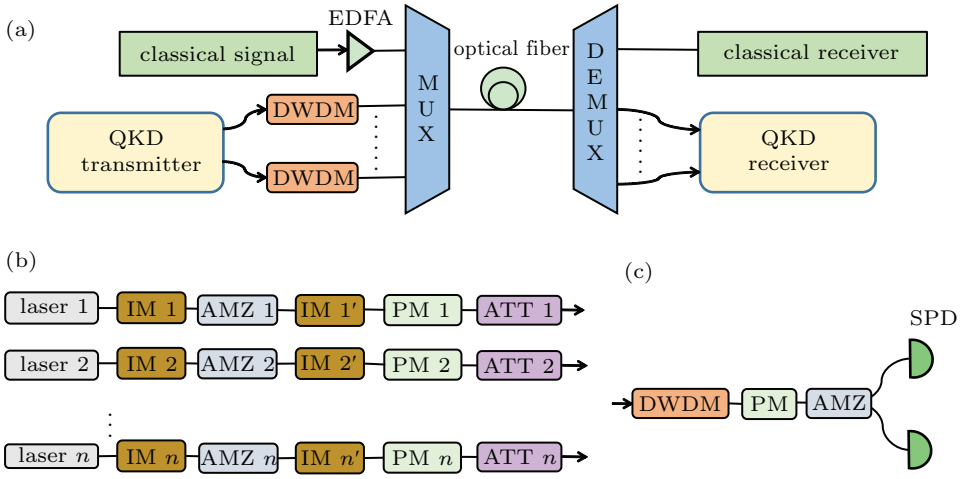


Fig. 1. (a) A scheme for multiplexing quantum channels with classical channels. DWDM: dense wavelength division multiplexer. EDFA: erbium-doped fiber amplifier. MUX: multiplexer. DEMUX: demultiplexer. (b) QKD transmitter. IM: intensity modulator. PM: phase modulator. ATT: attenuator. (c) QKD receiver. AMZ: asymmetrical Mach–Zehnder interferometer. SPD: single photon detector.

These parameters are usually derived under the "infinite key limit" assumption, i.e, the assumption that an infinite number of quantum states are sent and that all the subprotocols of the scheme (especially privacy amplification) are executed on these infinite blocks. This assumption usually simplifies the analysis; however, it may also lead to overly optimistic values about the parameter discussed.[28,29] In the finite-key case,[30] the lower bound of single-photon events $S_{s\beta j\alpha,1}$ is as follows:

$$\begin{aligned} s_{s\beta j\alpha,1}^{\rm L} = {} & \frac{\tau_1\mu_1\left(\frac{{\rm e}^{\mu_2}}{p_{\mu_2}} N_{s\beta j\alpha,\mu_2}^{\rm L} - \frac{{\rm e}^{\mu_3}}{p_{\mu_3}} N_{s\beta j\alpha,\mu_3}^{\rm U}\right)}{\mu_1(\mu_2-\mu_3) - \mu_2^2 + \mu_3^2} \\ & - \frac{\tau_1\mu_1\frac{\mu_2^2-\mu_3^2}{\mu_1^2}\left(\frac{{\rm e}^{\mu_1}}{p_{\mu_1}} N_{s\beta j\alpha,\mu_1}^{\rm U} - \frac{s_{s\beta j\alpha,0}^{\rm L}}{\tau_0}\right)}{\mu_1(\mu_2-\mu_3) - \mu_2^2 + \mu_3^2}, \end{aligned} \tag{7}$$

where $\tau_n = \sum_{k\in\{\mu_1,\mu_2,\mu_3\}} \frac{{\rm e}^{-k} k^n p_k}{n!}$ is the probability that Alice sends an n-photon state and p_k is the probability of preparing a signal, decoy or vacuum state. The lower bound of vacuum events[30] is given by

$$s_{s\beta j\alpha,0}^{\rm L} = \tau_0 \frac{\mu_2 \frac{{\rm e}^{\mu_3}}{p_{\mu_3}} N_{s\beta j\alpha,\mu_3}^{\rm L} - \mu_3 \frac{{\rm e}^{\mu_2}}{p_{\mu_2}} N_{s\beta j\alpha,\mu_2}^{\rm U}}{\mu_2 - \mu_3}. \tag{8}$$

According to the Hoeffding inequality,[31] detected counts denoted by $N_{s\beta j\alpha,k}^{\rm U}$ and $N_{s\beta j\alpha,k}^{\rm L}$ are written as

$$\begin{aligned} N_{s\beta j\alpha,k}^{\rm U} &= N_{s\beta j\alpha,k} + \sqrt{\frac{N_{s\beta j\alpha}}{2}\ln\frac{1}{\varepsilon_{\rm sec}}}, \\ N_{s\beta j\alpha,k}^{\rm L} &= N_{s\beta j\alpha,k} - \sqrt{\frac{N_{s\beta j\alpha}}{2}\ln\frac{1}{\varepsilon_{\rm sec}}}. \end{aligned} \tag{9}$$

In the WDM system, optical noise with power $P_{\rm Bob}(\lambda_n, B_{\rm Q})$ at the wavelength λ_n, within the quantum channel bandwidth $B_{\rm Q}$, which is present in the input of Bob's receiver, induces excessive noise, which is expressed as

$$P_{\rm c} = 2\eta_{\rm Bob}\frac{P_{\rm Bob}(\lambda_{\rm Q}, B_{\rm Q})}{h\nu_{\rm Q} B_{\rm Q}}. \tag{10}$$

Here, $\nu_{\rm Q}$ is the optical central frequency of the quantum signal, $\eta_{\rm Bob}$ is the inherent loss of devices at Bob's site and h is the Planck constant. To quantify $N_{s\beta j\alpha,k}$, the modeling formula of the corresponding gain denoted by $Q_{s\beta j\alpha,k}$ is written as

$$Q_{s\beta j\alpha,k} = \frac{1}{2}[1-(e_{\rm dark}+P_{\rm c}-1)(\mathrm{e}^{-k\eta(1-C_{s\beta j\alpha})} - \mathrm{e}^{-k\eta C_{s\beta j\alpha}} + \mathrm{e}^{-k\eta}(e_{\rm dark}+P_{\rm c})-1)]. \quad (11)$$

3. Numerical simulations

We also perform a simulation to illustrate our results. The parameters are chosen as $f_{\rm EC}=1.15$, $\varepsilon_{\rm sec}=10^{-9}$ and $\eta_{\rm Bob}=4.8$ dB. In the simulation, it is assumed that the intensity of the signal state is 0.7 and the intensity of the decoy states is 0.2. The probabilities that Alice selects the signal state and decoy states are 0.8 and 0.2, respectively. The dark count rate is $e_{\rm dark}=2\times10^{-6}$, and the total number of phase-randomized weak coherent pulses is 10^{10}. The wavelength is selected for intensive WDM in the C-band; for the 40-channel WDM system, the channel interval is approximately 0.8 nm. The wavelength range is from 1529.55 nm to 1560.61 nm.

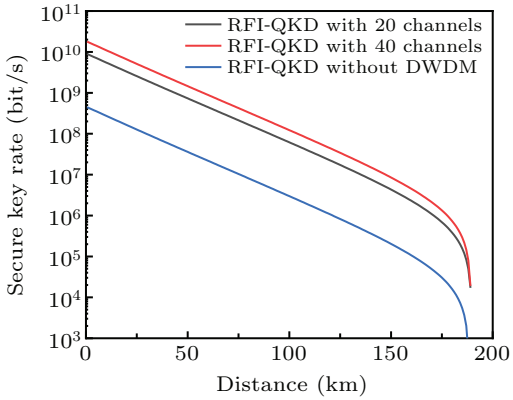


Fig. 2. Simulation results of the secret key rate with wavelength division multiplexing technology. The lines from top to bottom are the secret key rates for different number ($n=40$, 20, and 1) of channels ($N=10^9$).

As illustrated in Fig. 2, it is evident that the key rate of RFI-QKD without WDM is lower than that of RFI-QKD based on DWDM for the same transmission distance. The key rate of the protocols increases with an increase in the multiplexing number N. Furthermore, the communication distance can reach approximately 190 km. However, multiplexing greatly reduces the channel spacing, which introduces crosstalk between adjacent channels. If the quantum channel is launched into a fibre accompanied by other quantum signals, channel crosstalk can severely degrade the QKD system operation, or worse, prevent it completely. Therefore, we consider the $n^{\rm th}$ QKD channel as an example and investigate its performance in the presence of other channels. In Figs. 3 and 4, the red line represents the secret key rate with crosstalk only affected by one channel, corresponding to the first and last channels, while the blue line represents the secret key rate with crosstalk affected by two channels, corresponding to the middle channels. If the quantum signal is multiplexed with the classical signal, the crosstalk between channels will be greatly increased, in which the key rate corresponds to the green line.

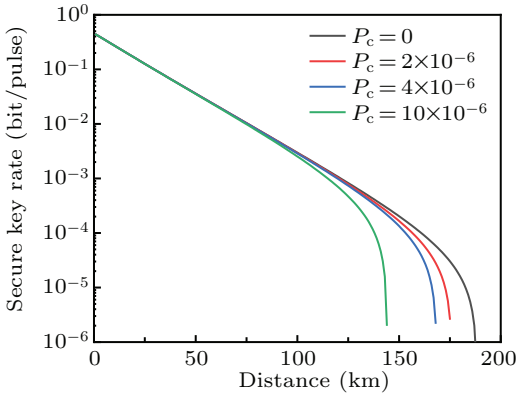


Fig. 3. Secret key rate per pulse of RFI-QKD based on WDM when considering crosstalk.

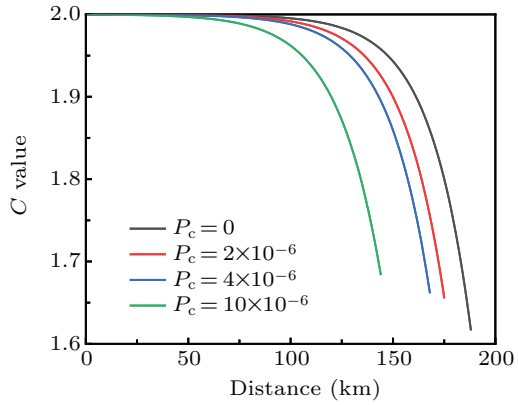


Fig. 4. Values of C at crosstalk signals intensities in RFI-QKD when $N=10^{10}$.

4. Conclusion

In summary, we have investigated the performance of RFI-QKD based on WDM technology considering finite-key analysis and channel crosstalk. The simulation results demonstrate that WDM technology can improve the secret key rate of RFI-QKD. However, the performance of a single channel is significantly reduced when considering multiplexing channel crosstalk. Therefore, RFI-QKD based on WDM improves the secret key rate of the entire system at the expense of the communication distance of each channel. According to finite-key analysis of and crosstalk, the secret key rate of RFI-QKD, which is more rigorous, is obtained. This paper thus presents a method to improve the secret key rate and provides a reference for the implementing QKD based on WDM technology in the near future.

References

[1] Gisin N, Ribordy G, Tittel W and Zbinden H 2002 *Rev. Mod. Phys.* **74** 145

[2] Lo H K, Curty M and Tamaki K 2014 *Nat. Photon.* **8** 595
[3] Bennett C H and Brassard G 2014 *Theor. Comput. Sci.* **560** 7
[4] Wang F, Xue Q X, Ji T, Li Y L, Xu T and Peng X S 2017 *Chin. Phys. Lett.* **34** 035201
[5] Wang F X, Chen W, Yin Z Q, Wang S, Guo G C and Han Z F 2019 *Phys. Rev. Appl.* **11** 024070
[6] Zhang C M, Zhu J R and Wang Q 2018 *Commun. Theor. Phys.* **70** 379
[7] Tang Z, Wei K, Bedroya O, Qian L and Lo H K 2016 *Phys. Rev. A* **93** 042308
[8] Zhang C M, Wang Q, Li X and Yuan H W 2020 *Chin. Phys. B* **29** 70303
[9] Xu P, Bao W S, Li H W, Wang Y and Bao H Z 2017 *Chin. Phys. Lett.* **34** 020302
[10] Braunstein S L and Pirandola S 2012 *Phys. Rev. Lett.* **108** 130502
[11] Lo H K, Curty M and Qi B 2012 *Phys. Rev. Lett.* **108** 130503
[12] Lucamarini M, Yuan Z, Dynes J and Shields A 2018 *Nature* **557** 400
[13] Laing A, Scarani V, Rarity J G and Brien J L 2010 *Phys. Rev. A* **82** 012304
[14] Lu F Y, Yin Z Q and Yuan F 2020 *Phys. Rev. A* **101** 052318
[15] Chen H, Wang J, Tang B, Li Z, Liu B and Sun S H 2020 *Opt. Lett.* **45** 3022
[16] Li J J, Wang Y, Li H W and Bao W S 2020 *Chin. Phys. B* **29** 030303
[17] Gu W Y, Zhao S H, Dong C, Wang X Y and Yang D 2019 *Acta Phys. Sin.* **68** 240301 (in Chinese)
[18] He R S, Jiang M S, Wang Y *et al.* 2019 *Chin. Phys. B* **28** 040303
[19] Townsend P 1997 *Electron. Lett.* **33** 188
[20] Nweke N I 2005 *Appl. Phys. Lett.* **87** 174103
[21] Tanaka A, Fujiwara M *et al.* 2008 *Opt. Express* **16** 11354
[22] Yoshino K, Ochi T, Fujiwara M, Sasaki M and Tajima A 2013 *Opt. Express* **21** 31395
[23] Eraerds P, Walenta N, Gisin N and Zbinden H 2010 *New J. Phys.* **12** 063027
[24] Patel K A, Dynes J F *et al.* 2014 *Appl. Phys. Lett.* **104** 051123
[25] Wang L J, Zou K H *et al.* 2017 *Phys. Rev. A* **95** 012301
[26] Sun W, Wang L J *et al.* 2018 *J. Appl. Phys.* **123** 043105
[27] Eriksson T, Hirano T *et al.* 2019 *Commun. Phys.* **2** 9
[28] Zhang H, Mao Y, Huang R, Guo Y, Wu X D and Zhang L 2018 *Chin. Phys. B* **27** 090307
[29] Zhang X Z, Gong W G, Tan Y G *et al.* 2009 *Chin. Phys. B* **18** 2143
[30] Tomamichel M, Lim C, Gisin N and Renner R 2012 *Nat. Commun.* **3** 634
[31] Wang Y, Bao W S, Zhou C, Jiang M S and Li H W 2016 *Phys. Rev. A* **94** 032335