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A new optical scheme for teleportation of entangled coherent state*

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We propose a nearly perfect optical scheme for the quantum teleportation of entangled coherent states using optical devices such as nonlinear Kerr media, beam splitters, phase shifters, and photon detectors. Different from those previous schemes, our scheme needs only "yes' or 'no' measurements of the photon number of the related modes, i.e. nonzero- and zero-photon measurements, while in previous schemes one has to exactly identify the even or odd parity character of the photon numbers detected by detectors.

Keywords: quantum teleportation, entangled coherent state, detection of photon

PACC: 0365, 4250

1. Introduction

Quantum teleportation is a process in which an arbitrary quantum state of a system can be transported from one location to another. The state of the system is destroyed in one place and a perfect replica can be created at a distant site by making measurements on the system and classical communication of the results to the remote location. The original proposals for quantum teleportation[1,2] focused on teleporting quantum states of a system in a finite-dimensional (discrete variable) state space, such as the two polarizations of a photon or the discrete levels of an atom.[3−14] Discrete–variable teleportation has been demonstrated experimentally in optical systems[15] and liquid-state nuclear magnetic resonance systems.[16]

Recently, quantum teleportation has been extended to continuous variables corresponding to states of infinite-dimensional (continuous-variable) systems[17−29] such as optical field or the motion of massive particle. In particular, following the theoretical proposal in Ref.[14], the continuous-variable teleportation has been realized for coherent states of a light field[20] by using entangled two-mode squeezed optical beams produced by parametric down-conversion in a sub-threshold optical parametric oscillator. Although coherent states are continuous and nonorthogonal states, they are very close to classical states. A real challenge to quantum teleportation is to teleport truly nonclassical states like squeezed states, quantum superposition states and entangled states. van Enk and Hirota[20] proposed a scheme for faithfully teleporting a superposition state of two coherent states with equal amplitudes and opposite-phases through a quantum channel described by a maximally entangled coherent state with one ebit of entanglement. Wang considered the teleportation of the entangled coherent state.[27]

In this paper we propose a nearly perfect optical scheme for the quantum teleportation of entangled coherent states (ECS) by using optical devices. In the present scheme, only measurements of zero photons and nonzero photons are needed. Hence, the major difficulty in clearly identifying odd or even photon numbers in previous schemes is overcome. The rest of this paper is organized as follows. In Section 2, we show how to teleport entanglement coherent states. And the discussion and remarks are given in Section 3.

2. Teleportation of entangled coherent state

Now assume that we want to teleport the following state:

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$$|\phi\rangle_{12} = \mathcal{N}(x|\alpha,\alpha\rangle + y|-\alpha,-\alpha\rangle)_{12},$$
$$\mathcal{N}^{-2} = [|x|^2 + |y|^2 + 2\mathrm{e}^{-4|\alpha|^2}\mathrm{Re}(xy^*)], \quad (1)$$

where $|\alpha\rangle$ is a normal Glauber coherent state defined by

$$|\alpha\rangle = \mathrm{e}^{-\frac{|\alpha|^2}{2}} \sum_{n=0}^{\infty} \frac{\alpha^n}{\sqrt{n!}}|n\rangle. \quad (2)$$

According to the conditional methods, if the ECS $|\phi\rangle_{12}$ is to be teleported, at least a tripartite entangled state is required as a quantum channel. However, our scheme is quite different from those traditional schemes. Our presented schematic diagram for quantum teleportation of the ECS is shown in Fig.1. Technically, we need eight modes of light for teleporting an unknown ECS given by Eq.(1) from modes 1 and 2 on Alice side to modes 5 and 6 on Bob side. Other four modes are ancillary modes. Four Kerr media, three beam splitters, and six photodetectors are needed to realize the teleportation scheme. Bob prepares the ancillary modes 3, 4, 5, and 6 in state $|\alpha,\alpha,\alpha,\alpha\rangle_{3,4,5,6}$, mixes modes 3 and 5 by the cross Kerr media $\hat{K}_{35}$, and mixes modes 4 and 6 by the cross Kerr media $\hat{K}_{46}$. Having waited a time for high speed transmission of the twin beams of light that are marked by modes 3 and 4, Alice acquires the twin modes 3 and 4, mixes modes 1 and 3 by the cross Kerr media $\hat{K}_{13}$, and mixes modes 2 and 4 by the cross Kerr media $\hat{K}_{24}$. As is well known, a cross Kerr interaction can be described by the Hamiltonian[24]

$$\hat{H} = -\chi\hat{a}^\dagger\hat{a}\hat{b}^\dagger\hat{b}, \quad (3)$$

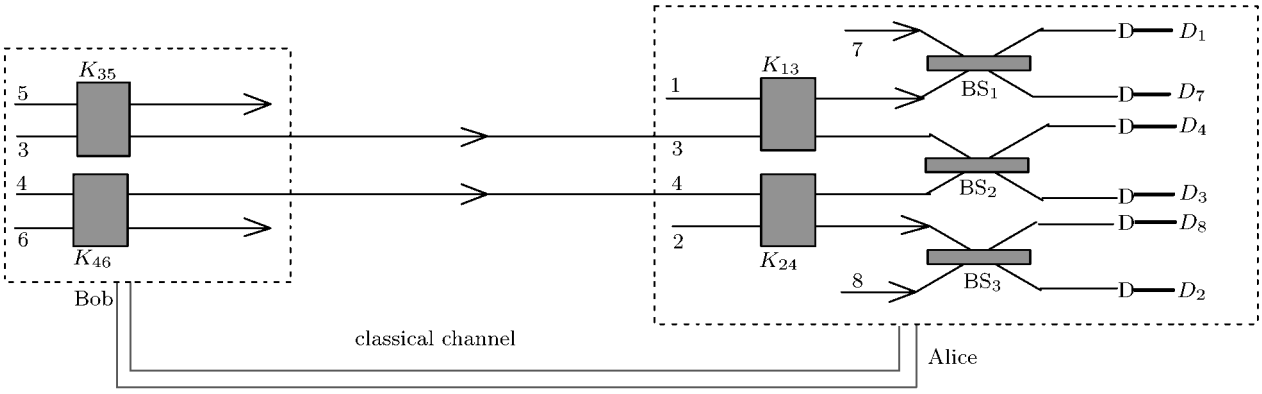


Fig.1. The schematic diagram for teleportation of the ECS.

which leads to the following unitary evolution operator:

$$\hat{K}_{ab}(\tau) = \mathrm{e}^{\mathrm{i}\tau\hat{a}^\dagger\hat{a}\hat{b}^\dagger\hat{b}}, \quad (4)$$

where $\tau = \chi t$, with t being the evolution time, $\hat{a}^\dagger(\hat{b}^\dagger)$ and $\hat{a}(\hat{b})$ are the creation and annihilation operators for modes $a(b)$, respectively.

It is easy to see that when $\chi t = \pi$ the action of the cross Kerr unitary evolution operator on two modes with the coherent-state input $|\alpha\rangle_a|\beta\rangle_b$ is given by

$$\hat{K}_{ab}(\pi)|\alpha\rangle_a|\beta\rangle_b = \frac{1}{2}[|\alpha\rangle_a(|\beta\rangle_b + |-\beta\rangle_b) + |-\alpha\rangle_a(|\beta\rangle_b - |-\beta\rangle_b)]. \quad (5)$$

After passing the above process, the initial state $|\Psi\rangle_{123456} = |\phi\rangle_{12}|\alpha,\alpha,\alpha,\alpha\rangle_{3456}$ becomes

$$\begin{aligned}
|\Phi\rangle_{123456} = {} & \hat{K}_{13}\hat{K}_{24}\hat{K}_{35}\hat{K}_{46}|\Psi\rangle_{123456} \\
= {} & \frac{\mathcal{N}}{4}[|\alpha,\alpha\rangle_{12}(|\alpha,\alpha\rangle + |-\alpha,-\alpha\rangle)_{34} \times (x|\alpha,\alpha\rangle + y|-\alpha,-\alpha\rangle)_{56} \\
& + |\alpha,\alpha\rangle_{12}(|\alpha,-\alpha\rangle + |-\alpha,\alpha\rangle)_{34} \times (x|\alpha,\alpha\rangle + y|-\alpha,-\alpha\rangle)_{56} \\
& + |-\alpha,-\alpha\rangle_{12}(|\alpha,\alpha\rangle + |-\alpha,-\alpha\rangle)_{34} \times (x|-\alpha,-\alpha\rangle + y|\alpha,\alpha\rangle)_{56} \\
& + |-\alpha,-\alpha\rangle_{12}(|\alpha,-\alpha\rangle + |-\alpha,\alpha\rangle)_{34} \times (-x|-\alpha,-\alpha\rangle + y|\alpha,\alpha\rangle)_{56} \\
& + |\alpha,-\alpha\rangle_{12}(|\alpha,\alpha\rangle - |-\alpha,-\alpha\rangle)_{34} \times (x|\alpha,-\alpha\rangle + y|-\alpha,\alpha\rangle)_{56}
\end{aligned}$$

$$
\begin{aligned}
&+|\alpha,-\alpha\rangle_{12}(|\alpha,-\alpha\rangle-|-\alpha,\alpha\rangle)_{34}\times(-x|\alpha,-\alpha\rangle+y|-\alpha,\alpha\rangle)_{56}\\
&+|-\alpha,\alpha\rangle_{12}(|\alpha,\alpha\rangle-|-\alpha,-\alpha\rangle)_{34}\times(x|-\alpha,\alpha\rangle+y|\alpha,-\alpha\rangle)_{56}\\
&+|-\alpha,\alpha\rangle_{12}(|\alpha,-\alpha\rangle-|-\alpha,\alpha\rangle)_{34}\times(x|-\alpha,\alpha\rangle-y|\alpha,-\alpha\rangle)_{56}]. \qquad (6)
\end{aligned}
$$

From Eq.(6) we can see that quantum teleportation of the ECS given by Eq.(1) from modes 1 and 2 to modes 5 and 6 may be realized if one can discriminate eight quantum states of modes 1, 2, 3, and 4 on the right-hand side of Eq.(6). Unfortunately, no one can discriminate decisively the eight states since they are nonorthogonal to each other. In order to overcome this discrimination problem of the eight states, we further introduce two ancillary modes 7 and 8. Let modes 1 and 7, and modes 2 and 8 mix at lossless symmetric 50/50 beam splitters BS_1 and BS_2, respectively. The beam splitter transformation on modes i and j is described by $\hat{B}_{ij}=\exp[i(\pi/4)(\hat{a}_i^{\dagger}\hat{a}_j+\hat{a}_j^{\dagger}\hat{a}_i)]$. Each beam splitter is equipped together with a pair of $\pi/2$ phase shifters described by the unitary operator $\hat{P}_i=\exp(-\mathrm{i}\pi\hat{a}_i^{\dagger}\hat{a}_i/2)$ with i being mode label. Then we have the total unitary operator $\hat{\mathcal{B}}_{ij}=\hat{P}_j\hat{B}_{ij}\hat{P}_j$, which transforms the state $|\alpha,\beta\rangle_{ij}$ as

$$
\hat{\mathcal{B}}_{i,j}|\alpha\rangle_i|\beta\rangle_j=|(\alpha+\beta)/\sqrt{2}\rangle_i|(\alpha-\beta)/\sqrt{2}\rangle_j. \qquad (7)
$$

After passing the cross-Kerr media, beam splitters and phase shifts, the output state of the five modes is given by

$$
\begin{aligned}
|\Phi\rangle'_{1-8}&=\hat{\mathcal{B}}_{17}\hat{\mathcal{B}}_{28}\hat{\mathcal{B}}_{34}|\Phi\rangle_{123456}|\alpha,\alpha\rangle_{78}\\
&=\frac{\mathcal{N}}{4}[|\sqrt{2}\alpha\rangle_1|0\rangle_7|\sqrt{2}\alpha\rangle_2|0\rangle_8(|\sqrt{2}\alpha\rangle+|-\sqrt{2}\alpha\rangle)_3|0\rangle_4(x|\alpha,\alpha\rangle+y|-\alpha,-\alpha\rangle)_{56}\\
&\quad+|\sqrt{2}\alpha\rangle_1|0\rangle_7|\sqrt{2}\alpha\rangle_2|0\rangle_8|0\rangle_3(|\sqrt{2}\alpha\rangle+|-\sqrt{2}\alpha\rangle)_4(x|\alpha,\alpha\rangle-y|-\alpha,-\alpha\rangle)_{56}\\
&\quad+|0\rangle_1|-\sqrt{2}\alpha\rangle_7|0\rangle_2|-\sqrt{2}\alpha\rangle_8(|\sqrt{2}\alpha\rangle+|-\sqrt{2}\alpha\rangle)_3|0\rangle_4(x|-\alpha,-\alpha\rangle+y|\alpha,\alpha\rangle)_{56}\\
&\quad+|0\rangle_1|-\sqrt{2}\alpha\rangle_7|0\rangle_2|-\sqrt{2}\alpha\rangle_8|0\rangle_3(|\sqrt{2}\alpha\rangle+|-\sqrt{2}\alpha\rangle)_4(-x|-\alpha,-\alpha\rangle+y|\alpha,\alpha\rangle)_{56}\\
&\quad+|\sqrt{2}\alpha\rangle_1|0\rangle_7|0\rangle_2|-\sqrt{2}\alpha\rangle_8(|\sqrt{2}\alpha\rangle-|-\sqrt{2}\alpha\rangle)_3|0\rangle_4(x|\alpha,-\alpha\rangle+y|-\alpha,\alpha\rangle)_{56}\\
&\quad+|\sqrt{2}\alpha\rangle_1|0\rangle_7|0\rangle_2|-\sqrt{2}\alpha\rangle_8|0\rangle_3(|\sqrt{2}\alpha\rangle-|-\sqrt{2}\alpha\rangle)_4(-x|\alpha,-\alpha\rangle+y|-\alpha,\alpha\rangle)_{56}\\
&\quad+|0\rangle_1|-\sqrt{2}\alpha\rangle_7|\sqrt{2}\alpha\rangle_2|0\rangle_8(|\sqrt{2}\alpha\rangle-|-\sqrt{2}\alpha\rangle)_3|0\rangle_4(x|-\alpha,\alpha\rangle+y|\alpha,-\alpha\rangle)_{56}\\
&\quad+|0\rangle_1|-\sqrt{2}\alpha\rangle_7|\sqrt{2}\alpha\rangle_2|0\rangle_8|0\rangle_3(|\sqrt{2}\alpha\rangle-|-\sqrt{2}\alpha\rangle)_4(x|-\alpha,\alpha\rangle-y|\alpha,-\alpha\rangle)_{56}]. \qquad (8)
\end{aligned}
$$

From Eq.(8) it can be seen that the nearly perfect quantum teleportation of the ECS given by Eq.(1) can be realized through photon-number measurements of modes 1, 2, 3, 4, 7, and 8, classical communication between Alice and Bob, and Bob's proper operations. In what follows, we investigate the successful probabilities of the teleportation scheme for different measurements of photon numbers. We denote the photon numbers counted by detectors D_1, D_7, D_8, D_2, D_4, and D_3 by n_1, n_7, n_8, n_2, n_4, and n_3, respectively. All of the detectors are on Alice's side. Looking carefully at Eq.(8), we recognize that the perfect or approximate teleportation of the SCS can succeed with respect to the outcomes of the following eight cases of photon-number measurements made by detectors D_1, D_7, D_8, D_2, D_4, and D_3,

$$
\begin{aligned}
&n_1>0, \quad n_2>0, \quad n_3>0, \quad n_7=n_8=n_4=0, &(9)\\
&n_7>0, \quad n_8>0, \quad n_3>0, \quad n_1=n_2=n_4=0, &(10)\\
&n_1>0, \quad n_8>0, \quad n_3>0, \quad n_7=n_2=n_4=0, &(11)\\
&n_7>0, \quad n_2>0, \quad n_3>0, \quad n_1=n_8=n_4=0, &(12)
\end{aligned}
$$

$$n_1 > 0, \quad n_2 > 0, \quad n_4 > 0, \quad n_7 = n_8 = n_3 = 0, \tag{13}$$

$$n_7 > 0, \quad n_8 > 0, \quad n_4 > 0, \quad n_1 = n_2 = n_3 = 0, \tag{14}$$

$$n_1 > 0, \quad n_8 > 0, \quad n_4 > 0, \quad n_7 = n_2 = n_3 = 0, \tag{15}$$

$$n_7 > 0, \quad n_2 > 0, \quad n_4 > 0, \quad n_1 = n_8 = n_3 = 0. \tag{16}$$

Anyway, there may exist other combinations of the outcomes that detectors counted. But they are negligible for a sufficiently large α; we can give a reason for the approximation later.

The analysis below indicates that corresponding to the outcomes given by Eqs.(9)–(12), a perfect teleportation of the ECS can be realized. Indeed, for the outcomes of the photon-number measurements given by Eq.(9), from Eq.(8) we can see that Alice sends Bob outcomes ($n_1 > 0$, $n_7 = 0$, $n_8 = 0$, $n_2 > 0$, $n_3 > 0$, $n_4 > 0$) of D_1, D_7, D_8, D_2, D_3, and D_4 through a classical communication, and a perfect teleportation of the ECS is realized. In this case, Bob need not do any other operation. The successful probability is

$$P_1 = \sum_{n,m,p=1}^{\infty} |_1\langle n|_7\langle 0|_2\langle m|_8\langle 0|_3\langle 2p|_4\langle 0|\,\Phi\rangle'_{1-8}|^2. \tag{17}$$

When the outcome (10) takes place, Bob makes phase shifters $\hat{P}_5(\pi)\hat{P}_6(\pi)$ on both modes 5 and 6. The action of a π phase shifter described by the unitary operator $\hat{P} = \mathrm{e}^{\mathrm{i}\pi\hat{a}^\dagger\hat{a}}$ can transform the state $|\alpha\rangle$ as $\hat{P}|\alpha\rangle = |-\alpha\rangle$. In this case, the successful probability is

$$P_2 = \sum_{n,m,p=1}^{\infty} |_1\langle 0|_7\langle n|_2\langle 0|_8\langle m|_3\langle 2p|_4\langle 0|\,\Phi\rangle'_{1-8}|^2. \tag{18}$$

When the outcome (11) appears, Bob makes phase shifter $\hat{P}_6(\pi)$ on mode 6, and the successful probability is

$$P_3 = \sum_{n,m,p=1}^{\infty} |_1\langle n|_7\langle 0|_2\langle 0|_8\langle m|_3\langle 2p-1|_4\langle 0|\,\Phi\rangle'_{1-8}|^2. \tag{19}$$

In case the outcome (12) appears, Bob makes phase shifter $\hat{P}_5(\pi)$ on mode 5, and the successful probability is

$$P_4 = \sum_{n,m,p=1}^{\infty} |_1\langle 0|_7\langle n|_2\langle m|_8\langle 0|_3\langle 2p-1|_4\langle 0|\,\Phi\rangle'_{1-8}|^2. \tag{20}$$

However, corresponding to the outcomes given by Eqs.(13) and (16), the situation is different. Only an approximate teleportation of the ECS is possible in those cases. For the outcome of the photon-number measurements given by Eq.(13), the state of modes 5 and 6 is $|\varphi\rangle_{56} = \mathcal{M}(x|\alpha,\alpha\rangle - y|-\alpha,-\alpha\rangle)_{56}$. Here $\mathcal{M}^{-2} = [|x|^2 + |y|^2 - 2\mathrm{e}^{-4|\alpha|^2}\mathrm{Re}(xy^*)]$ is the normalization constant. The corresponding probability is

$$P_5 = \sum_{n,m,p=1}^{\infty} |_1\langle n|_7\langle 0|_2\langle m|_8\langle 0|_3\langle 0|_4\langle 2p|\,\Phi\rangle'_{1-8}|^2. \tag{21}$$

For the case of outcome (14), Bob obtains a state that can easily be converted into $|\varphi\rangle_{56} = \mathcal{M}(x|\alpha,\alpha\rangle - y|-\alpha,-\alpha\rangle)_{56}$ by the action of $\hat{P}_5(\pi)\hat{P}_6(\pi)$. And the corresponding probability is

$$P_6 = \sum_{n,m,p=1}^{\infty} |_1\langle 0|_7\langle n|_2\langle 0|_8\langle m|_3\langle 0|_4\langle 2p|\,\Phi\rangle'_{1-8}|^2. \tag{22}$$

Corresponding to the outcome (15), Bob has a state that can easily be converted into $|\varphi\rangle_{56} = \mathcal{M}(x|\alpha,\alpha\rangle - y|-\alpha,-\alpha\rangle)_{56}$ by the action of $\hat{P}_6(\pi)$. And the corresponding probability is

$$P_7 = \sum_{n,m,p=1}^{\infty} |_1\langle n|_7\langle 0|_2\langle 0|_8\langle m|_3\langle 0|_4\langle 2p-1|\,\Phi\rangle'_{1-8}|^2. \tag{23}$$

For the case of outcome (16) happening, Bob acquires a state that can easily be converted into $|\varphi\rangle_{56} = \mathcal{M}(x|\alpha,\alpha\rangle - y|-\alpha,-\alpha\rangle)_{56}$ by the action of $\hat{P}_5(\pi)$. And the corresponding probability is

$$P_8 = \sum_{n,m,p=1}^{\infty} |_1\langle 0|_7\langle n|_2\langle m|_8\langle 0|_3\langle 0|_4\langle 2p-1|\,\Phi\rangle'_{1-8}|^2. \tag{24}$$

Making use of Eq.(8) we calculate the successful probabilities as follows:

$$P_1 = P_2 = P_5 = P_6 = \mathrm{e}^{-4|\alpha|^2} \sinh^2 |\alpha|^2 (\cosh 2|\alpha|^2 - 1),$$
$$P_3 = P_4 = P_7 = P_8 = \mathrm{e}^{-4|\alpha|^2} \sinh^2 |\alpha|^2 \sinh 2|\alpha|^2. \quad (25)$$

Thus, the total probability is given by $P = \sum_{i=1}^{8} P_i$, we plot the total probability as a function of α in Fig.2. The figure shows that neglecting the

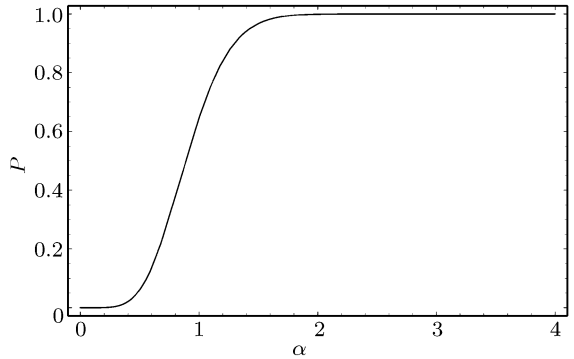


Fig.2. The probability of successful teleportation as a function of α.

other combinations of the outcomes is reasonable for a sufficiently large α. So, from the case of (13) to that of (16), for realizing a perfect teleportation, we need the following transformation:

$$\mathcal{M}(x|\alpha,\alpha\rangle - y|-\alpha,-\alpha\rangle)_{56}$$
$$\Rightarrow \mathcal{N}(x|\alpha,\alpha\rangle + y|-\alpha,-\alpha\rangle)_{56}, \quad (26)$$

where the normalization constant is given by Eq.(1). Equation (26) implies the transformation $|-\alpha\rangle|-\alpha\rangle \rightarrow -|-\alpha\rangle|-\alpha\rangle$ and $|\alpha\rangle|\alpha\rangle \rightarrow |\alpha\rangle|\alpha\rangle$, which is not a unitary transformation except for $|\alpha| \gg 1$. For simplicity, we assume α to be a real number. In order to achieve the transformation, we consider the following scheme: we use the displacement transformation with a parameter value of $i\pi/(8\alpha)$ to approximately realize the transformation with the outcome

$$|\beta\rangle = D_5\left(\frac{\mathrm{i}\pi}{8\alpha}\right) D_6\left(\frac{\mathrm{i}\pi}{8\alpha}\right) \mathcal{M}(x|\alpha,\alpha\rangle - y|-\alpha,-\alpha\rangle)_{56}$$
$$= \mathrm{e}^{\mathrm{i}\frac{\pi}{4}} \mathcal{M}(x|\alpha_+\rangle|\alpha_+\rangle + \mathrm{i}y|\alpha_-\rangle|\alpha_-\rangle)_{5,6}, \quad (27)$$

where $\alpha_\pm = \mathrm{i}\pi/8\alpha \pm \alpha$. The displacement operator $D(\mathrm{i}\pi/8\alpha)$ can be effectively performed using a beam splitter with a transmission coefficient close to unity and a high-intensity coherent field [25]. And the fidelity of the transformation is

$$F = |\langle\beta|\Phi\rangle|^2$$
$$= \mathrm{e}^{-\frac{\pi^2}{32\alpha^2}} \mathcal{N}^2 \mathcal{M}^2 |[|x|^2 + |y|^2 - 2\mathrm{e}^{-4\alpha^2} \mathrm{Im}(x^* y)]|^2. \quad (28)$$

Letting $x = \cos\theta$, and $y = \sin\theta$, we plot the fidelity as a function of θ and α in Fig.3. Figure 3

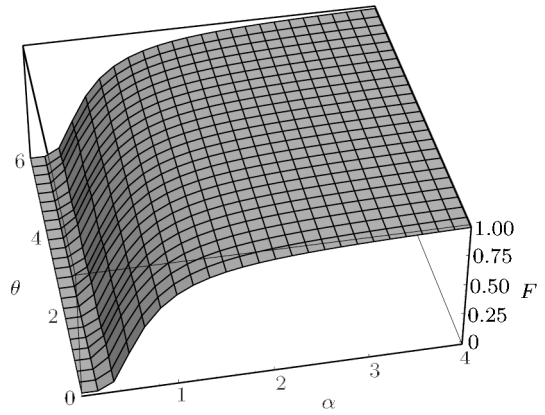


Fig.3. The fidelity of the nonunitary transformation as a function of α and θ.

indicates that the fidelity is independent of the parameter θ, and it approaches 1 for a large coherent amplitude α. The average fidelity of the whole quantum teleportation process is determined by

$$F_{av} = \sum_{i=1}^{8} P_i F_i, \quad (29)$$

where $F_1 = F_2 = F_3 = F_4 = 1$, and $F_5 = F_6 = F_7 = F_8 = F$. We plot F_{av} as a function of θ and α in Fig.4. From Fig.4 we can see that the average fidelity of the

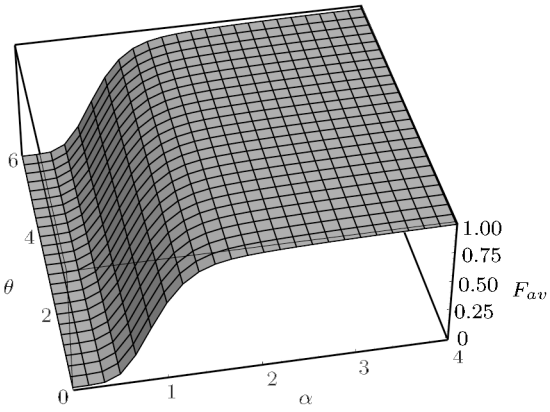


Fig.4. The average fidelity of teleportation as a function of α and θ.

whole teleportation process is independent of the parameter θ. This means that the present teleportation scheme has the same quality for an arbitrary teleported state as that for the state given by Eq.(1). We

can also see that the average fidelity of the scheme approaches 1 for a large coherent amplitude α. Therefore, we conclude that the present scheme can realize a nearly perfect quantum teleportation of entangled coherent states.

3. Concluding remarks

We have proposed an optical scheme for the quantum teleportation of entangled coherent states by using optical elements such as nonlinear Kerr media, beam splitters, phase shifters, and photon detectors. We have shown that this scheme has the same teleportation quality, i.e. the same average fidelity for arbitrary entangled coherent states. In particular, it is found that the average fidelity can approach unit for a large amplitude of the entangled coherent states. Comparing with the previous optical schemes, this is an important advantage. As is well known, one has to make the exact photon-number measurements to distinguish between even and odd photons in all of the previous optical schemes for the teleportation of the superposed and entangled coherent states. However, in our scheme what we need is only the 'yes' or 'no' measurements of the photon number of the related modes.

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