A new synchronization scheme based on time division multiplexing and wavelength division multiplexing technology for practical quantum key distribution system*

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Three clock synchronization schemes for a quantum key distribution system are compared experimentally through the outdoor fibre and the interaction physical model of the the clock signal and the the quantum signal in the quantum key distribution system is analysed to propose a new synchronization scheme based on time division multiplexing and wavelength division multiplexing technology to reduce quantum bits error rates under some transmission rate conditions. The proposed synchronization scheme can not only completely eliminate noise photons from the bright background light of the the clock signal, but also suppress the fibre nonlinear crosstalk.

Keywords: quantum key distribution, clock synchronization, wavelength division multiplexing, time division multiplexing

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1. Introduction

Since BB84 protocol was proposed by Bennett and Brassard in 1984,[1] quantum key distribution (QKD) has gone through a rapid development. Many other protocols have been put forward such as the two-state protocol, six-state protocol and Einstein–Podolsk–Rosen protocol.[2−9] The unconditional security for BB84 has been proven even with an attenuated laser source.[10−17] Recently, much QKD research has focused on the QKD network.[18−21] However, there are still several key problems when the QKD system is put into practical operation, such as single photon sources, single-photon detectors and clock synchronization technology. Nowadays, the single photon sources have been studied widely by various physical systems and the primary single photon sources in use are heralded as single photon sources based on parametric processes either in the form of spontaneous parametric down-conversion[22,23] or four-wave mixing.[24,25] As for single-photon detectors, superconducting single photon detectors (SSPD), which offer a very low dark counting (a few Hz) and small timing jitter, have been applied to the QKD system.[26−28]

Clock synchronization technology is crucial for a practical QKD system besides single photon sources and single-photon detectors, because base comparison over a public classical channel requires accurate synchronization. In particular, when InGaAs avalanche photodiodes (APDs) are used and operated in Geiger mode, it meets higher demands for clock synchronization. There are many ways for clock transmission in the QKD system, such as transmitting clock in an electrical cable,[29] in the paired fibres[19,30,31] and in the same fibre with the quantum signal.[32,33] Wavelength division multiplexing is employed to transmit the optical the clock signal and the quantum signal in the same

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fibre to compensate the fluctuation of the photon arrival time, in parallel with the quantum signal.[28,32,33] However, this synchronization technique of the QKD system suffers badly from the bright background of optical clock signal and the interaction of the the clock signal and the quantum signal.[34−36] A main method for avoiding these impacts is to use a low-loss, high-isolation filter architecture to suppress the noise photons from the clock signal and nonlinear effects.[28] However, if the frequencies of the noise photons are just in the quantum bandwidth, they cannot be eliminated by this method.

In this work, three clock synchronization schemes for the QKD system are compared experimentally through the outdoor fibre, which shows that transmitting the the clock signal and the the quantum signal in the same fibre is more suitable for the practical operation of QKD. When two signals propagate in the same fibre, there is interaction between them. We analyse the interaction physical model of the the clock signal and the the quantum signal in the QKD system and give a method based on wavelength division multiplexing (WDM) and time division multiplexing (TDM) to reduce quantum bits error rates (QBER) induced by the the clock signal under some transmission rate condition. This method can not only completely eliminate noise photons from the bright background light of the clock signal, but also suppress the fibre nonlinear crosstalk.

2. Three different schemes for clock synchronization

Clock synchronization is absolutely necessary in the QKD system. Without the time gate being synchronized to the photon arrival, the receiver cannot identify the the quantum signal correctly, because the photon arrival time may drift due to the change in the long transmission fibre. Importantly, without the time gate synchronized to the photon arrival, Bob cannot record accurately the photon arrival time which is required in the next step, where Alice and Bob determine, by public exchange of message, which photons are successfully received and among these which are received with the correct basis. We have researched the three different schemes for clock synchronization experimentally. As we know, though using a single fibre channel for QKD has been proposed in prior publications, there is no experimental proof.

The experimental setups are shown in Fig. 1. A pulse generator was used as a clock source to trigger PLS PDL 808 produced by PicoQuant GmbH. Single photons at 1546 nm from an attenuated PLS were transmitted through 75 km single mode fibre (SMF) which was placed outdoors and then detected by SPD with a 2.5 ns-width time gate. The attenuator FVA3100 is produced by Exfo and the single photon detector ID201 by IDquantique. the clock signals are transmitted in an electrical cable in Fig. 1(a), in a paired fibre in Fig. 1(b) and in the same fibre as the quantum signal in Fig. 1(c), respectively.

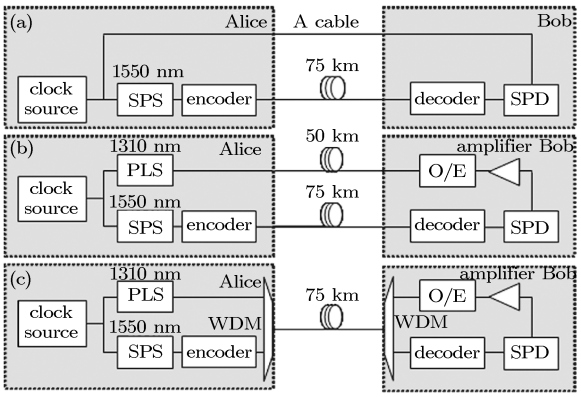


Fig. 1. Three different schemes for clock synchronization. (a) the clock signal transmitted in 1-m electrical cable, (b) the clock signal transmitted in the other fibre, (c) the clock signal transmitted in the same fibre with the quantum signal. SPS: single photon source, PLS: pulse laser source, O/E: photoelectric converter, SPD: single photon detector.

When clock synchronization is set to be the best value, there is a maximum count in single photon detector, which indicates the best detection efficiency. If the position of the maximum count is stable, the detection time gate of SPD can be set there. However, the position of the maximum count may drift with the change in the transmission distance, resulting in rapid decline in accuracy of clock synchronization and a decline in detection efficiency. As shown in Fig. 2, the position of the maximum count drifts more quickly in an electrical cable and in the paired fibres system than in the same fibre system. The maximum drift is about 8.5 ns in a cable system, 6.2 ns in the paired fibres system, but only 0.3 ns in the same fibre system. When the detection time gate was set to be 2.5 ns in width, the position of the maximum count drifted out of the detection time gate in the first two systems, leading to a rapid decline in detection efficiency, even avoiding detection, while it did not drift out in the same fibre system. Therefore, it is impossible to achieve the reasonable synchronization performance that clock signal and the quantum signal are not transmitted in the same fibre, because they experience different ambient environments, which will degrade the accuracy of synchronization, resulting in a lower detection efficiency

and a raw key rate. Meanwhile, it is costly to maintain a separate cable or fibre infrastructure solely for QKD. From the above analysis, we can find that transmitting the clock signal and the the quantum signal in the same fibre is the best synchronization scheme.

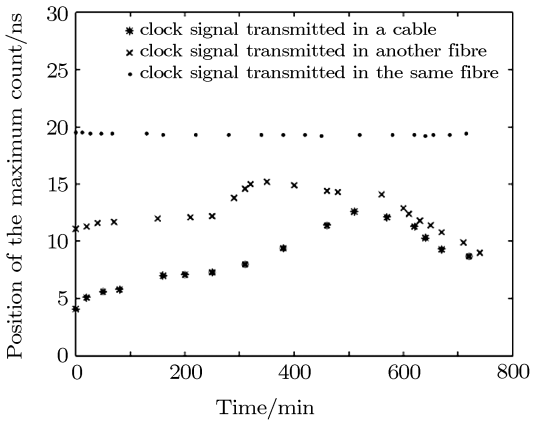


Fig. 2. The position of the maximum count drifts with time.

There are two schemes for delivering the the clock signal in the same fibre: TDM and WDM. Both of them have its advantages and disadvantages. TDM has an advantage of avoiding crosstalk between clock and the quantum signals, but requires optical switch,[37] sufficiently long time interval between quantum and clock pulses, extremely high extinction ratio of the clock pulses and precise waveform distortion compensation, to avoid interference between these pulses, which limit the key sharing speed.[28] Compared with TDM scheme, WDM synchronization is free from speed limitations, but the the clock signal will provide a strong background light especially when its side-mode suppression ratio is not high enough, and will produce noise photons through χ^3 fibre nonlinear effects, such as stimulated Raman scattering and parametric amplification.[35,36] These photons accumulate easily to a critical level, because the clock signal is extremely larger than the the quantum signal. If the nonlinear crosstalk could be sufficiently suppressed, then the WDM system would be an ideal synchronization system.

3. Physical models of the interaction between the clock signal and the quantum signal in the WDM+QKD system

When the clock signal and the quantum signal are transmitted in the same optical fibre, it will introduce some new problems and the most critical problem is that the the clock signal will produce noise photons which have an impact on the performances of the QKD system. The noise photons impact the WDM+QKD system in two ways. First, because of the low isolation of WDM, some of the the clock signal will not be completely separated from the the quantum signal and if these photons and quantum signal overlap or propagate closely enough, they will fall on the detection time gate at the same time and can be detected simultaneously by SPD, resulting in the increase of QBER. Secondly, nonlinear noises produced in the process of signal transmission may fall on the detection time gate together with the quantum signal at the same time, which also results in an increase of QBER.

The noises generated in the first case can be removed by increasing the isolation of the WDM or using a low-loss, high-isolation narrow-band filter architecture. In the second case, those noise photons with different frequencies from the the quantum signal can be eliminated by using filtering architecture, but other noise photons with the same frequency as the quantum signal cannot be eliminated by the filtering method. However, we can suppress the nonlinear effects to reduce these noise photons. According to the walk-off effect, there will be no nonlinear interaction between two optical pulses when the faster moving pulse completely walks through the slower moving pulse. Therefore, in the WDM+QKD system, because clock signal and the quantum signal have different frequencies, the nonlinear crosstalk between them occurs only in a certain length of transmission link referred to as the effective interaction length, where the two pulses overlap or partially overlap. The distribution of the effective interaction length between the clock signal and quantum signal takes three forms. In the first form, there is no effective interaction in the whole transmission link, that is, the clock signal pulse and the the quantum signal pulse propagate separately in the whole transmission process; the second one, the effective interaction between the two pulses occurs during the transmission process, but the interaction will stop when they reach the detector; the third one, the the clock signal pulse and the quantum signal pulse propagate separately at the beginning, but will overlap when they arrive at the detector.

In the first case, there is no interaction between the the clock signal and the quantum signal, but the the clock signal itself has nonlinear effects and may produce noise photons. However, these noise photons have little impact on the QBER, for they are always separated from the the quantum signal in the whole transmission link and so long as the two pulses

separate at a greater time-interval than the detection time gate of SPD, the noise photons can be hardly detected by SPD in Geiger mode. In the second case, there is interaction between the the clock signal and the quantum signal and the noise photons with the same frequencies as the quantum signal will increase the QBER of the WDM+QKD system, because they propagate at the same speed as the quantum signal, and arrive at the detector simultaneously, while the noise photons with different frequencies from the quantum signal can be eliminated for their different speeds from the quantum signal or by filters In the third case, the interaction happens at the receiver and the noise photons, with the same frequencies as the quantum signal or not, will increase the QBER of the WDM+QKD system, because they arrive at the detector at the same time as the quantum signal and then can be detected by SPD.

4. A solution to reduce noise photons produced by the clock signal

Since quantum pulses and clock pulses have different wavelengths in the WDM+QKD system, they propagate at different speeds inside the fibre because of chromatic dispersion and there will be no nonlinear interaction between them when the faster moving pulse completely walks through the slower moving pulse. Therefore, there is an effective interaction length, where the nonlinear interaction happens rather than in the entire transmission fibre. If we can change the effective interaction length, we can control the nonlinear interaction. A method for reducing QBER of the WDM+QKD system by controlling the effective interaction length is then proposed as follows. This method using wavelength-division and time-division transmission but time-division detection, combines the advantages of WDM and TDM. By using this method, it is not necessary to add any other optical components to the QKD system, resulting in reduced channel loss, streamlined system structure and cutting cost. Most importantly, when the effective interaction length is set to be zero, it can not only eliminate the nonlinear crosstalk, but also remove the effects of noise photons from the bright background light of the clock signal, because this method make noise photons and quantum signal arrive at SPD at different times. If noise photons arrive at SPD out of the detection time gate, they will not be detected and have no effect on the quantum signal. This research is also very useful for coexistence of QKD and telecom channels in shared-fibre networks.[38]

There are two methods to make the effective interaction length be zero. The first one is letting faster moving pulses travel ahead with a certain delay Δt into the WDM; the second one is letting slower moving pulses travel ahead into the WDM. We study the both cases in experiment and in theory.

4.1. Experimental research

Figure 3 shows the experimental setup to investigate the influence of the clock signal. At Alice, a 1546 nm directly modulated laser diode created 100 ps-wide pulses with a repetition of 1 MHz and the average photon number is 0.1 photons every pulse. A 1309 nm clock source created 100 ps-wide clock pulses with a repetition of 1 MHz by the same clock source. the clock signal and the quantum signal were combined into the same fibre by a high-isolation WDM coupler (80 dB) and then were divided by WDM in the receiver. At Bob, single photon detectors based on avalanche photodiodes, with 2.5 ns-width time gate and 10% detection efficiency, were used to detect single photons. The length of transmission fibre was about 50 km. The delay fibre was used to change the effective interaction length between the quantum signal and the clock signal.

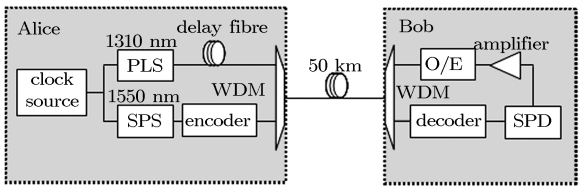


Fig. 3. Experimental setup.

To study the effects of the the clock signal on the QKD system, the quantum channel was cut off and then a higher photon count than dark count was observed. These noise photons probably came from the clock signal which was not isolated enough by WDM and new frequency photons produced by fibre nonlinear effects. If they are not suppressed to an extremely low level, the QBER of the QKD system will increase sharply and the secret key rate will reduce. A narrowband optical filter for the the quantum signal is used to eliminate these noise photons after being divided from the WDM in many laboratories.[28] However, it cannot eliminate all of the noise photons, especially when the noise photon frequencies are just in quantum bandwidth. By our reported method, the noise

photons can be completely eliminated and the QBER can be reduced to the minimum value limited by dark counts of SPD.

Figure 4 shows the QBER versus the arrival time delay between the the quantum signal and the clock signal into the WDM. When the quantum signal transmits 105 ns ahead of clock quantum or 67 ns behind the clock signal into the WDM, they do not overlap in the whole transmission link (50 km fibre can produce about 100 ns time delay) and then there is no interaction, resulting in the decrease of the QBER to 0.7%. When the quantum signal transmits 0 ns–100 ns ahead into the WDM, there is interaction between them, resulting in the increase of QBER. The maximum value shows that the clock signal and the quantum signal arrive at the detector at the same time. Therefore, whether noise photons exist or not, there is little impact on QBER when the quantum signal and the clock signal are transmitted with a certain delay in the same fibre.

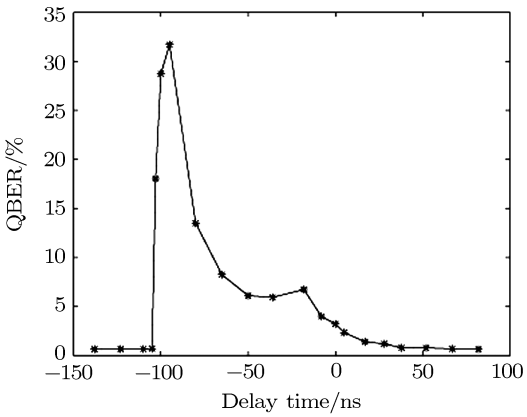


Fig. 4. Relationship between QBER and delay arrival time.

4.2. Theoretical analysis

An important feature of chromatic dispersion is that pulses at different wavelengths propagate at different speeds inside the fibre because of the group-velocity mismatch. This feature leads to a walk-off effect that plays an important role in the description of the nonlinear effects involving two or more overlapping optical pulses. More specifically, there will be no nonlinear interaction between two optical pulses when the faster moving pulse completely walks through the slower moving pulse. As the quantum signal and clock signal have different frequencies, they travel at different group velocities. Therefore, it is possible to transmit the quantum signal pulses and the clock signal pulses in the same fibre without overlapping and also possible to make them arrive at single photon detection with a certain delay, resulting in completely eliminating noise photons produced by the clock signal.

When the clock signal transmits Δt ahead of the quantum signal into the WDM, as the clock signal travel faster than the quantum signal in SMF, the delay time of the two signals will increase with the increase of transmission length. In order to make sure the two kinds of pulses do not overlap, the delay time must meet the following relationship:

$$\Delta t \Delta\tau + T_{\rm c} + T_{\rm q} \leq T, \tag{1}$$

where $\Delta\tau$ is the delay time caused by the group-velocity mismatch, the parameters $T_{\rm c}$ and $T_{\rm q}$ stand for the full width of the broadened clock pulses and quantum pulses respectively and the quantity T represents the transmission repetition period. By using

$$\Delta\tau = L\left|\beta_1\left(\lambda_{\rm c}\right) - \beta_1\left(\lambda_{\rm q}\right)\right|, \quad T_{\rm c} = T_{\rm c0} + D_{\rm c} L \Delta\lambda_{\rm c}$$

and $T_{\rm q} = T_{\rm q0} + D_{\rm q} L \Delta\lambda_{\rm q}$,[39] where $D_{\rm c}$ and $D_{\rm q}$ are the dispersion parameters of the clock signal and the quantum signal respectively and L represents the length of transmission fibre, Eq. (1) can be written as

$$\begin{aligned} &\Delta t + L\left|\beta_1\left(\lambda_{\rm c}\right) - \beta_1\left(\lambda_{\rm q}\right)\right| \\ &+ T_{\rm c0} + D_{\rm c} L \Delta\lambda_{\rm c} + T_{\rm q0} + D_{\rm q} L \Delta\lambda_{\rm q} \leq T. \end{aligned} \tag{2}$$

By using $T = 1/f$, equation (2) can be written as

$$\begin{aligned} f \leq\ & 1/(\Delta t + L\left|\beta_1\left(\lambda_{\rm c}\right) - \beta_1\left(\lambda_{\rm q}\right)\right| \\ & + T_{\rm c0} + D_{\rm c} L \Delta\lambda_{\rm c} + T_{\rm q0} + D_{\rm q} L \Delta\lambda_{\rm q}). \end{aligned} \tag{3}$$

When clock the quantum signal transmits Δt ahead of the quantum signal into the WDM, the minimum Δt to avoid their overlapping is the full width of clock pulses, for the group-velocity mismatch makes them separate farther and farther and they are not overlapping at a later time. Therefore, we obtain the maximum transmission repetition rate as

$$\begin{aligned} f_{\max} =\ & 1/(T_{\rm c0} + L\left|\beta_1\left(\lambda_{\rm c}\right) - \beta_1\left(\lambda_{\rm q}\right)\right| \\ & + T_{\rm c0} + D_{\rm c} L \Delta\lambda_{\rm c} + T_{\rm q0} + D_{\rm q} L \Delta\lambda_{\rm q}). \end{aligned} \tag{4}$$

Mathematically, $\beta_1(\lambda)$ can be expanded in a Taylor series about the center wavelength $\lambda_{\rm q}$

$$\begin{aligned} \beta_1(\lambda) =\ & \beta_{10}\left(\lambda_{\rm q}\right) + \beta_{11}\left(\lambda_{\rm q}\right)\left(\lambda - \lambda_{\rm q}\right) \\ & + \frac{1}{2}\beta_{12}\left(\lambda_{\rm q}\right)\left(\lambda - \lambda_{\rm q}\right) + \cdots, \end{aligned} \tag{5}$$

where

$$\beta_{1m} = \frac{{\rm d}^m \beta_1}{{\rm d}\lambda^m} \quad (m = 0, 1, 2, \ldots). \tag{6}$$

When we just take the first derivative into account and suppose $\lambda = \lambda_{\rm c}$, we can obtain the following equation from Eq. (5):

$$\Delta\tau = L\left|\beta_1\left(\lambda_{\rm c}\right) - \beta_1\left(\lambda_{\rm q}\right)\right| \approx L D_{\rm q} \Delta\lambda_{\rm q,c}, \tag{7}$$

then, equation (2) can be written as

$$f_{\max} = 1/(LD_{\rm q}\Delta\lambda_{\rm q,c} + 2T_{\rm c0} + D_{\rm c}L\Delta\lambda_{\rm c} + T_{\rm q0} + D_{\rm q}L\Delta\lambda_{\rm q}). \quad (8)$$

This equation shows that the maximum transmission repetition rate is dependent on the frequencies of quantum and the clock signals, the dispersion parameter D, the line-width of the light sources and the fibre length.

When the wavelengths of the quantum signal and the clock signal are 1550 nm and 1310 nm, respectively, the wavelength mismatch $\lambda_{\rm q,c}$ is far longer than the line-width of the light source $\Delta\lambda_{\rm c}$ or $\Delta\lambda_{\rm q}$. As a result, the extent of signal pulses broadening can be neglected. Meanwhile, the pulse-width of the light sources is about 100 ps and can also be neglected. By using these two approximations, equation (8) can be written as

$$f_{\max} \approx 1/\left(LD_{\rm q}\Delta\lambda_{\rm q,c}\right). \quad (9)$$

For example, if $L = 100$ km and $D_{1546} = 14$ ps·nm^{-1}·km^{-1}, then the maximum transmission frequency is about 3 MHz.

When the quantum clock signal travels Δt ahead of the quantum signal into the WDM, as the clock signal travels faster than the quantum signal in SMF, the delay time of the two signals will reduce with the increase of transmission length. In order to make sure the two kinds of pulses do not overlap, the delay time must meet the following relationship:

$$\Delta t - \Delta\tau - \Delta T_{\rm c} - \Delta T_{\rm q} \geq 0. \quad (10)$$

The parameters $\Delta\tau$ are defined as above, by using $\Delta T_{\rm c} = D_{\rm c}L\Delta\lambda_{\rm c}$ and $\Delta T_{\rm q} = D_{\rm q}L\Delta\lambda_{\rm q}$, equation (10) can be written as

$$\Delta t - L\left|\beta_1\left(\lambda_{\rm c}\right) - \beta_1\left(\lambda_{\rm q}\right)\right| - D_{\rm c}L\Delta\lambda_{\rm c} - D_{\rm q}L\Delta\lambda - D_{\rm q} \geq 0. \quad (11)$$

When Δt is set to be the approximate maximum delay $1/f$, we can obtain the relationship as follows:

$$f_{\max} = 1/\left(LD_{\rm q}\Delta\lambda_{\rm q,c} + D_{\rm c}L\Delta\lambda_{\rm c} + D_{\rm q}L\Delta\lambda_{\rm q}\right). \quad (12)$$

The above theoretical analysis shows that this method, which makes sure that the clock signal and the quantum signal do not overlap in the transmission fibre and arrive at single photon detection with a certain delay, can not only completely eliminate noise photons from the bright background light of the clock signal, but also suppress the fibre nonlinear crosstalk. However, it has a frequency limit. When the transmission repetition rate is higher than a certain value, it is certain that the two kinds of signal pulses will overlap, resulting in new noise photons produced by nonlinear effects to increase the QBER.

5. Conclusion

In this paper, three different schemes for clock synchronization in the QKD system are compared experimentally and transmitting the clock signal and the the quantum signal in the same fibre is demonstrated to be the best synchronization scheme. In the WDM+QKD system, the physical model of the interaction between the clock and quantum signal inside the transmission fibre is analysed to introduce a method to reduce the QBER of the QKD system. Using this method, it is not necessary to add any other optical components to the QKD system, resulting in reduced channel loss, streamlined system structure and cutting cost. Most importantly, it can not only completely eliminate noise photons from the bright background light of the clock signal, but also suppress the fibre nonlinear crosstalk. We also calculate the maximum transmission repetition rate for a certain fibre length limited by this method. We expect that improvements to QKD systems for longer fibre transmission distances will extend the application of this approach to metropolitan area networks.

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