Complete Bell-state analysis for a single-photon hybrid entangled state*

Sheng Yu-Bo(盛宇波)[a)c)], Zhou Lan(周 澜)[a)b)†], Cheng Wei-Wen(程维文)[a)c)], Gong Long-Yan(巩龙龑)[a)b)c)], Wang Lei(王 磊)[a)c)], and Zhao Sheng-Mei(赵生妹)[a)c)]

[a)] *Institute of Signal Processing Transmission, Nanjing University of Posts and Telecommunications, Nanjing* 210003, *China*
[b)] *College of Mathematics & Physics, Nanjing University of Posts and Telecommunications, Nanjing* 210003, *China*
[c)] *Key Laboratory of Broadband Wireless Communication and Sensor Network Technology, Ministry of Education, Nanjing University of Posts and Telecommunications, Nanjing* 210003, *China*

(Received 30 August 2012; revised manuscript received 13 October 2012)

We propose a scheme capable of performing complete Bell-state analysis for a single-photon hybrid entangled state. Our single-photon state is encoded in both polarization and frequency degrees of freedom. The setup of the scheme is composed of polarizing beam splitters, half wave plates, frequency shifters, and independent wavelength division multiplexers, which are feasible using current technology. We also show that with this setup we can perform complete two-photon Bell-state analysis schemes for polarization degrees of freedom. Moreover, it can also be used to perform the teleportation scheme between different degrees of freedom. This setup may allow extensive applications in current quantum communications.

Keywords: quantum communication, hybrid entangled state, Bell-state analysis

PACS: 03.67.Dd, 03.67.Hk, 03.65.Ud **DOI:** 10.1088/1674-1056/22/3/030314

1. Introduction

Quantum information processes have demonstrated an important development in recent years,[1] where the most important branches are long-distance quantum communication and quantum computation. Quantum entanglement is a key resource in both branches. Quantum teleportation,[2–4] optical cryptographic schemes,[5,6] quantum gates in quantum computing with linear optics,[7] quantum repeaters,[8–16] quantum secure direct communication,[17–31] quantum dense coding,[32,33] quantum secret sharing,[34–37] and quantum state sharing[38–44] all need entangled states. Usually, in an optical system the basic entangled state, named the Bell state, is encoded in the polarization degree of freedom, since it is easy to manipulate and control. The four orthogonal Bell states are

$$|\phi^{\pm}\rangle = \frac{1}{\sqrt{2}}(|HH\rangle \pm |VV\rangle),$$
$$|\psi^{\pm}\rangle = \frac{1}{\sqrt{2}}(|HV\rangle \pm |VH\rangle), \quad (1)$$

where $|H\rangle$ and $|V\rangle$ represent the horizontal and vertical polarization of photons, respectively.

In order to perform quantum communication processes successfully, many applications, such as quantum teleportation,[2–4] quantum swapping in quantum repeaters,[8,9] and quantum dense coding,[32,33] resort to Bell-state analysis (BSA). However, with linear optics, complete BSA is impossible because one can only distinguish two Bell states, whereas two Bell states are undistinguishable. Therefore, the whole probability of success is only 1/2.[45–47] In the optimal optical system, the BSA scheme has been realized experimentally with a success probability of 50%.[33,48,49] In 1998, Kwait and Weinfurter first proposed a method of performing a complete BSA.[50] By using hyperentangled states, which simultaneously entangle in more than one degree of freedom, such as polarization-momentum and polarization-spatial modes, it is indeed possible to achieve complete BSA.[51–54] The group of Kwait also argued that if the additional degree of freedom is thought of as qubit-like, one can only discriminate seven states from the whole 16 states. They concluded that the upper bound of the maximal number of the Bell-like states is $2^{n+1}-1$, where n is the number of degrees of freedom.[55] In 2010, we presented a complete hyperentangled Bell-state analysis, resorting to cross-Kerr nonlinearity.[56]

Interestingly, there is another kind of entangled state that is different from both the conventional entangled state and the hyperentangled state, and this is called the hybrid entangled state.[14–16,57–61] It refers to the entanglement between different degrees of freedom. The hybrid entangled state can exhibit entanglement either in a single photon, or in the photon pair. In 2009, Neves *et al.* realized hybrid photonic entanglement, and

*Project supported by the National Natural Science Foundation of China (Grant Nos. 11104159, 61201164, and 61271238), the Open Research Fund Program of the State Key Laboratory of Low-Dimensional Quantum Physics Scientific, Tsinghua University, China, the Open Research Fund Program of National Laboratory of Solid State Microstructures, Nanjing University, China (Grant Nos. M25020 and M25022), the Priority Academic Development Program of Jiangsu Higher Education Institutions, China, the Open Research Fund of National Mobile Communications Research Laboratory of Southeast University, China (Grant No. 2011D05), and the Specialized Research Fund for the Doctoral Program of Higher Education of China (Grant No. 20123223110003).

†Corresponding author. E-mail: zhoul@njupt.edu.cn

© 2013 Chinese Physical Society and IOP Publishing Ltd

they also discussed some of the applications.[57] Fujiwara *et al.* reported their experiment to demonstrate a source of hybrid entanglement pairs between two different degrees of freedom, that is, a 1550 nm time bin and 810 nm polarization qubit.[58] Recently, the hybrid entangled state has also been used to perform quantum repeaters,[14–16] and the group of Kwait reported on their experiment of a remote preparation of a single-photon hybrid entangled state.[59]

Similar to the conventional Bell state, if the hybrid entangled state can be prepared experimentally, another task would be to perform BSA. In this paper, we will devise a method to complete single-photon hybrid Bell-state analysis (HBSA). Our single-photon hybrid entangled state is encoded in both polarization and frequency degrees of freedom. Then we will show that with this setup, we can perform complete polarization BSA by hyperentanglement. Moreover, we can achieve a teleportation scheme between different degrees of freedom.

This paper is organized as follows. In Section 2, we explain the basic principle of HBSA. In Section 3, we discuss the applications of HBSA, and in Section 4, we end with a discussion and conclusion.

2. HBSA for polarization and frequency degrees of freedom

The four orthogonal single-photon hybrid Bell states can be described as

$$|\Phi^{\pm}\rangle = \frac{1}{\sqrt{2}}(|H\omega_1\rangle \pm |V\omega_2\rangle),$$
$$|\Psi^{\pm}\rangle = \frac{1}{\sqrt{2}}(|H\omega_2\rangle \pm |V\omega_1\rangle), \quad (2)$$

where ω_1 and ω_2 are the frequency of the photon. For a parametric down-conversion (PDC) source, if suitable phase match conditions can be satisfied, one can easily prepare the hyperentangled state both in polarization and frequency degrees of freedom, which can be described as

$$\begin{aligned}|\varphi\rangle &= |\phi_P^+\rangle \otimes |\psi_F^+\rangle \\ &\equiv (|HH\rangle + |VV\rangle)/\sqrt{2} \otimes (|\omega_1\omega_2\rangle + |\omega_2\omega_1\rangle)/\sqrt{2} \\ &= \frac{1}{2}(|\Phi^+\rangle_A \otimes |\Psi^+\rangle_B + |\Phi^-\rangle_A \otimes |\Psi^-\rangle_B \\ &+ |\Psi^+\rangle_A \otimes |\Phi^+\rangle_B + |\Psi^-\rangle_A \otimes |\Phi^-\rangle_B), \end{aligned} \quad (3)$$

where the subscripts P and F denote the polarization and frequency, respectively. If we trace one of two particles, say A, the other particle B must be in a mixed hybrid state

$$\begin{aligned}\rho_B &= \frac{1}{4}(|\Phi^+\rangle_B\langle\Phi^+| + |\Phi^-\rangle_B\langle\Phi^-| \\ &+ |\Psi^+\rangle_B\langle\Psi^+| + |\Psi^-\rangle_B\langle\Psi^-|). \end{aligned} \quad (4)$$

The setup for HBSA is shown in Fig. 1. Independent wavelength division multiplexers (WDMs) can guide the photon to different spatial modes according to their frequency. In detail, if the frequency is ω_1, this will be in the spatial mode a_1. If the frequency is ω_2, it will be in the spatial mode a_2. A polarizing beam splitter (PBS) is used to transmit a horizontally ($|H\rangle$) polarized photon and reflect a vertically ($|V\rangle$) polarized one. A frequency shifter (FS) is used to complete the frequency transformation. If the initial frequency of the photon is ω_1, it can be converted to ω_2 after the photon passes through the FS. If the initial frequency of the photon is ω_2, the frequency does not change. Therefore, the FS plays the role of a quantum eraser for the frequency degree of freedom. The role of the quarter wave plate (R_{45}) can be viewed as the Hadamard operation

$$|H\rangle \to \frac{1}{\sqrt{2}}(|H\rangle + |V\rangle),$$
$$|V\rangle \to \frac{1}{\sqrt{2}}(|H\rangle - |V\rangle). \quad (5)$$

By virtue of the quantum nondemolition detectors (QNDs), a conventional polarization BSA can be divided into two steps,[62] where the parity check has to be performed twice. The first step is to distinguish $|\phi^{\pm}\rangle$ from $|\psi^{\pm}\rangle$. We call $|\phi^{\pm}\rangle$ the even parity states, and $|\psi^{\pm}\rangle$ the odd parity states. The second step is to distinguish $|\phi^+\rangle$ from $|\phi^-\rangle$, and $|\psi^+\rangle$ from $|\psi^-\rangle$. From Eq. (2), $|\Phi^{\pm}\rangle$ and $|\Psi^{\pm}\rangle$ can also be viewed as even and odd parity states. As shown in Fig. 1, after WDM and PBS, the items $|H\omega_1\rangle$ and $|V\omega_2\rangle$ will be in the spatial mode b_2 , but the items $|V\omega_1\rangle$ and $|H\omega_2\rangle$ will be in the spatial mode b_1. Therefore, WDM and PBS can guide different parity states into different spatial modes, which leads to $|\Phi^{\pm}\rangle$ in the spatial mode b_2 and $|\Psi^{\pm}\rangle$ in the spatial mode b_1. Then after the FS, $|\Phi^{\pm}\rangle$ becomes

$$\begin{aligned}|\Phi^{\pm}\rangle &= \frac{1}{\sqrt{2}}(|H\omega_1\rangle \pm |V\omega_2\rangle) \to \frac{1}{\sqrt{2}}(|H\omega_2\rangle \pm |V\omega_2\rangle) \\ &= \frac{1}{\sqrt{2}}(|H\rangle \pm |V\rangle)|\omega_2\rangle. \end{aligned} \quad (6)$$

It is easy to find that with FS, we have erased different frequencies, making them have the same frequency. Then, after the H operation

$$\frac{1}{\sqrt{2}}(|H\rangle + |V\rangle) \to |H\rangle,$$

$$\frac{1}{\sqrt{2}}(|H\rangle - |V\rangle) \to |V\rangle,$$

one can distinguish $|\Phi^+\rangle$ from $|\Phi^-\rangle$ by the detectors D_1 and D_2. If D_1 is registered, it must be $|\Phi^+\rangle$. Otherwise, it must be $|\Phi^-\rangle$. Following the same principle, $|\Psi^{\pm}\rangle$ can also be distinguished easily. In other words, if D_3 is registered, it must be $|\Psi^+\rangle$, and if D_4 is registered, it must be $|\Psi^-\rangle$.

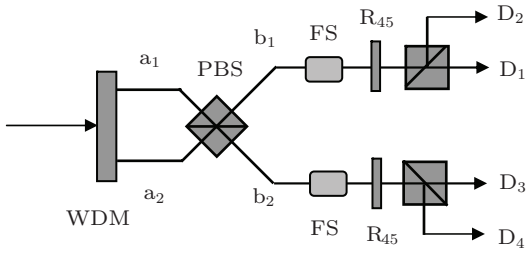


Fig. 1. A schematic diagram of HBSA. WDM denotes the independent wavelength division multiplexer, which can guide the photon to different spatial modes according to their frequencies. FS denotes the frequency shifter, which is used to eliminate the frequency difference. PBS denotes the polarizing beam splitters in the H–V basis.

Up to this point, we have briefly described the basic principle of our HBSA. It is interesting to compare it with the polarization BSA with linear optics. Theoretically speaking, the Bell state given by Eq. (1) can also be distinguished with the same method, where $|\phi^{\pm}\rangle$ is first distinguished from $|\psi^{\pm}\rangle$, and $|\phi^{\pm}\rangle$ and $|\psi^{\pm}\rangle$ are then distinguished from themselves, respectively. Without doubt, with PBS, the even parity states $|\phi^{\pm}\rangle$ can be easily distinguished from the odd parity states $|\psi^{\pm}\rangle$, because $|HH\rangle$ and $|VV\rangle$ always put the two photons in the two output modes, and each output mode contains exactly one photon. However, $|HV\rangle$ and $|VH\rangle$ result in photons in the same output modes. Fortunately, the single-photon hybrid Bell state is quite different from the conventional Bell state. It does not exist in the case where the two photons are in the same spatial mode, because it is only one photon. Therefore, WDM combined with PBS can easily lead to $|\Phi^{\pm}\rangle$ and $|\Psi^{\pm}\rangle$ in different spatial modes. Certainly, it is worth noting that FS is a key element in this process. Because $|\Phi^{\pm}\rangle$ cannot be distinguished directly, it can be distinguished in the next step with the help of H operation. However, if the two photons have different frequencies, one cannot perform such a transformation successfully.

3. The practical application of HBSA

Interestingly, this setup can be used to construct the complete polarization BSA. In our scheme, the initial state is one of the following four hyperentangled states, e.g.,

$$|\phi_{\rm P}^{\pm}\rangle\otimes|\psi_{\rm F}^{+}\rangle, |\psi_{\rm P}^{\pm}\rangle\otimes|\psi_{\rm F}^{+}\rangle. \tag{7}$$

As shown in Fig. 2, we make the two photons, A and B, enter the setup, respectively. The polarization BSA relies on the observation that the states can be rewritten as superpositions of the single-photon hybrid Bell states of polarization and frequency. On the basis of Eq. (2), the initial states we analyze have the form

$$\begin{aligned}|\phi_{\rm P}^{-}\rangle\otimes|\psi_{\rm F}^{+}\rangle &\equiv \frac{1}{\sqrt{2}}(|HH\rangle-|VV\rangle)\otimes\frac{1}{\sqrt{2}}(|\omega_1\omega_2\rangle+|\omega_2\omega_1\rangle)\\ &= \frac{1}{2}(|\Phi^{+}\rangle_{\rm A}\otimes|\Psi^{-}\rangle_{\rm B}+|\Phi^{-}\rangle_{\rm A}\otimes|\Psi^{+}\rangle_{\rm B}\\ &\quad +|\Psi^{+}\rangle_{\rm A}\otimes|\Phi^{-}\rangle_{\rm B}+|\Psi^{-}\rangle_{\rm A}\otimes|\Phi^{+}\rangle_{\rm B}), \quad (8)\\ |\psi_{\rm P}^{+}\rangle\otimes|\psi_{\rm F}^{+}\rangle &\equiv \frac{1}{\sqrt{2}}(|HV\rangle+|VH\rangle)\otimes\frac{1}{\sqrt{2}}(|\omega_1\omega_2\rangle+|\omega_2\omega_1\rangle)\\ &= \frac{1}{2}(|\Phi^{+}\rangle_{\rm A}\otimes|\Phi^{+}\rangle_{\rm B}-|\Phi^{-}\rangle_{\rm A}\otimes|\Phi^{-}\rangle_{\rm B}\\ &\quad +|\Psi^{+}\rangle_{\rm A}\otimes|\Psi^{+}\rangle_{\rm B}-|\Psi^{-}\rangle_{\rm A}\otimes|\Psi^{-}\rangle_{\rm B}), \quad (9)\\ |\psi_{\rm P}^{-}\rangle\otimes|\psi_{\rm F}^{+}\rangle &\equiv \frac{1}{\sqrt{2}}(|HV\rangle-|VH\rangle)\otimes\frac{1}{\sqrt{2}}(|\omega_1\omega_2\rangle+|\omega_2\omega_1\rangle)\\ &= \frac{1}{2}(-|\Phi^{+}\rangle_{\rm A}\otimes|\Phi^{-}\rangle_{\rm B}+|\Phi^{-}\rangle_{\rm A}\otimes|\Phi^{+}\rangle_{\rm B}\\ &\quad -|\Psi^{+}\rangle_{\rm A}\otimes|\Psi^{-}\rangle_{\rm B}+|\Psi^{-}\rangle_{\rm A}\otimes|\Psi^{+}\rangle_{\rm B}), \quad (10)\end{aligned}$$

while another item, $|\phi_{\rm P}^{+}\rangle\otimes|\psi_{\rm F}^{+}\rangle$, is given by Eq. (3). From Eq. (3) and (8)–(10), we note that all four polarization Bell states can be recognized on the coincidence basis. For example, from the above discussion, if the detectors D_1 and D_5, D_2 and D_6, D_3 and D_7, or D_4 and D_8 are registered, the initial state must be $|\psi_{\rm P}^{+}\rangle\otimes|\psi_{\rm F}^{+}\rangle$. Following the same principle, we can easily distinguish other states. If D_1 and D_8, D_2 and D_7, D_3 and D_6, or D_4 and D_5 are registered, it must be $|\phi_{\rm P}^{-}\rangle\otimes|\psi_{\rm F}^{+}\rangle$. If D_1 and D_7, D_2 and D_8, D_3 and D_5, or D_4 and D_6 are registered, it must be $|\phi_{\rm P}^{+}\rangle\otimes|\psi_{\rm F}^{+}\rangle$. If D_1 and D_6, D_2 and D_5, D_3 and D_8, or D_4 and D_7 are registered, it must be $|\psi_{\rm P}^{-}\rangle\otimes|\psi_{\rm F}^{+}\rangle$.

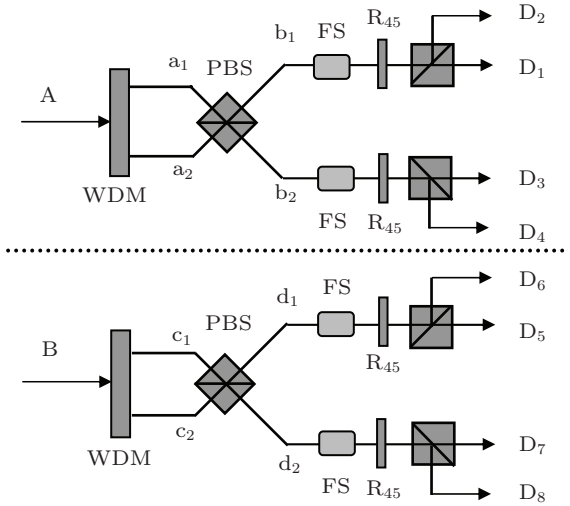


Fig. 2. A schematic diagram of complete polarization BSA using frequency entanglement. Two devices similar to those shown in Fig. 1 are used here. After coincidence detection, one can distinguish four polarization Bell states deterministically.

Another interesting application of our HBSA is to perform entanglement teleportation between different degrees of freedom. This is a polarization to frequency teleportation using the frequency entangled state. By making a joint projection of the polarization and frequency parity of a single photon, we are able, in principle, to teleportate the polarization single photon to a frequency single photon. The polarization quantum state of photon A can be described as

$$|\xi\rangle_{\rm A}=\alpha|H\rangle_{\rm A}+\beta|V\rangle_{\rm A}, \tag{11}$$

where $|\alpha|^2+|\beta|^2=1$. Meanwhile, the entanglement channel between two parties, say Alice and Bob, is set up with the frequency entanglement as

$$|\Psi\rangle_{\rm AB}=\frac{1}{\sqrt{2}}(|\omega_1\rangle_{\rm A}|\omega_2\rangle_{\rm B}+|\omega_2\rangle_{\rm A}|\omega_1\rangle_{\rm B}). \tag{12}$$

In current experimental conditions, the frequency entanglement can be generated with parametric down conversion in a 3 cm-long periodically poled lithium niobate (PPLN) waveguide (HC photonics).[63] The polarization entanglement can also be converted to frequency entanglement,[64] which can be used for entanglement purification, entanglement distribution, and so on.[65,66]

From Eqs. (11) and (12), we use two degrees of freedom to describe the states of photons A and B. That is, photon A at Alice's location is in the state $|\xi\rangle_{\rm A}$ in the polarization degree of freedom. Meanwhile, it is also entangled with photon B in the frequency degree of freedom. On the other hand, photon B at Bob's location also entangles with photon A in the frequency degree of freedom. We let photon B be $|\xi\rangle_{\rm B}=|H\rangle_{\rm B}$ in polarization. In this way, the whole system with two different degrees of freedom can be described as

$$\begin{aligned}|\chi\rangle_{\rm AB} &= |\xi\rangle_{\rm A}\otimes|\xi\rangle_{\rm B}\otimes|\Psi\rangle_{\rm AB}\\ &= (\alpha|H\rangle_{\rm A}+\beta|V\rangle_{\rm A})\otimes|H\rangle_{\rm B}\\ &\quad\otimes\left(\frac{1}{\sqrt{2}}(|\omega_1\rangle_{\rm A}|\omega_2\rangle_{\rm B}+|\omega_2\rangle_{\rm A}|\omega_1\rangle_{\rm B})\right)\\ &= |\Phi^+\rangle_{\rm A}(\alpha|\omega_2\rangle_{\rm B}+\beta|\omega_1\rangle_{\rm B})|H\rangle_{\rm B}\\ &\quad+|\Phi^-\rangle_{\rm A}(\alpha|\omega_2\rangle_{\rm B}-\beta|\omega_1\rangle_{\rm B})|H\rangle_{\rm B}\\ &\quad+|\Psi^+\rangle_{\rm A}(\alpha|\omega_1\rangle_{\rm B}+\beta|\omega_2\rangle_{\rm B})|H\rangle_{\rm B}\\ &\quad+|\Psi^-\rangle_{\rm A}(\alpha|\omega_1\rangle_{\rm B}-\beta|\omega_2\rangle_{\rm B})|H\rangle_{\rm B},\end{aligned} \tag{13}$$

where $|\Phi^\pm\rangle_{\rm A}$ and $|\Psi^\pm\rangle_{\rm A}$ are described by Eq. (2).

From Eq. (13), an arbitrary quantum state is first encoded in the polarization of photon A, and then teleportated to the frequency of photon B by a complete HBSA. If the HBSA result of photon A is $|\Phi^+\rangle_{\rm A}$, photon B will be $\alpha|\omega_2\rangle_{\rm B}+\beta|\omega_1\rangle_{\rm B}$, which has the same form as $|\xi\rangle_{\rm A}$. This idea is similar to the scheme proposed by Khoury and Milman.[67] In fact, this method provides us with a different way of preparing the frequency-multiplexed entangled (FME) single-photon state. It has been studied in three-level, (double-) multi-configuration atomic systems,[68,69] based on coherent conversion.[70,71] It is worth mentioning that Bajjani *et al.* recently demonstrated the quantum superposition of a single microwave photon in two different color states with parametric frequency conversion.[72] Our method is quite different from theirs. It can be easily performed in current experiments. The single photon encoded in a polarization degree of freedom can be prepared by a sequence of wave plates. The entangled state with a frequency degree of freedom can be created with a current PDC source.

4. Discussion and conclusion

It is interesting to compare the polarization BSA with that in Refs. [55] and [51]. In Ref. [55], the authors designed hyperentangled BSA with polarization-spatial-mode hyperentanglement. They could only distinguish the polarization Bell state locally, and should resort to the two-photon interference effects. In this scheme, the polarization BSA can be operated nonlocally at the cost of two bits of classical communication. On the other hand, in Ref. [51], the authors used the spatial entanglement to distinguish the polarization Bell state nonlocally. However, similar to spin–orbital angular momentum entanglement, which is easily decohered by atmospheric turbulence,[54,73] spatial mode entanglement is also sensitive to path length instability.[13] Therefore, it does not seem to be suitable for complete entanglement nonlocally. In our scheme, as the frequency is a classical degree of freedom, the frequency entanglement is more stable during transmission,[74–79] which makes our scheme more suitable for BSA. Finally, let us briefly discuss the key element (e.g. FS) in this scheme. With the current technique, FS can be implemented by several means.[80–85] One of the basic techniques is to use frequency up-conversion. Takesue *et al.* reported their experimental results that internal conversion efficiency from a 1560 nm photon to a 715 nm photon exceeds 99%.[81] In addition, with an acousto-optical modulator (AOM), one can make a polarization-dependent frequency shift.[84] Recently, Wang *et al.* also proposed a scheme to make the frequency shift by using an electro-optical modulator.[85] They showed that the fidelity of the outcome state and a perfect polarization entangled state is larger than $1-10^{-3}$.

In conclusion, we have proposed a scheme for single-photon HBSA. The success probability is 100% in principle, which is different from polarization BSA with linear optics. We also showed that this setup can be used to equip the complete two-photon polarization BSA and perform the polarization to frequency teleportation scheme. Compared with the other polarization BSA with hyperentanglement, this scheme has several advantages. First, we do not need the two-photon interference, only conventional photon detectors are required, which is feasible in current experiments. Second, this scheme can be operated nonlocally, and finally, the frequency entanglement is more stable, which makes this scheme more valuable in practical applications. This scheme may therefore have more valuable applications in current quantum communication.

References

[1] Nielsen M A and Chuang I L 2000 *Quantum Computation and Quantum Information* (Cambridge: Cambridge University Press)
[2] Bennett C H, Brassard G, Crépeau C, Jozsa R, Peres A and Wootters W K 1993 *Phys. Rev. Lett.* **70** 1895
[3] Karlsson A and Bourennane M 1998 *Phys. Rev. A* **58** 4394

[4] Deng F G, Li C Y, Li Y S, Zhou H Y and Wang Y 2005 *Phys. Rev. A* **72** 022338
[5] Ekert A K 1991 *Phys. Rev. Lett.* **67** 661
[6] Bennett C H, Brassard G and Mermin N D 1992 *Phys. Rev. Lett.* **68** 557
[7] Knill E, Laflamme R and Milburn G 2001 *Nature* **409** 46
[8] Briegel H J, Dür W, Cirac J I and Zoller P 1998 *Phys. Rev. Lett.* **81** 5932
[9] Briegel H J, Dür W, Cirac J I and Zoller P 1999 *Phys. Rev. A* **59** 169
[10] Wang T J, Song S Y and Long G L 2012 *Phys. Rev. A* **85** 062311
[11] Sheng Y B, Zhou L, Cheng W W, Gong L Y, Zhao S M and Zheng B Y 2012 *Chin. Phys. B* **21** 030307
[12] Duan L M, Lukin M D, Cirac J T and Zoller P 2001 *Nature* **414** 413
[13] Zhao B, Chen Z B, Chen Y A, Schmiedmayer J and Pan J W 2007 *Phys. Rev. Lett.* **98** 240502
[14] van Loock P, Ladd T D, Sanaka K, Yamaguchi F, Nemoto K, Munro W J and Yamamoto Y 2006 *Phys. Rev. Lett.* **96** 240501
[15] Munro W J, van Meter R, Louis S G R and Nemoto K 2008 *Phys. Rev. Lett.* **101** 040502
[16] Azuma K, Sota N, Namiki R, Özdemir Ş K, Yamamoto T, Koashi M and Imoto N 2009 *Phys. Rev. A* **80** 060303
[17] Deng F G, Long G L and Liu X S 2003 *Phys. Rev. A* **68** 042317
[18] Wang C, Deng F G, Li Y S, Liu X S and Long G L 2005 *Phys. Rev. A* **71** 042305
[19] Wang C, Deng F G and Long G L 2005 *Opt. Commun.* **253** 15
[20] Deng F G, Li X H, Li C Y, Zhou P and Zhou H Y 2006 *Phys. Lett. A* **359** 359
[21] Gu B, Huang Y G, Fang X and Zhang C Y 2011 *Chin. Phys. B* **20** 100309
[22] Li X H, Deng F G, Zhou H Y 2006 *Phys. Rev. A* **74** 054302
[23] Li X H, Duan X J, Sheng Y B, Zhou H Y and Deng F G 2009 *Chin. Phys. B* **18** 3710
[24] Yang J, Wang C and Zhang R 2010 *Chin. Phys. B* **19** 110306
[25] Zhang X L, Zhang Y X and Wei H 2009 *Chin. Phys. B* **18** 435
[26] Liu W J, Chen H W, Ma T H, Li Z Q, Liu Z H and Hu W B 2009 *Chin. Phys. B* **18** 4105
[27] Man Z X, Zhang Z J and Li Y 2005 *Chin. Phys. Lett.* **22** 18
[28] Yan F L and Zhang X 2004 *Eur. Phys. J. B* **41** 75
[29] Gao T, Yan F L and Wang Z X 2005 *Chin. Phys.* **14** 893
[30] Gao T, Yan F L and Wang Z X 2005 *J. Phys. A* **38** 5761
[31] Gao T, Yan F L and Wang Z X 2005 *Int. J. Mod. Phys. C* **16** 1293
[32] Bennett C H and Wiesner S J 1992 *Phys. Rev. Lett.* **69** 2881
[33] Liu X S, Long G L, Tong D M and Feng L 2002 *Phys. Rev. A* **65** 022304
[34] Hillery M, Bužek V and Berthiaume A 1999 *Phys. Rev. A* **59** 1829
[35] Karlsson A, Koashi M and Imoto N 1999 *Phys. Rev. A* **59** 162
[36] Xiao L, Long G L, Deng F G and Pan J W 2004 *Phys. Rev. A* **69** 052307
[37] Deng F G, Li X H and Zhou H Y 2008 *Phys. Lett. A* **372** 1957
[38] Cleve R, Gottesman D and Lo H K 1999 *Phys. Rev. Lett.* **83** 648
[39] Lance A M, Symul T, Bowen W P, Sanders B C and Lam P K 2004 *Phys. Rev. Lett.* **92** 177903
[40] Deng F G, Li X H, Li C Y, Zhou P and Zhou H Y 2005 *Phys. Rev. A* **72** 044301
[41] Deng F G, Li X H, Li C Y, Zhou P and Zhou H Y 2006 *Eur. Phys. J. D* **39** 459
[42] Li X H, Zhou P, Li C Y, Zhou H Y and Deng F G 2006 *J. Phys. B* **39** 1975
[43] Sheng Y B, Deng F G and Zhou H Y 2008 *Eur. Phys. J. D* **48** 279
[44] Wang T J, Zhou H Y and Deng F G 2008 *Physica A* **387** 4716
[45] Vaidman L and Yoran N 1999 *Phys. Rev. A* **59** 116
[46] Lütkenhaus N, Calsamiglia J and Suominen K A 1999 *Phys. Rev. A* **59** 3295
[47] Calsamiglia J 2002 *Phys. Rev. A* **65** 030301
[48] van Houwelingen J A W, Brunner N, Beveratos A, Zbinden H and Gisin N 2006 *Phys. Rev. Lett.* **96** 130502
[49] Ursin R, Jennewein T, Aspelmeyer M, Kaltenbaek R, Lindenthal M, Walther P and Zeilinger A 2004 *Nature* **430** 849
[50] Kwiat P G and Weinfurter H 1998 *Phys. Rev. A* **58** 2623
[51] Walborn S P, P ádua S and Monken C H 2003 *Phys. Rev. A* **68** 042313
[52] Schuck C, Huber G, Kurtsiefer C and Weinfurter H 2006 *Phys. Rev. Lett.* **96** 190501
[53] Barbieri M, Vallone G, Mataloni P and de Martini F 2007 *Phys. Rev. A* **75** 042317
[54] Barreiro J T, Wei T C and Kwiat P G 2008 *Nature Phys.* **4** 282
[55] Wei T C, Barreiro J T and Kwiat P G 2007 *Phys. Rev. A* **75** 060305
[56] Sheng Y B, Deng F G and Long G L 2010 *Phys. Rev. A* **82** 032318
[57] Neves L, Lima G, Delgado A and Saavedra C 2009 *Phys. Rev. A* **80** 042322
[58] Fujiwara M, Toyoshima M, Sasaki M, Yoshino K, Nambu Y and Tomita A 2009 *Appl. Phys. Lett.* **95** 261103
[59] Barreiro J T, Wei T C and Kwiat P G 2010 *Phys. Rev. Lett.* **105** 030407
[60] Karimi E, Leach J, Slussarenko S, Piccirillo B, Marrucci L, Chen L, She W, Arnold S F, Padgett M J and Santamato E 2010 *Phys. Rev. A* **82** 022115
[61] Waks E and Monroe C 2009 *Phys. Rev. A* **80** 062330
[62] Barrett S D, Kok P, Nemoto K, Beausoleil R G, Munro W J and Spiller T P 2005 *Phys. Rev. A* **71** 060302
[63] Olislager L, Cussey J, Nguyen A T, Emplit P, Massar S, Merolla J M and Phan Huy K 2010 *Phys. Rev. A* **82** 060302
[64] Ramelow S, Ratschbacher L, Fedrizzi A, Langford N K and Zeilinger A 2009 *Phys. Rev. Lett.* **103** 253601
[65] Xiao L, Wang C, Zhang W, Huang Y, Peng J and Long G 2008 *Phys. Rev. A* **77** 042315
[66] Wang C, Sheng Y B, Li X H, Deng F G, Zhang W and Long G L 2009 *Sci. China Ser. E* **52** 3464
[67] Khoury A Z and Milman P 2011 *Phys. Rev. A* **83** 060301
[68] Wanare H 2006 *Phys. Rev. Lett.* **96** 183601
[69] Li P, Nakajima T and Ning X J 2006 *Phys. Rev. A* **74** 043408
[70] Chen L Q, Zhang G W, Bian C, Yuan C H, Ou Z Y and Zhang W 2010 *Phys. Rev. Lett.* **105** 133603
[71] Yuan C H, Chen L Q, Ou Z Y and Zhang W 2011 *Phys. Rev. A* **83** 054302
[72] Zakka-Bajjani E, Nguyen F, Lee M, Vale L R, Simmonds R W and Aumentado J 2011 *Nature Phys.* **7** 599
[73] Paterson C 2005 *Phys. Rev. Lett.* **94** 153901
[74] Sheng Y B and Deng F G 2010 *Phys. Rev. A* **81** 032307
[75] Sheng Y B and Deng F G 2010 *Phys. Rev. A* **81** 042332
[76] Li X H and Duan X J 2011 *J. Phys. B* **44** 065503
[77] Deng F G 2011 *Phys. Rev. A* **83** 062316
[78] Zhang T, Yin Z Q, Han T F and Guo G C 2008 *Opt. Commun.* **281** 4800
[79] Bloch M, Mclaughlin S W, Merolla J M and Patois F 2007 *Opt. Lett.* **32** 301
[80] Langrock C, Diamanti E, Roussev R V, Yamamoto Y and Fejer M M 2005 *Opt. Lett.* **30** 1725
[81] Takesue H, Diamanti E, Honjo T, Langrock C, Fejer M M, Inoue K and Yamamoto Y 2005 *New J. Phys.* **7** 232
[82] Takesue H 2008 *Phys. Rev. Lett.* **101** 173901
[83] Takesue H 2010 *Phys. Rev. A* **82** 013833
[84] Jones N S and Stace T M 2006 *Phys. Rev. A* **73** 033813
[85] Wang X B, Yang C X and Liu Y B 2010 *Appl. Phys. Lett.* **96** 201103