Quantum superdense coding based on hyperentanglement*

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(Received 16 December 2011; revised manuscript received 12 February 2012)

We present a scheme for quantum superdense coding with hyperentanglement, in which the sender can transfer four bits of classical information by sending only one photon. The important device in the scheme is the hyperentangled Bell-state analyzer in both polarization and frequency degrees of freedom, which is also constructed in the paper by using a quantum nondemolition detector assisted by cross-Kerr nonlinearity. Our scheme can transfer more information with less resources than the existing schemes and is nearly deterministic and nondestructive.

Keywords: quantum superdense coding, hyperentangled state, Bell-state analysis

PACS: 03.65.Ud, 03.67.–a, 03.67.Hk **DOI:** 10.1088/1674-1056/21/8/080303

Many applications of bipartite entanglement, such as quantum teleportation,[1] quantum key distribution,[2,3] quantum dense coding,[4,5] and quantum secret sharing,[6,7] have been presented, which are foundational schemes for quantum communication. Here we focus our attention on quantum dense coding, which can transmit two bits of classical information by sending only one quantum bit.[4] In 1996, Mattle *et al.*[8] demonstrated quantum dense coding with polarization entangled photons experimentally. Quantum dense coding has been generalized to multi-parties[9] and realized using high-dimensional states.[10] Many schemes for implementing quantum dense coding with the tripartite Greenberger–Horne–Zeilinger (GHZ) state and W state,[11−13] and even a mixed state[14] have been proposed. Other physical approaches to quantum dense coding include a feasible scheme for implementing four-atom quantum dense coding in an atom–cavity system,[15] a scheme in which the atoms interacted simultaneously with a highly detuned cavity mode with the assistance of a classical field,[16] and an implementation with continuous variables.[17] However, photons are the optimal carriers due to the fact that they are uneasy to interact with the environment in the transmission process.

To accomplish quantum dense coding, the receiver needs to perform a Bell-state analysis (BSA), by which we can distinguish the Bell states. But the complete BSA remains a big challenge with only linear optical elements,[18] leading to the reduction of the channel capacity from 2 to $\log_2 3$ bits. Although some probabilistic schemes for complete BSA that can distinguish all Bell states have been reported, the maximum probability is 1/2,[19] by which the channel capacity is not increased. Hyperentanglement,[20,21] which is being entangled in more than one degree of freedom, provides us with the possibility for increasing the channel capacity. Walborn *et al*. proposed a hyperentanglement-assisted BSA in polarization of photons using momentum entanglement as an auxiliary,[22] which has been reported experimentally.[23] However, these schemes cannot increase the channel capacity in quantum dense coding, although the complete BSA has been achieved. Sheng *et al.*[24] proposed a complete hyperentangled BSA scheme in both polarization and spatial-mode degrees of freedom of photons with cross-Kerr nonlinearity in 2010. They used the cross-Kerr nonlinearity to construct parity-check measurements and analyse the hyperentangled Bell states. Also, they discussed the applications of the hyperentangled BSA in the quantum teleportation of an unknown state in two differ-

*Project supported by the National Natural Science Foundation of China (Grant Nos. 61068001 and 11147174).
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ent degrees of freedom and in the entanglement swapping of hyperentangled states. These applications will increase the channel capacity of long-distance quantum communication, and demonstrate that schemes for quantum communication based on the hyperentangled state will be more efficient.

In this paper, a scheme for quantum superdense coding with a hyperentangled state is presented and these entangled states contain two different kinds of degrees of freedom, that is, polarization and frequency degrees of freedom. Alice and Bob share a photon-pair in a hyperentangled state. After performing a local operation on her own photon, Alice sends the photon to Bob. Then Bob can discriminate the operations which Alice performs on her photon with the help of a hyperentangled BSA on the two photons, as well as the information that Alice wants to transfer. In order to accomplish the quantum superdense coding, we also present a hyperentangled Bell-state analyzer in frequency and polarization degrees of freedom.

Now we discuss the quantum superdense coding scheme in detail. Suppose that two photons are entangled in both polarization subspace $\{H, V\}$ and frequency subspace $\{\omega_1, \omega_2\}$, and the initial state shared by Alice and Bob is

$$\begin{aligned}|\Psi\rangle_{ab} &= \frac{1}{2}(|HH\rangle + |VV\rangle)_{ab} \otimes (|\omega_1\omega_1\rangle + |\omega_2\omega_2\rangle)_{ab} \\ &= |\Phi^+\rangle^p_{ab} \otimes |\Phi^+\rangle^f_{ab}, \end{aligned} \tag{1}$$

where $|\Phi^+\rangle^p_{ab}$ and $|\Phi^+\rangle^f_{ab}$ are Bell states in polarization and frequency degrees of freedom, respectively. The subscripts a and b represent the photons a and b belong to Alice and Bob, respectively. The superscripts p and f denote polarization and frequency degrees of freedom, respectively.

We describe four Bell states in polarization degree of freedom as

$$\begin{aligned}|\Phi^\pm\rangle^p_{ab} &= \frac{1}{\sqrt{2}}(|HH\rangle_{ab} \pm |VV\rangle_{ab}), \\ |\Psi^\pm\rangle^p_{ab} &= \frac{1}{\sqrt{2}}(|HV\rangle_{ab} \pm |VH\rangle_{ab}), \end{aligned} \tag{2}$$

while four Bell states in frequency degree of freedom can be denoted as

$$\begin{aligned}|\Phi^\pm\rangle^f_{ab} &= \frac{1}{\sqrt{2}}(|\omega_1\omega_1\rangle_{ab} \pm |\omega_2\omega_2\rangle_{ab}), \\ |\Psi^\pm\rangle^f_{ab} &= \frac{1}{\sqrt{2}}(|\omega_1\omega_2\rangle_{ab} \pm |\omega_2\omega_1\rangle_{ab}). \end{aligned} \tag{3}$$

Here H and V are the horizontal and vertical polarizations, respectively. ω_1 and ω_2 are the different frequencies of photons. So, there are 16 hyperentangled Bell states $\{|\Phi^\pm\rangle^p_{ab}, |\Psi^\pm\rangle^p_{ab}\} \otimes \{|\Phi^\pm\rangle^f_{ab}, |\Psi^\pm\rangle^f_{ab}\}$.

In order to realize quantum superdense coding, one of the local operations $\{I^p, \sigma^p_x, \sigma^p_z, \mathrm{i}\sigma^p_y\} \otimes \{I^f, \sigma^f_x, \sigma^f_z, \mathrm{i}\sigma^f_y\}$ is performed on the photon a by Alice, in which I^i and σ^i_j ($i = p, f$ and $j = x, y, z$) are identity operator and Pauli operators in polarization or frequency degrees of freedom. After Alice performs an appropriate operation on the photon a, the initial total state $|\Psi\rangle_{ab}$ will convert to one of the 16 hyperentangled Bell states, and then Alice sends the photon a to Bob. Table 1 illustrates the correspondence between the classical information transferred by Alice, the operations performed on the photon a, and the total states received by Bob.

Bob can distinguish which state the two photons are by a hyperentangled BSA in polarization and frequency degrees of freedom, then Bob will be aware of which operation Alice performed on the photon a and the classical information that Alice wants to transfer. The hyperentangled BSA can be divided into two steps. The first step is used to distinguish the Bell states in frequency degree of freedom and then the states in polarization will be distinguished in the second step.

Before expounding the BSA in frequency and polarization degrees of freedom, we first introduce the quantum nondemolition detector (QND) based on cross-Kerr nonlinearity. The cross-Kerr nonlinearity has a Hamiltonian of the following form[25]

$$H = \hbar\chi a^\dagger_s a_s a^\dagger_p a_p. \tag{4}$$

Here $a^\dagger_s$ ($a^\dagger_p$) and a_s (a_p) represent creation and annihilation operations respectively, and the subscript s (p) denotes signal (probe) mode. χ is the strength of coupling, which is decided by the property of the cross-Kerr medium. Suppose that the signal field contains n_a photons and the probe beam is the coherent state $|\alpha\rangle$. After the interaction with cross-Kerr nonlinearity, the joint state of the combined system will evolve into

$$|\Psi\rangle = \mathrm{e}^{\mathrm{i}\chi t a^\dagger_s a_s a^\dagger_p a_p}|n_a\rangle|\alpha\rangle = |n_a\rangle|\alpha\,\mathrm{e}^{\mathrm{i}n_a\theta}\rangle, \tag{5}$$

where $\theta = \chi t$ and t is the interaction time. The state $|\Psi\rangle$ will project into a definite number state through a homodyne measurement on the phase of the coherent state.

The protocol of the BSA in frequency degree of freedom is shown in Fig. 1.

Table 1. The correspondence between the classical information transferred by Alice, the operations performed on the photon a, and the total states received by Bob.

Classical information	Operations	Total states
0000	$I^p \otimes I^f$	$\|\Psi\rangle_{ab}^{0000} = \|\Phi^+\rangle_{ab}^p \otimes \|\Phi^+\rangle_{ab}^f$
0001	$I^p \otimes \sigma_x^f$	$\|\Psi\rangle_{ab}^{0001} = \|\Phi^+\rangle_{ab}^p \otimes \|\Psi^+\rangle_{ab}^f$
0010	$I^p \otimes \sigma_z^f$	$\|\Psi\rangle_{ab}^{0010} = \|\Phi^+\rangle_{ab}^p \otimes \|\Phi^-\rangle_{ab}^f$
0011	$I^p \otimes \mathrm{i}\sigma_y^f$	$\|\Psi\rangle_{ab}^{0011} = \|\Phi^+\rangle_{ab}^p \otimes \|\Psi^-\rangle_{ab}^f$
0100	$\sigma_x^p \otimes I^f$	$\|\Psi\rangle_{ab}^{0100} = \|\Psi^+\rangle_{ab}^p \otimes \|\Phi^+\rangle_{ab}^f$
0101	$\sigma_x^p \otimes \sigma_x^f$	$\|\Psi\rangle_{ab}^{0101} = \|\Psi^+\rangle_{ab}^p \otimes \|\Psi^+\rangle_{ab}^f$
0110	$\sigma_x^p \otimes \sigma_z^f$	$\|\Psi\rangle_{ab}^{0110} = \|\Psi^+\rangle_{ab}^p \otimes \|\Phi^-\rangle_{ab}^f$
0111	$\sigma_x^p \otimes \mathrm{i}\sigma_y^f$	$\|\Psi\rangle_{ab}^{0111} = \|\Psi^+\rangle_{ab}^p \otimes \|\Psi^-\rangle_{ab}^f$
1000	$\sigma_z^p \otimes I^f$	$\|\Psi\rangle_{ab}^{1000} = \|\Phi^-\rangle_{ab}^p \otimes \|\Phi^+\rangle_{ab}^f$
1001	$\sigma_z^p \otimes \sigma_x^f$	$\|\Psi\rangle_{ab}^{1001} = \|\Phi^-\rangle_{ab}^p \otimes \|\Psi^+\rangle_{ab}^f$
1010	$\sigma_z^p \otimes \sigma_z^f$	$\|\Psi\rangle_{ab}^{1010} = \|\Phi^-\rangle_{ab}^p \otimes \|\Phi^-\rangle_{ab}^f$
1011	$\sigma_z^p \otimes \mathrm{i}\sigma_y^f$	$\|\Psi\rangle_{ab}^{1011} = \|\Phi^-\rangle_{ab}^p \otimes \|\Psi^-\rangle_{ab}^f$
1100	$\mathrm{i}\sigma_y^p \otimes I^f$	$\|\Psi\rangle_{ab}^{1100} = \|\Psi^-\rangle_{ab}^p \otimes \|\Phi^+\rangle_{ab}^f$
1101	$\mathrm{i}\sigma_y^p \otimes \sigma_x^f$	$\|\Psi\rangle_{ab}^{1101} = \|\Psi^-\rangle_{ab}^p \otimes \|\Psi^+\rangle_{ab}^f$
1110	$\mathrm{i}\sigma_y^p \otimes \sigma_z^f$	$\|\Psi\rangle_{ab}^{1110} = \|\Psi^-\rangle_{ab}^p \otimes \|\Phi^-\rangle_{ab}^f$
1111	$\mathrm{i}\sigma_y^p \otimes \mathrm{i}\sigma_y^f$	$\|\Psi\rangle_{ab}^{1111} = \|\Psi^-\rangle_{ab}^p \otimes \|\Psi^-\rangle_{ab}^f$

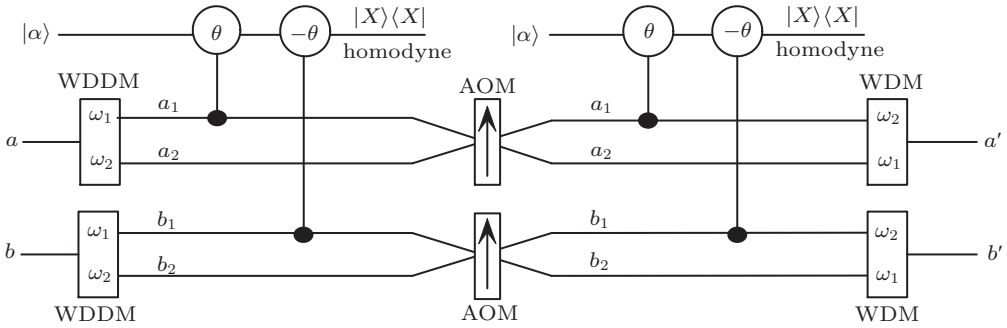


Fig. 1. The diagram for the Bell-state analysis in frequency degree of freedom. WDDMs and WDMs are wavelength division demultiplexers and wavelength division multiplexers, respectively. AOMs denote acousto-optic modulators.

As a result of the wavelength division demultiplexers, which guide photons with different frequencies in a spatial mode into different spatial modes, and the first QND with cross-Kerr nonlinearity, the states $|\Phi^{\pm}\rangle_{ab}^f$ and the coherent state $|\alpha\rangle$ will evolve as

$$\begin{aligned}|\Phi^{\pm}\rangle_{ab}^f|\alpha\rangle &= \frac{1}{\sqrt{2}}(|\omega_1\omega_1\rangle_{ab} \pm |\omega_2\omega_2\rangle_{ab})|\alpha\rangle \\ &\to \frac{1}{\sqrt{2}}(|\omega_1\omega_1\rangle_{a_1b_1} \pm |\omega_2\omega_2\rangle_{a_2b_2})|\alpha\rangle, \quad (6)\end{aligned}$$

while the states $|\Psi^{\pm}\rangle_{ab}^f$ with the coherent state $|\alpha\rangle$ will evolve as

$$\begin{aligned}|\Psi^{\pm}\rangle_{ab}^f|\alpha\rangle &= \frac{1}{\sqrt{2}}(|\omega_1\omega_2\rangle_{ab} \pm |\omega_2\omega_1\rangle_{ab})|\alpha\rangle \\ &\to \frac{1}{\sqrt{2}}(|\omega_1\omega_2\rangle_{a_1b_2}|\alpha\,\mathrm{e}^{\mathrm{i}\theta}\rangle \\ &\quad \pm |\omega_2\omega_1\rangle_{a_2b_1}|\alpha\,\mathrm{e}^{-\mathrm{i}\theta}\rangle. \quad (7)\end{aligned}$$

It can be found that the states $|\omega_1\omega_1\rangle$ and $|\omega_2\omega_2\rangle$ will not cause phase shifts of the the coherent state $|\alpha\rangle$. However, the states $|\omega_1\omega_2\rangle$ and $|\omega_2\omega_1\rangle$ will lead to phase shifts θ and $-\theta$, respectively. By performing an X homodyne measurement,[26] with which the states $|\alpha\,\mathrm{e}^{\mathrm{i}\theta}\rangle$ and $|\alpha\,\mathrm{e}^{-\mathrm{i}\theta}\rangle$ cannot be distinguished, on the coherent beam, we can distinguish $|\Phi^{\pm}\rangle_{ab}^f$ from $|\Psi^{\pm}\rangle_{ab}^f$ with different phase shifts. If θ or $-\theta$ phase shift is obtained, the two photons are originally in the states $|\Psi^{\pm}\rangle_{ab}^f$; if no phase shift, the photons are in the states $|\Phi^{\pm}\rangle_{ab}^f$. By means of the first QND, the Bell states are divided into even parity states $|\Phi^{\pm}\rangle_{ab}^f$ and odd parity states $|\Psi^{\pm}\rangle_{ab}^f$.

As the next task, we will distinguish the two states in each group. The function of AOMs can be described by the following transformations[27]

$$\begin{aligned}|\omega_1\rangle_{a_1} &\to \frac{1}{\sqrt{2}}(|\omega_1\rangle_{a_2} + |\omega_2\rangle_{a_1}), \\ |\omega_2\rangle_{a_2} &\to \frac{1}{\sqrt{2}}(|\omega_2\rangle_{a_1} - |\omega_1\rangle_{a_2}),\end{aligned}$$

$$|\omega_1\rangle_{b_1} \to \frac{1}{\sqrt{2}}(|\omega_1\rangle_{b_2} + |\omega_2\rangle_{b_1}),$$
$$|\omega_2\rangle_{b_2} \to \frac{1}{\sqrt{2}}(|\omega_2\rangle_{b_1} - |\omega_1\rangle_{b_2}). \quad (8)$$

So the AOMs can achieve the following transformations

$$\begin{aligned}
|\Phi^+\rangle_{ab}^{f'} &= \frac{1}{\sqrt{2}}(|\omega_1\omega_1\rangle_{a_1b_1} + |\omega_2\omega_2\rangle_{a_2b_2}) \\
&\to \frac{1}{\sqrt{2}}(|\omega_1\omega_1\rangle_{a_2b_2} + |\omega_2\omega_2\rangle_{a_1b_1}), \\
|\Phi^-\rangle_{ab}^{f'} &= \frac{1}{\sqrt{2}}(|\omega_1\omega_1\rangle_{a_1b_1} - |\omega_2\omega_2\rangle_{a_2b_2}) \\
&\to \frac{1}{\sqrt{2}}(|\omega_1\omega_2\rangle_{a_2b_1} + |\omega_2\omega_1\rangle_{a_1b_2}), \\
|\Psi^+\rangle_{ab}^{f'} &= \frac{1}{\sqrt{2}}(|\omega_1\omega_2\rangle_{a_1b_2} + |\omega_2\omega_1\rangle_{a_2b_1}) \\
&\to -\frac{1}{\sqrt{2}}(|\omega_1\omega_1\rangle_{a_2b_2} - |\omega_2\omega_2\rangle_{a_1b_1}), \\
|\Psi^-\rangle_{ab}^{f'} &= \frac{1}{\sqrt{2}}(|\omega_1\omega_2\rangle_{a_1b_2} - |\omega_2\omega_1\rangle_{a_2b_1}) \\
&\to \frac{1}{\sqrt{2}}(|\omega_1\omega_2\rangle_{a_2b_1} - |\omega_2\omega_1\rangle_{a_1b_2}). \quad (9)
\end{aligned}$$

Utilizing the method mentioned above, the two states in each group can be distinguished with the second QND. For the states $|\Phi^{\pm}\rangle_{ab}^{f}$, the two photons are originally in state $|\Phi^{+}\rangle_{ab}^{f}$ when no phase shift appears; they are in state $|\Phi^{-}\rangle_{ab}^{f}$ when θ or $-\theta$ phase shift appears. The states $|\Psi^{\pm}\rangle_{ab}^{f}$ can be distinguished with the same method as $|\Phi^{\pm}\rangle_{ab}^{f}$. That is, the two photons are originally in state $|\Psi^{+}\rangle_{ab}^{f}$ when no phase shift appears; they are in state $|\Psi^{-}\rangle_{ab}^{f}$ when θ or $-\theta$ phase shift appears. By wavelength division multiplexers, which guide photons with different frequencies in different spatial modes into the same spatial mode, and the single-photon operations which depend on the result of the homodyne measurement, the initial states can be reconstructed in spatial modes a' and b'. Up to now, the BSA in frequency degree of freedom has been achieved. From the above discussion, it is found that the most important process in the present scheme is the parity check with QND and this scheme is nondestructive to the photon states.

In the second step of the hyperentangled BSA, we introduce a BSA in polarization. The device of the proposal proposed by Guo *et al.*[28] is shown in Fig. 2.

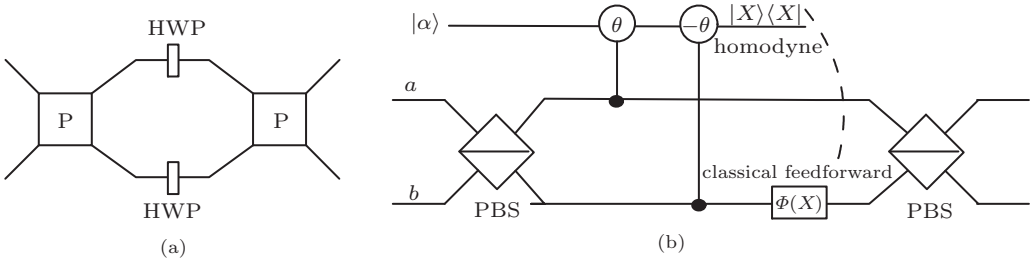


Fig. 2. (colour online) (a) Diagrammatic illustration of the Bell-state analysis in polarization. The device P is the parity meter shown in panel (b). PBS and HWP indicate polarizing beam splitter and half-wave plate, respectively. $\Phi(X)$ represents a phase shift dependent on the feedforward result of the homodyne measurement.

Four Bell states in polarization $|\Phi^{\pm}\rangle_{ab}^{p}$ and $|\Psi^{\pm}\rangle_{ab}^{p}$ can be distinguished by linear optical elements and two parity checks based on QNDs. This BSA does not destroy the measured state, therefore, it is nearly deterministic and nondestructive. What is more, this scheme has lower error probability and can be achieved with weaker cross-Kerr nonlinearities.

From the above discussion, it can be found that Bob can distinguish Alice's operations on the photon a with the outcome of the BSA on the two photons. So Alice can transfer four bits of classical information to Bob by sending only one photon. That is, the quantum superdense coding is achieved.

The initial state shared by Alice and Bob, which contains entanglement in frequency and polarization degrees of freedom, can be obtained by spontaneous parametric down-conversion (SPDC) with two adjacent thin type-II barium borate (BBO) crystals,[29] similar to the generation of conventional entangled photon pairs.[30] To accomplish the quantum superdense coding based on the hyperentangled state, Alice needs to perform local operations on photon a, and the operations are implemented in frequency and polarization degrees of freedom. The operations in polarization can be achieved with a half-wave plate which is used to make arbitrary rotations of a polarization state. Huntington *et al.*[31] have shown a device which is able to produce arbitrary rotations in the frequency

basis, and this work has been demonstrated experimentally in 2005.[32] The key of the device is AOM mentioned in Section 2. So the operations needed in our scheme can be implemented experimentally. For the hyperentangled BSA used in this scheme, the indispensable element is the parity check with QND, by which we can control the photons but not destroy them. The success of this scheme is dependent on the implementation of cross-Kerr nonlinearity. The error probability of the parity check in frequency degree of freedom is $P_{\rm error} = \frac{1}{2}\,{\rm erfc}(\alpha\theta^2/2\sqrt{2})$,[25] while that in polarization is $P'_{\rm error} = \frac{1}{2}\,{\rm erfc}(\sqrt{2}\alpha\theta^2)$.[28] If we choose certain coherent probe beam and weak cross-Kerr nonlinearities, taking $\alpha\theta^2 > 9$ for example, $P_{\rm error}$ is less than 10^{-5}, while $P'_{\rm error}$ is less than 10^{-12}. So the success probability of the superdense coding is $P = (1 - P_{\rm error})^2(1 - P'_{\rm error})^2 \approx 99.998\%$, which is very approximately unitary. What is more, lots of progress has been made in Kerr nonlinearity and homodyne detection.[33,34] In 2003, Hofmann *et al.*[33] showed that the maximal nonlinear phase shift of π can be obtained by using a single two-level atom in a one-sided cavity with negligible losses and it was possible to use resonant light to obtain a nonlinearity sensitive to individual excitations of the atom. That is to say if we can choose appropriate Kerr media and effective measurement of phase shift of the coherent beam, the QND can be achieved efficiently, which makes our Bell-state analysis more feasible. The wavelength division demultiplexers and the wavelength division multiplexers can be substituted by a fiber bragg grating.[35] In brief, this scheme for quantum superdense coding is more efficient than conventional quantum dense coding and can be successfully realized.

In summary, we proposed a scheme for quantum superdense coding which is based on hyperentanglement in both polarization and frequency degrees of freedom. The sender Alice can transfer four bits of classical information by sending only one photon, with the help of the hyperentangled BSA performed by the receiver Bob. The hyperentangled BSA is divided into frequency BSA and polarization BSA, by which we can distinguish the Bell states in frequency and polarization based on the QND with cross-Kerr nonlinearity. Just two photons are required in our scheme, so we can transfer more information with less resources. Further more, this scheme is nearly deterministic and nondestructive. The hyperentangled Bell-state analyzer can be also used in quantum teleportation, entanglement swapping, quantum key distribution, and other applications in quantum communication.

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