Deterministic Secure Quantum Communication Without Maximally Entangled States

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Two deterministic secure quantum communication schemes are proposed, one based on pure entangled states and the other on d-dimensional single-photon states. In these two schemes, only single-photon measurements are required for the two authorized users, which makes the schemes more convenient than others in practical applications. Although each qubit can be read out after a transmission of additional classical bit, it is unnecessary for the users to transmit qubits double the distance between the sender and the receiver, which will increase their bit rate and their security. The parties use decoy photons to check eavesdropping efficiently. The obvious advantage in the first scheme is that the pure entangled source is feasible with present techniques.

Keywords: Deterministic secure quantum communication, Pure entangled states, Decoy photons, Single photons

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I. INTRODUCTION

In the last decade, scientists have made dramatic progress in the field of quantum communication [1, 2]. The quantum key distribution (QKD), whose task is to create a private key between two remote authorized users, is one of the most remarkable applications of quantum mechanics. By far, there has been much attention focused on the QKD [3, 4, 5, 6, 7, 8, 9, 10, 11] since Bennett and Brassard (BB84) [3] proposed an original protocol in 1984. In recent years, a novel concept, quantum secure direct communication (QSDC) was put forward and studied by some groups [12, 13, 14, 15, 16, 17]. It allows two remote parties to communicate directly without creating a private key in advance and then using it to encrypt the secret message [12, 13, 14, 15, 16, 17]. Thus, the sender should confirm whether the channel is secure before he encodes his message on the quantum states because the message cannot be discarded, unlike that in QKD protocols [13, 14, 15]. In 2002, following some ideas in quantum dense coding [18], Bosström and Felbinger [12] proposed a ping-pong QSDC scheme by using Einstein-Podolsky-Rosen (EPR) pairs as quantum information carriers, but it has been proven to be insecure in a noise channel [19]. Recently, Deng et al. [13] proposed a two-step QSDC scheme with an EPR pair block and another scheme with a sequence of single photons [14]. Wang et al. [17] introduced a high-dimensional QSDC protocol by following some ideas in quantum superdense coding [20]. Now, QSDC has also been studied in the case of a network [21, 22, 23].

Another class of quantum communication protocols [24, 25, 26, 27, 28, 29, 30, 31, 32] used to transmit secret messages is called deterministic secure quantum communication (DSQC). Certainly, the receiver can read out the secret message only after he exchanges at least one bit of classical information for each qubit with the sender in a DSQC protocol, which is different from QSDC. DSQC is similar to QKD, but it can be used to obtain deterministic information, not a random binary string, which is different from the QKD protocols [2, 3, 4] in which the users cannot predict whether an instance is useful or not. For transmitting a secret message, those protocols [24, 25, 26, 27, 28, 29, 30, 31, 32] can be replaced with an efficient QKD protocol, such as those in Refs. 6-11, because the users can retain or flip the bit value in the key according to the secret message after they obtain the private key [14]. Schimizu and Imoto [24] and Beige et al. [25] presented some novel DSQC protocols with entanglement or a single photon. More recently, Gao and Yan [26, 27] and Man et al. [28] proposed several DSQC schemes based on quantum teleportation [33] and entanglement swapping [34]. The users should complete the eavesdropping check before they take a swapping or teleportation. Although the secret message can be read out only after transmitting an additional classical bit for each qubit, do not have the users to transmit the qubits that carry the secret message. Therefore, these schemes may be more secure than others in a noise channel, and they are more convenient for quantum error correction. On the other hand, a Bell-basis measurement is required inevitably for the parties in both entanglement swapping [34] and quantum teleportation [33], which will increase the difficulty of implementing these schemes in laboratory.

In Ref. 35, Yan and Gao introduced an interesting DSQC protocol following some ideas in Ref. 11 with EPR pairs. After sharing a sequence of EPR pairs securely, the
two parties of a quantum communication only need perform single-photon measurements on their photons and can communicate directly by exchanging a bit of classical information for each qubit. Obviously, their DSQC protocol is more convenient than other quantum communication protocols (Ref. 36). Then, we will discuss it with a sequence of d-dimensional single photons. We use some decoy photons to ensure the security of the whole quantum communication. In both schemes, single-photon measurements are enough. Moreover, we redefine the total efficiency of quantum communication. Compared with the old one presented in Ref. 36, our definition is more reasonable.

II. DSQC WITH PURE ENTANGLED STATES

A. DSQC with Two-dimensional Quantum Systems

In the DSQC schemes with entanglement swapping and teleportation, the parties usually use EPR pairs as the quantum information carriers. An EPR pair is in one of the four Bell states, the four maximally two-qubit entangled states, as follows:

\[ |\psi^\pm\rangle_{AB} = \frac{1}{\sqrt{2}}(|0\rangle_A|1\rangle_B \pm |1\rangle_A|0\rangle_B), \]
\[ |\phi^\pm\rangle_{AB} = \frac{1}{\sqrt{2}}(|0\rangle_A|0\rangle_B \pm |1\rangle_A|1\rangle_B), \]

where \( |0\rangle \) and \( |1\rangle \) are the eigenvectors of the measuring basis (MB) Z. The subscripts A and B indicate the two correlated photons in each EPR pair. For the Bell state \( |\psi^\pm\rangle \) (\( |\phi^\pm\rangle \)), if the two photons are measured with the same MB Z, the outcomes will always be anti-correlated (correlated). The correlation of the entangled quantum system plays an important role in quantum communication as it provides a tool for checking eavesdropping. For example, the two photons A and B are anti-correlated in the Bennett-Brassard-Mermin 1992 QKD protocol even though the users measure them with the MB Z or X as

\[ |\psi^-\rangle_{AB} = \frac{1}{\sqrt{2}}(|0\rangle_A|1\rangle_B - |1\rangle_A|0\rangle_B) = \frac{1}{\sqrt{2}}(|+\rangle_A|-\rangle_B - |\rangle_A|+\rangle_B). \]

Here, \( |\pm\rangle = \frac{1}{\sqrt{2}}(|0\rangle \pm |1\rangle) \) are the two eigenvectors of the basis X. This nature forbids an eavesdropper to eavesdrop on the quantum communication freely with an intercepting-resending strategy.

In experiment, however, the two photons are usually not in the maximally entangled state \( |\psi^-\rangle_{AB} \). That is, a practical quantum signal source usually produces a pure entangled state, such as \( |\Psi\rangle_{AB} = a|0\rangle_A|1\rangle_B + b|1\rangle_A|0\rangle_B \) (here \( |a|^2 + |b|^2 = 1 \)). In this time, the two photons are always anti-correlated with the basis Z, but not with the basis X, as

\[ |\Psi\rangle_{AB} = a|0\rangle_A|1\rangle_B + b|1\rangle_A|0\rangle_B = \frac{1}{2}(a + b)(|+\rangle_A|+\rangle_B - |\rangle_A|\rangle_B) \]
\[ - (a - b)(|+\rangle_A|-\rangle_B - |\rangle_A|\rangle_B). \]

That is, the security of the quantum communication with pure entangled states is lower than that with Bell states if the users use the two bases Z and X to measure them for the eavesdropping check directly. On the other hand, the quantum source is more convenient than maximally entangled states.

In the present DSQC scheme, we will use pure entangled states as the quantum information carriers for DSQC. This scheme has the advantage of a practical entangled source and of high security with decoy photons, compared with those in Refs. 26-28 and 35. For the integrity of our point-to-point DSQC scheme, we give all the steps as follows:

(1) The sender Alice prepares N two-photon ordered pairs in which each is randomly in one of the two pure entangled states \( \{ |\Psi\rangle_{AB}, |\Psi'\rangle_{AB} \} \). Here, \( |\Psi'\rangle_{AB} = a|1\rangle_A|0\rangle_B + b|0\rangle_A|1\rangle_B \) which can be prepared by flipping the bit value of the two photons in the state \( |\Psi\rangle_{AB} \), i.e., \( (\sigma^A_x \otimes \sigma^B_x)|\Psi\rangle_{AB} = |\Psi'\rangle_{AB} \), similar to Ref. 10. Alice picks out photon A from each pair to form an ordered sequence \( S_A \), say \( [A_1, A_2, ..., A_N] \), and the other partner photons compose the sequence \( S_B = [B_1, B_2, ..., B_N] \), similar to Refs. 6, 13, 37, 38.

For checking eavesdropping efficiently, Alice replaces some photons in the sequence \( S_B \) with her decoy photons \( S_{de} \), which are randomly in one of the states \( \{ |0\rangle, |1\rangle, |+\rangle, |-\rangle \} \). They can be prepared with an ideal single-photon source. Also, Alice can get a decoy photon by measuring photon A in a photon pair \( |\Psi\rangle_{AB} \) in the sequence \( S_A \) with the MB Z and then operating on photon B with the local unitary operation \( \sigma_x \) or a Hadamard (H) operation:

\[ H|0\rangle = |+\rangle, \quad H|1\rangle = |-\rangle. \]

We will discuss the reason that Alice inserts the decoy photons in the sequence \( S_B \) in detail below.

(2) Alice encodes her secret message \( M_A \) on the photons in the sequence \( S_B \) with the two unitary operations I and \( U = \sigma_x \), which represent bits 0 and 1, respectively. Obviously, she can choose all the decoy photons, \( S_{de} \), as samples for checking eavesdropping.

(3) Alice sends sequence \( S_B \) to Bob and always keeps the sequence \( S_A \) at home.
(4) After Bob confirms the receipt of sequence $S_B$, Alice tells Bob the positions and the states of the decoy photons $S_{de}$. Bob performs a suitable measurement on each photon in $S_{de}$ with the same basis as Alice chose for preparing it, and completes the error rate analysis of the samples. If the error is very low, Alice and Bob continue their communication to next step; otherwise, they abandon the result of the transmission and repeat the quantum communication from the beginning.

(5) Alice and Bob measure their photons remaining in the sequences $S_A$ and $S_B$ with the same basis $Z$, and they get the results $R_A$ and $R_B$, respectively.

(6) Alice publicly broadcasts her results $R_A$.

(7) Bob reads out the secret message $M_A$ with his outcomes $R_B$ directly; i.e., $M_A = R_A \otimes R_B \oplus 1$.

It is interesting to point out that it is unnecessary for the receiver Bob and the sender Alice to perform Bell-basis measurements on their photons, they only perform single-photon measurements, which makes this scheme more convenient than others [20, 21, 22] with entanglement swapping and quantum teleportation. Moreover, the quantum sources are just a practical pure entangled states, not maximally entangled states, which makes this DSQC scheme easier than those with Bell states [15, 18]. As each photon just transmits the distance between the sender and the receiver, its bit rate is higher than those with two-way quantum communication as the attenuation of a signal in a practical channel is exponential; i.e., $N_s(L) = N_s(0)e^{-\lambda L}$. Here, $N_s(L)$ is the photon number after being transmitted the distance $L$, and $\lambda$ is the attenuation parameter.

As the security of a quantum communication scheme depends on the error rate analysis of samples chosen randomly, the present DSQC scheme can be made to be secure as the decoy photons are prepared randomly in one of the four states $\{|0\rangle, |1\rangle, |+\rangle, |-\rangle\}$ and are distributed in the sequence $S_B$ randomly. An eavesdropper, say Eve, knows neither the states of the decoy photons nor their positions in the sequence $S_B$, so her action will inevitably perturb the decoy photons and be detected by the users. As the basis for the measurement on each decoy photon is chosen after the sender has told the receiver its basis, all of the decoy photons can be used for checking eavesdropping, not just a fraction of them as Ref. 9.

Without the decoy photons, the security of the present DSQC scheme will decrease as the two photons in a pure entangled state $|\Psi\rangle$ or $|\Psi'\rangle$ have not deterministic relation when they are measured with the MB X. That is, the parties cannot determine whether the errors of their outcomes comes from eavesdropping done by Eve or the nondeterministic relation obtained with the MB X if they only transmit a sequence of pure entangled states. In this way, Eve can obtain a fraction of the secret message without being detected.

### B. DSQC with d-dimensional Quantum Systems

It is straightforward to generalize our DSQC scheme to the case with $d$-dimensional quantum systems (such as the orbit momentum of a photon [23]). A pure symmetric $d$-dimensional two-photon entangled state can be described as

$$|\Psi_p\rangle_{AB} = \sum_j a_j |j\rangle_A \otimes |j\rangle_B,$$

where

$$\sum_j |a_j|^2 = 1.$$  

Defining

$$U_m = \sum_j |j + m \mod d\rangle \langle j|,$$

which is used to transfer the state $|j\rangle$ into the state $|j + m\rangle$; i.e.,

$$(U_m \otimes U_m)|\Psi_p\rangle_{AB} = \sum_j a_j |j + m \mod d\rangle_A \otimes |j + m \mod d\rangle_B,$$

where $m = 1, 2, \cdots, d - 1$.

As in Ref. 23, the MB $Z_d$ is made up of the $d$ eigenvectors as

$$|0\rangle, |1\rangle, |2\rangle, \cdots, |d - 1\rangle.$$  

The $d$ eigenvectors of the MB $X_d$ can be described as

$$|0\rangle_x = \frac{1}{\sqrt{d}} \left(|0\rangle + |1\rangle + \cdots + |d - 1\rangle\right),$$

$$|1\rangle_x = \frac{1}{\sqrt{d}} \left(|0\rangle + e^{\frac{2\pi i}{d}} |1\rangle + \cdots + e^{\frac{(d - 1)2\pi i}{d}} |d - 1\rangle\right),$$

$$|2\rangle_x = \frac{1}{\sqrt{d}} \left(|0\rangle + e^{\frac{4\pi i}{d}} |1\rangle + \cdots + e^{\frac{(d - 1)4\pi i}{d}} |d - 1\rangle\right),$$

$$|d - 1\rangle_x = \frac{1}{\sqrt{d}} \left(|0\rangle + e^{\frac{2(d - 1)\pi i}{d}} |1\rangle + \frac{2 \times (d - 1) \pi i}{d} |2\rangle + \cdots + e^{\frac{(d - 1)4\pi i}{d}} |d - 1\rangle\right).$$

The two vectors $|k\rangle$ and $|l\rangle_x$ coming from two MBs satisfy the relation $|k\rangle_x |l\rangle_x = \frac{1}{d}$. As in Ref. 23, we can construct the $d$-dimensional Hadamard ($H_d$) operation as follows:

$$H_d = \frac{1}{\sqrt{d}} \begin{pmatrix}
1 & 1 & \cdots & 1 \\
1 & e^{2\pi i/d} & \cdots & e^{(d - 1)2\pi i/d} \\
1 & e^{4\pi i/d} & \cdots & e^{(d - 1)4\pi i/d} \\
\vdots & \vdots & \ddots & \vdots \\
1 & e^{2(d - 1)\pi i/d} & \cdots & e^{(d - 1)2(d - 1)\pi i/d}
\end{pmatrix}$$

That is, $H_d |j\rangle = |j\rangle_x$. 
For quantum communication, Alice prepares $N$ ordered $d$-dimensional two-photon pure entangled states. Each pair is randomly in one of the states $\{ (U_m^{A} \otimes U_m^{B}) | \Psi_p \rangle_{AB} \} (m = 0, 1, 2, \ldots, d-1)$, similar to the case with two-dimensional two-photon pure entangled states. The uniform distribution of the pure entangled states will make the users obtain outcomes $0, 1, 2, \ldots, d-1$ with the same probability. Before the communication, Alice divides the photon pairs into two sequences, $S'_A$ and $S'_B$. That is, the sequence $S'_A$ is composed of photons $A$ in the $N$ ordered photon pairs, and the sequence $S'_B$ is made up of photons $B$.

The sender Alice can also prepare decoy photons, similar to the case with two-dimensional photons. In detail, Alice measures some of the photons $A$ in the sequence $S'_A$ with the basis $Z_d$ and then operates on them with $I$ or $H_B$. She inserts the decoy photons in the sequence $S'_B$ and keeps their positions secret. For the other photons in the sequence $S'_B$, Alice encodes her secret message on the sequence $S'_B$ with the unitary operations $\{ U_m^B \}$. After Bob receives the sequence $S'_B$, Alice requires Bob to measure the decoy photons with the suitable bases $\{ Z_d, X_d \}$, the same as those used for preparing them. If the transmission is secure, Alice and Bob can measure the photons remaining in the sequences $S'_A$ and $S'_B$ with the basis $Z_d$, respectively. After Alice publishes her outcomes $R'_A$, Bob can obtain the secret message $M_A$ directly with his own outcomes $R'_B$.

C. The Capacity and Efficiency

In each pure entangled state $\rho$, such as $| \Psi_p \rangle_{AB} = \sum_j a_j | j \rangle_A \otimes | j \rangle_B$, the von Neumann entropy for each photon is

$$S(\rho) = - \sum_i \lambda_i \log 2 \lambda_i = - \sum_{i=0}^{d-1} |a_i|^2 \log_2 |a_i|^2, \quad (13)$$

where $\lambda_i = |a_i|^2$ is the probability that one gets the result $|i\rangle$ when one measures photon $A$ or $B$ in the state $| \Psi_p \rangle_{AB} = \sum_j a_j | j \rangle_A \otimes | j \rangle_B$ with the basis $Z_d$. When $|a_i|^2 = \frac{1}{d}$ (for each $i = 0, 1, \ldots, d-1$), the von Neumann entropy has its maximal value $S(\rho)_{\text{max}} = \log_2 d$. In other cases, $S(\rho)_{\text{max}} < \log_2 d$. For each photon pair, its von Neumann entropy is $\log_2 d$.

In fact, each pure entangled state $\rho$ in the present DSQC scheme can carry $\log_2 d$ bits of classical information. It is obvious that photon $B$ is randomly in the state $|i\rangle$ with the probability $P(i) = \frac{1}{d}$ when Bob measures it with the basis $Z_d$. The reason is $P(i) = \frac{1}{d} \sum_{m} |a_m|^2 = \frac{1}{d}$ as the photon pair is randomly in one of the states $\{ (U_m^{A} \otimes U_m^{B}) | \Psi_p \rangle_{AB} \} (m = 0, 1, 2, \ldots, d-1)$. That is, the distribution of the pure entangled states $\{ (U_m^{A} \otimes U_m^{B}) | \Psi_p \rangle_{AB} \}$ provides a way for carrying information efficiently.

As almost all the quantum source (except for the decoy photons used for eavesdropping check) can be used to carry the secret message, the intrinsic efficiency $\eta_q$, for qubits in our schemes approaches 100%. Here,

$$\eta_q = \frac{q_u}{q_t}, \quad (14)$$

where $q_u$ is the number of useful qubits in the quantum communication and $q_t$ is the number of total qubits used (not the ones transmitted; this is different from the definition proposed by Cabello [36]). We define the total efficiency of a quantum communication scheme as

$$\eta_t = \frac{m_u}{q_t + b_t}, \quad (15)$$

where $m_u$ and $b_t$ are the numbers of message transmitted and the classical bits exchanged, respectively. In the present DSQC scheme, $m_u = \log_2 d, \ q_t = 2S(\rho)$ and $b_t = \log_2 d$ as the users pay $\log_2 d$ bits of classical information and $q_t = 2S(\rho)$ bits of quantum information (a photon pair) for $m_u = \log_2 d$ bits of the secret message. Thus, its total efficiency is $\eta_t = \frac{\log_2 d}{\log_2 d + 2S(\rho)} \geq \frac{1}{3}$ in theory.

It is of interest to point out that our definition of the total efficiency of a quantum communication scheme, $\eta_t$, is more reasonable, compared with the old one [22]. Even though Alice only transmits a sequence of photons to Bob, the source is an entangled one, which is different from the single photons discussed below. Obviously, the new definition can be used to distinguish a scheme with single photons from one with entangled ones if the efficiency for qubits and the classical information exchanged are both the same. Moreover, the total efficiency of dense coding according to this definition is no more than 100% as the traveling photon in an EPR pair carries two bits of information, and the quantum system used for the quantum channel is a two-qubit one.

III. EFFICIENT ONE-WAY DSQC WITH $d$-DIMENSIONAL SINGLE PHOTONS

In our DSQC scheme above, the parties only exploit the correlation of the two photons in a pure entangled state along the direction $z$ for transmitting the secret message. We can also simplify some procedures with single photons following some ideas in Ref. 14. Certainly, an ideal single-photon source is not available for a practical application at present, different from the pure entanglement source. With the development of technology, we believe that a practical ideal single-photon source can be produced without difficulty [10], so in theory, it is interesting to study the model for DSQC with single photons.

Similar to the case with pure entangled states, we can describe the principle of our DSQC scheme with single photons as follows:

(S1) Alice prepares a sequence of $d$-dimensional single photons $S$. She prepares them by choosing the MB $Z_d$ or the MB $X_d$ randomly, the same as in Ref. 14.
She chooses some photons as the decoys and encodes her secret message on the other photons with the unitary operations \( \{ U_m, U_m^x \} \), where

\[
U_m^x = \sum_j e^{\frac{2\pi i jm}{d}} |j + m \mod d \rangle \langle j |.
\]

That is, Alice encodes her secret message with the operations \( U_m \) if a single photon is in one of the eigenstates of the MB \( Z_d \). Otherwise, she will encode the message with the operations \( U_m^x \).

(S2) Alice sends the sequence \( S \) to Bob.

(S3) Bob completes the error rate analysis on the decoy photons. In detail, Alice tells Bob the positions and the states of the decoy photons. Bob measures them with the suitable MBs and analyzes their error rates.

(S4) If the transmission of the sequence \( S \) is secure, Alice tells Bob the original states of the photons retained. Bob measures them with the same MBs as those chosen by Alice for preparing them. Otherwise, they discard their transmission and repeat the quantum communication from the beginning.

(S5) Bob reads out the secret message \( M_A \) with his own outcomes.

In essence, this DSQC scheme is a revision of the QSDC protocol in Ref. 14, and is modified for transmitting the secret message in one-way quantum communication. Compared with the schemes based on entanglement [12, 13, 14, 17, 26, 27, 28, 29, 30], this DSQC scheme only requires the parties to prepare and measure single photons, which makes it more convenient in practical applications, especially with the development of techniques for storing quantum states [11]. Compared with the quantum one-time pad QSDC scheme [14], the photons in the present DSQC scheme need only be transmitted from the sender to the receiver, not double the distance between the parties, which will increase the bit rate in a practical channel as the channel will attenuate the signal exponentially with the distance \( L \). Certainly, the parties should exchange a classical bit for each qubit to read out the secret message. As the process for exchanging a classical bit is by far easier than that for a qubit, the present scheme still has an exciting nature for applications.

IV. DISCUSSION AND SUMMARY

Similar to DSQC protocols [26, 27, 28] with entanglement swapping and teleportation, Alice can also encode her secret message on the sequence \( S_A \) after she sends the sequence \( S_B \) to Bob and confirms the security of the transmission in our first DSQC scheme. Moreover, she can accomplish this task in a simple way. That is, Alice first measures her photons remaining in the sequence \( S_A \) and then publishes the difference between her outcomes and her secret message. In the DSQC scheme with single photons, Alice need only modify the process for publishing her information to encode her secret message after the transmission is confirmed to be secure. At this time, she only tells Bob the combined information about the original states of the single photons and the secret message, not just the states.

In summary, we have proposed two DSQC protocols. One is based on a sequence of pure entangled states, not maximally entangled ones. The obvious advantage is that a pure-entanglement quantum signal source is feasible at present. In the other scheme, the parties exploit only a sequence of \( d \)-dimensional single photons. In the present two DSQC protocols, only single-photon measurements are required for the authorized users, which makes them more convenient than those [26, 27, 28] with quantum teleportation and entanglement swapping. Even though it is necessary for the users to exchange one bit of classical information for each bit of the secret message, the qubits do not run through the quantum line twice, which will increase their bit rate and security in practical conditions as the qubits do not suffer from the noise and the loss aroused by the quantum line after they are transmitted from one party to the other. Also, they can be easily modified for encoding the secret message after confirming the security of the quantum channel, the same as in Refs. 26-28.

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[1] M. A. Nielsen and I. L. Chuang, Quantum Computation and Quantum Information (Cambridge University Press, Cambridge, UK, 2000)
[2] N. Gisin, G. Ribordy, W. Tittel, and H. Zbinden, Rev. Mod. Phys. 74, 145 (2002)
[3] C. H. Bennett and G. Brassard, Proc. IEEE Int. Conf. on Computers, Systems and Signal Processing, Bangalore, India (IEEE, New York, 1984), pp. 175-179.
[4] A. K. Ekert, Phys. Rev. Lett. 67, 661 (1991).
[5] C. H. Bennett, G. Brassard, and N. D. Mermin, Phys. Rev. Lett. 68, 557 (1992).
[6] G. L. Long and X. S. Liu, Phys. Rev. A 65, 032302 (2002).
[7] F. G. Deng and G. L. Long, Phys. Rev. A 68, 042315
(2003).

[8] F. G. Deng and G. L. Long Phys. Rev. A 70, 012311 (2004).

[9] H. K. Lo, H. F. Chau, and M. Ardehali, J. Cryptology 18, 122 (2005).

[10] P. Xue, C. F. Li, and G. C. Guo, Phys. Rev. A 64, 032305 (2001).

[11] F. G. Deng, G. L. Long, Y. Wang, and L. Xiao, Chin. Phys. Lett. 21, 2097 (2004).

[12] K. Bostr¨ om and T. Felbinger, Phys. Rev. Lett. 89, 187902 (2002).

[13] F. G. Deng, G. L. Long, and X. S. Liu, Phys. Rev. A 68, 042317 (2003).

[14] F. G. Deng, G. L. Long, and X. S. Liu, Phys. Rev. A 69, 052319 (2004).

[15] C. Wang, F. G. Deng, Y. S. Li, X. S. Liu, and G. L. Long, Phys. Rev. A 71, 044305 (2005); C. Wang, F. G. Deng, and G. L. Long, Opt. Commun. 253, 15 (2005).

[16] Q. Y. Cai and B. W. Li, Phys. Rev. A 69, 054301 (2004).

[17] Q. Y. Cai and B. W. Li, Chin. Phys. Lett. 21, 601 (2004).

[18] C. H. Bennett and S. J. Wiesner, Phys. Rev. Lett. 69, 2881 (1992).

[19] A. W´ ojcik, Phys. Rev. Lett. 90, 157901 (2003); Z. J. Zhang, Z. X. Man, and Y. Li, Phys. Lett. A 333, 46 (2004).

[20] X. S. Liu, G. L. Long, D. M. Tong, and F. Li, Phys. Rev. A 65, 022304 (2002); A. Grudka and A. W´ ojcik, Phys. Rev. A 66, 014301 (2002).

[21] X. H. Li, P. Zhou, Y. J. Liang, C. Y. Li, H. Y. Zhou, and F. G. Deng, Chin. Phys. Lett. 23, 1080 (2006).

[22] F. G. Deng, X. H. Li, C. Y. Li, P. Zhou, and H. Y. Zhou, Phys. Lett. A (in press).

[23] F. G. Deng, X. H. Li, C. Y. Li, P. Zhou, and H. Y. Zhou, quant-ph/0605214.

[24] K. Shimizu and N. Imoto, Phys. Rev. A 60, 157 (1999); K. Shimizu and N. Imoto, Phys. Rev. A 62, 054303 (2000).

[25] A. Beige, B. G. Englert, C. Kurtsiefer, and H. Weinfurter, Acta Phys. Pol. A 101, 357 (2002); J. Phys. A 35, L407 (2002).

[26] Z. X. Man, Z. J. Zhang, and Y. Li, Chin. Phys. Lett. 22, 18 (2005).

[27] F. L. Yan and X. Zhang, Euro. Phys. J. B 41, 75 (2004).

[28] T. Gao Z. Naturforsch. A 59, 597 (2004); T. Gao, F. L. Yan, and Z. X. Wang, Nuovo Cimento B 119, 313 (2004); T. Gao, F. L. Yan, and Z. X. Wang, J. Phys. A 38, 5761 (2005).

[29] Y. Xia, C. B. Fu, S. Zhang, S. K. Hong, K. H. Yeon, and C. I. Um, J. Korean Phys. Soc. 48, 24 (2006); A. D. Zhu, Y. Xia Y, Q. B. Fan, and S. Zhang, Phys. Rev. A 73, 022338 (2006).

[30] H. J. Cao and H. S. Song, Chin. Phys. Lett. 23, 290 (2006).

[31] H. Lee, J. Lim, and H. Yang, Phys. Rev. A 73, 042305 (2006).

[32] J. Wang, Q. Zhang and C. J. Tang, Phys. Lett. A 358, 256 (2006).

[33] C. H. Bennett, G. Brassard, C. Cr´ epeau, R. Jozsa, A. Peres, and W. K. Wootters, Phys. Rev. Lett. 70, 1895 (1993).

[34] M. Zukowski, A. Zeilinger, M. A. Horne, and A. K. Ekert, Phys. Rev. Lett. 71, 4287 (1993); J. W. Pan, D. Bouwmeester, H. Weinfurter, and A. Zeilinger, Phys. Rev. Lett. 80, 3891 (1998).

[35] F. L. Yan and T. Gao, quant-ph/0501055.

[36] A. Cabello, Phys. Rev. Lett. 85, 5635 (2000)

[37] C. Y. Li, H. Y. Zhou, Y. Wang, and F. G. Deng, Chin. Phys. Lett. 22, 1049 (2005).

[38] F. G. Deng, X. H. Li, C. Y. Li, P. Zhou, and H. Y. Zhou, Phys. Rev. A 72, 044301 (2005); F. G. Deng, C. Y. Li, Y. S. Li, H. Y. Zhou, and Y. Wang, Phys. Rev. A 72, 022338 (2005); X. H. Li, P. Zhou, C. Y. Li, H. Y. Zhou, and F. G. Deng, J. Phys. B 39, 1975 (2006).

[39] A. Mair, A. Vaziri, G. Weihs, and A. Zeilinger, Nature 412, 313 (2001).

[40] C. Brunel, B. Lounis, P. Tamarat, and M. Orrit, Phys. Rev. Lett. 83, 2722 (1999); P. Michler, A. Kiraz, C. Becker, W. V. Schoenfeld, P. M. Petroff, L. Zhang, E. Hu, and A. Imamoglu, Science 290, 2282 (2000); Z. Yuan, B. E. Kardynal, R. M. Stevenson, A. J. Shields, C. J. Lobo, K. Cooper, N. S. Beattie, D. A. Ritchie, and M. Pepper, Science 295, 102 (2002).

[41] C. Liu, Z. Dutton, C. H. Behroozi, and L. V. Hau, Nature 409, 490 (2001); D. F. Philips, A. Fleischhauer, A. Mair, R. L. Walsworth, and M. D. Lukin, Phys. Rev. Lett. 86, 783 (2001); C. P. Sun, Y. Li, and X. F. Liu, Phys. Rev. Lett. 91, 147903 (2003).