Teleportation of a controllable orbital angular momentum generator

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We report on a teleportation scheme, in which a controllable orbital angular momentum (OAM) generator is teleported. Via our scheme, Alice is able to—according to another independent photon's spin state (polarization) sent by Carol—electrically control the remote OAM generation on Bob's photon. To this end, we introduce a local electrically tunable and spin-dependent OAM generator to transfer a preliminary OAM-OAM entanglement to a spin-OAM hybrid entanglement, which then makes a joint Bell-state measurement on Alice and Carol's photons play its role. We show that the quantum state tomography can be introduced to evaluate the performance of the teleportation.

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I. INTRODUCTION

Quantum entanglement is one of the most striking features of quantum mechanics and has been widely used as an essential resource in the quantum information processing [1]. As one ingenious application of entanglement, quantum teleportation is playing an important role in revealing the fascination of quantum communication [2] and quantum computation protocols [3]. The discovery of teleportation in 1993 revealed the possibility to transfer a quantum state of a photon without transferring the state carrier itself [4]. The communication channel for a standard teleportation consists of a pair of entangled particles: one held by the sender, Alice, and the other held by the receiver, Bob. The third party, Carol, possesses another particle whose state constitutes the information. After Alice and Carol's photons are subjected to a Bell-state measurement (BSM), Bob's photon could acquire instantaneously the information (state) of Carol's particle, which is called "spooky action at a distance." Since 1993, quantum teleportation has raised much research interest and a number of experiments have been demonstrated with single-photonic qubits [5–7]. Also, some new teleportation schemes such as entanglement swapping [8], open-destination teleportation [9] and teleportation of a one-particle entangled qubit [10], teleportation of a quantum controlled-NOT gate [11], or teleportation of a two-qubit composite system [12] have been reported. Besides, long-distance experimental teleportation was realized, which moved a step toward the implementation of a quantum repeater [13–15].

On the other hand, spin and orbital angular momentum (OAM) are two different degrees of freedom of single photons. Spin is associated with the polarization state and can realize a qubit in a two-dimensional Hilbert space while OAM is associated with the helical phase front $\exp(im\phi)$ (m is integer) and allows a qudit in a high-dimensional Hilbert space [16,17]. Recently, the interaction between these two quantum variables of spin and OAM also received more and more research interest from both classical and quantum points of view [18–20]. In this paper, we report on another scheme of teleportation, in which an electrically tunable and spin-dependent OAM generator is teleported. Of particular interest is that, via our scheme, Alice is able to—according to another independent photon's spin state sent by Carol—electrically control the remote OAM generation on Bob's photon. We anticipate that such an integration of quantum teleportation with optical angular momentum would open new potential in the field of quantum information processing.

II. ELECTRICALLY TUNABLE AND SPIN-DEPENDENT OAM GENERATOR

Prior to discussing our teleportation scheme, we brief the controllable OAM generator recently demonstrated [21]. As shown in Fig. 1, the OAM generator consists of two nominally conjugated electro-optic spiral phase plates (SPPs) made of z-cut ZnTe crystals. Of particular importance is that the two SPPs are configured so that their transverse crystalline x-y axes have a relative rotation of 90°. Besides, both incident and exit interfaces of the device are coated with transparent electrodes, which enable us to apply a longitudinal even electric field. When the applied electric field is switched on, according to the refractive index ellipsoid theory [22], the refractive index ellipsoid of ZnTe undergoing the Pockels effect will be deformed and the refractive indices for two eigenmodes would turn out to be $n_1=n_0+n_0^3\gamma_{63}E_0/2$ and $n_2=n_0-n_0^3\gamma_{63}E_0/2$ (with n_0 and γ_{63} being the refractive index and electro-optic coefficient of ZnTe at wavelength λ), corresponding to two eigenvectors $\boldsymbol{\eta}_1=[1,-1,0]$ and $\boldsymbol{\eta}_2=[1,1,0]$, respectively [see Figs. 1(b) and 1(c)].

As the transverse crystalline x-y axes of SPP1 and SPP2 are configured to have a relative 90° rotation, i.e., the effective fast (or slow) axes of two deformed refractive index ellipsoids are crossed to each other, as shown in Figs. 1(b) and 1(c). Thus, in the single-photon space [23], the OAM generator can be described by a quantum operator as [21]

$$\hat{G}(Q)=\sum_m e^{ik_0n_0l_s}(e^{-iQ\pi}|H,m+Q\rangle\langle H,m|+e^{iQ\pi}|V,m-Q\rangle \times\langle V,m|), \quad (1)$$

where l_s is the height of the device, $|m\rangle$ denotes the eigen-

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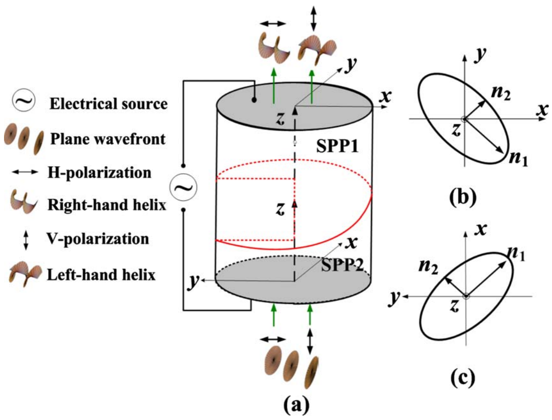

FIG. 1. (Color online) (a) Sketch of a controllable OAM generator consisting of two electro-optic ZnTe spiral phase plates (SPP1 and SPP2): they are configured so that their transverse x-y axes have a relative rotation of 90°. Both incident and exit interfaces of the device are coated with transparent electrodes, allowing us to apply an electric field. The OAM of horizontal and vertical polarization components of output light from the device acquire opposite helix owing to the Pockels effect. (b) and (c) are the deformed refractive index ellipsoids of SPP1 and SPP2 when undergoing the Pockels effect, respectively.

states of the OAM operator, and $Q=\kappa U$ $(\kappa=n_0^3\gamma_{63}/\lambda)$ [21]. Equation (1) shows clearly that two orthogonal polarization states $|H\rangle$ and $|V\rangle$ will generate two different optical vortices with opposite helicities, $|+Q\rangle$ and $|-Q\rangle$, respectively (i.e., spin dependent). This behavior of spin-controlled OAM generation is similar to that of a q plate [18]; however, the optical vortex Q generated here can be neatly adjusted by an applied voltage U, which is indicated by $Q=\kappa U$ (i.e., electrically tunable).

III. TELEPORTING A CONTROLLABLE OAM GENERATOR

Our scheme for teleporting such a controllable OAM generator described by Eq. (1) follows the main line of the original teleportation scenario. It is known that any teleportation necessitates the production of entangled states, for example, the production of an ordinary polarization entanglement [5–8]. In our scheme, however, the teleportation is assisted by a hybrid entanglement that two particles are entangled in different degrees of freedom between twin photons [24]. To achieve this, we introduce the aforementioned local OAM generator together with some linear optical elements to implement an entanglement transfer, namely, transferring a preliminary OAM-OAM entanglement into a spin-OAM hybrid entanglement. The proposed experimental setup is sketched in Fig. 2.

The spontaneous parametric down conversion (SPDC) is done with pump photons of zero OAM in a single beta barium borate crystal cut for type-I phase matching, so that the twin photons are produced in an OAM-OAM entangled state [25] without any polarization entanglement as follows:

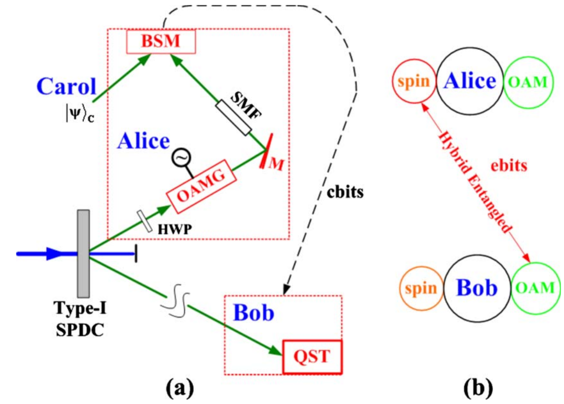

FIG. 2. (Color online) (a) Schematic diagram showing the principle for teleporting a controllable OAM generator: first, Alice transfers the preliminary OAM-OAM entanglement to a hybrid spin-OAM entanglement by a HWP, a local OAM generator (OAMG, as shown in Fig. 1), a mirror (M) and a SMF. Second, Alice performs BSM on her photon and another photon sent by Carol, and sends her BSM result to Bob via a classical channel (cbits). Finally, according to Alice's BSM result, Bob performs a local unitary transformation on his photon's OAM degree and thus completes the teleportation. QST is introduced to evaluate the teleportation. (b) is the illustration of hybrid entanglement between Alice's spin degree and Bob's OAM degree.

$$|\Psi\rangle_{OAM}=\left(\sum_m C_m|m\rangle_A|-m\rangle_B\right)|H\rangle_A|H\rangle_B, \quad (2)$$

where C_m indicate the down-converted entangled OAM spectrum. One member of the photon pair is sent to Alice while the other is sent to Bob. This OAM-OAM entanglement, however, cannot be yet directly utilized for teleporting the controllable OAM generator concerned. We can conclude from Eq. (1) that the reasons are twofold: first, the OAM generator to be teleported is electrically tunable, i.e., one would be able to manipulate the OAM generation and prepare it in a multidimensional quantum state by adjusting an applied electric field, while Eq. (2) contains no any information of the electrical entanglement manipulation. Second, the OAM generator to be teleported should be spin dependent, i.e., the correspondence between the two-dimensional spin and high-dimensional OAM Hilbert spaces should be established between twin photons, while Eq. (2) contains no such information. To realize our idea, Alice should transfer this preliminary OAM-OAM entanglement into a spin-OAM hybrid entanglement, therefore establishing the correspondence between the two-dimensional spin Hilbert space of Alice's photon and the high-dimensional OAM Hilbert space of Bob's photon. To do this, Alice first uses a half-wave-plate (HWP) (at 22.5°) to rotate the horizontal polarization into a diagonal one, namely, $\hat{W}_\pi|H\rangle=(|H\rangle+|V\rangle)/\sqrt{2}$ and then sends her photon into the aforementioned OAM generator of Fig. 1. To show clearly the "local property" of Alice's OAM generator, we rewrite Eq. (1) as

$$\hat{G}_{Local}(Q)=e^{-iQ\pi}|+Q\rangle_{AA}\langle H|+e^{iQ\pi}|-Q\rangle_{AA}\langle V|, \quad (3)$$

where the trivial propagation factor $e^{ik_0n_0l_s}$ has been omitted and the subscript "AA" is introduced to clarify that it is Alice using her photon spin degree to locally control the OAM degree of the same photon. Besides, it should be noted that our interest is focused on the spin-controlled electrically tunable OAM generation, so the input OAM state and the unchanged output polarization state are both trivial and omitted. This photon is then reflected by a following mirror (M), which flips an incoming photon's helix, namely, $\hat{M}|m\rangle = |-m\rangle$. Therefore, after Alice's local manipulation, the twin-photon entangled state (2) becomes

$$|\Psi\rangle'_{OAM} = [\hat{M}\hat{G}(Q)\hat{W}]_A|\Psi\rangle_{OAM} = \frac{1}{\sqrt{2}}\sum_m C_m(e^{-iQ\pi}|H,-m-Q\rangle_A + e^{iQ\pi}|V,-m+Q\rangle_A) \times |H,-m\rangle_B. \quad (4)$$

The key step is that Alice subsequently uses a single-mode fiber (SMF) to exclusively select the fundamental Gaussian mode with zero OAM. From the model of advanced waves [26], we know that this projective measurement simultaneously forces twin-photon state (4) collapse to a hybrid pattern,

$$|\Psi\rangle_{Hybrid} = \frac{1}{\sqrt{2}}(e^{-iQ^A\pi}|H\rangle_A|+Q^A\rangle_B + e^{iQ^A\pi}|V\rangle_A|-Q^A\rangle_B) \times |0\rangle_A|H\rangle_B. \quad (5)$$

It should be noticed that in the above derivation the relation $C_{-m}=C_m$ is utilized due to the symmetry of the SPDC process [27] and further analysis finds that the collapsing probability $P_{hybrid}=\Sigma_m|C_m \operatorname{sinc}(m-Q^A)|^2$, where $\operatorname{sinc}(x)=\frac{\sin(x)}{x}$. Now note that Eq. (5) has shown the twin-photon hybrid entanglement: the spin degree of Alice's photon is linked and entangled with the OAM degree of Bob's photon; while none of the entanglement is expected between Alice's OAM and Bob's spin degrees since there is only a direct product, $|0\rangle_A|H\rangle_B$ in Eq. (5). The superscript "A" here reminds that the generation of Bob's OAM state $|+Q^A\rangle_B$ or $|-Q^A\rangle_B$ right now can be remotely and electrically tuned by Alice, where $Q^A = \kappa U_A$ also indicates that Alice can prepare Bob's photon with an arbitrary fractional optical vortex by adjusting the voltage. To see clearly the OAM content of a fractional optical vortex, we make such a decomposition: $|Q\rangle = \Sigma_{m=-\infty}^{+\infty} a_m|m\rangle$ [28], where $a_m = \langle m|Q\rangle = e^{i(Q-m)\pi} \operatorname{sinc}[(Q-m)\pi]$, corresponding to a vector lying in an infinite Hilbert space spanned by pure integer OAM base. So Eq. (5) also suggests that two entangled different degrees of freedom in a hybrid entanglement may even be defined in two Hilbert spaces of different dimensionalities: the OAM controlled by Alice is defined in a multidimensional Hilbert space (qudit) while the spin is defined in a two-dimensional one (qubit). Note that such a hybrid entanglement is evidently different from the hyperentanglement reported [29]. A hyperentangled state is a tensor product of entangled states in each individual degree of freedom. Therefore, there is no entanglement between different degrees of freedom for hyperentanglement. Up to now, Alice has successfully transferred the OAM-OAM entanglement described by Eq. (2) into the spin-OAM hybrid entanglement described by Eq. (5) in virtue of her local OAM generator together with a key projection $|0\rangle\langle 0|$. This spin-OAM hybrid entanglement not only establishes the correspondence between the spin Hilbert space of Alice's photon and the OAM Hilbert space of Bob's photon, but also makes Bob's OAM state remotely and electrically tunable by Alice, which is of fundamental importance in the realization of the teleportation of a controllable OAM generator. In the following, we will show Alice how to complete this process based on this spin-orbit hybrid entanglement created.

Besides holding one member of the hybrid entangled photon pair, Alice is also in possession of another independent photon sent by Carol, which serves as the role to implement the spin-dependent OAM generation on Bob's photon. Assume that Carol's photon spin state is an arbitrary polarization one, $|\psi\rangle_C = \alpha|H\rangle_C + \beta|V\rangle_C$ with $\alpha\alpha^* + \beta\beta^* = 1$. The combined state of the three photons, respectively, possessed by Alice, Bob, and Carol can thus be written as

$$|\Xi\rangle = \frac{1}{\sqrt{2}}(e^{-iQ^A\pi}|H\rangle_A|+Q^A\rangle_B + e^{iQ^A\pi}|V\rangle_A|-Q^A\rangle_B) \times (\alpha|H\rangle_C + \beta|V\rangle_C), \quad (6)$$

where the trivial factorable product of Alice's OAM and Bob's spin states, namely, $|0\rangle_A|H\rangle_B$ in Eq. (5), has been discarded. To make a deep insight into this combined state, we rewrite Eq. (6) in terms of the four well-known Bell states of Alice and Carol's photons,

$$|\Phi_{AC}^{(\pm)}\rangle = (|H\rangle_A|H\rangle_C \pm |V\rangle_A|V\rangle_C)/\sqrt{2}$$

and

$$|\Psi_{AC}^{(\pm)}\rangle = (|H\rangle_A|V\rangle_C \pm |V\rangle_A|H\rangle_C)/\sqrt{2}.$$

It turns out to be

$$\begin{aligned}|\Xi\rangle &= \tfrac{1}{2}|\Phi_{AC}^{(+)}\rangle(e^{-iQ^A\pi}|+Q^A\rangle_{BC}\langle H| + e^{iQ^A\pi}|-Q^A\rangle_{BC}\langle V|)|\psi\rangle_C \\ &+ \tfrac{1}{2}|\Phi_{AC}^{(-)}\rangle(e^{-iQ^A\pi}|+Q^A\rangle_{BC}\langle H| - e^{iQ^A\pi}|-Q^A\rangle_{BC}\langle V|)|\psi\rangle_C \\ &+ \tfrac{1}{2}|\Psi_{AC}^{(+)}\rangle(e^{-iQ^A\pi}|+Q^A\rangle_{BC}\langle V| + e^{iQ^A\pi}|-Q^A\rangle_{BC}\langle H|)|\psi\rangle_C \\ &+ \tfrac{1}{2}|\Psi_{AC}^{(-)}\rangle(e^{-iQ^A\pi}|+Q^A\rangle_{BC}\langle V| - e^{iQ^A\pi}|-Q^A\rangle_{BC}\langle H|)|\psi\rangle_C.\end{aligned} \quad (7)$$

This equation forms one of the kernel results in present work, which tells the way of teleporting a controllable OAM generator: Alice performs a joint BSM on her own photon and Carol's. If the BSM gives particularly $|\Phi_{AC}^{(+)}\rangle$, one of the four possible outcomes, then we know from the first line of Eq. (7) that the local operator of OAM generator at Alice's side described by Eq. (3) has been teleported to Bob's side, taking this form

$$\hat{G}_{Tele}(Q) = e^{-iQ^A\pi}|+Q^A\rangle_{BC}\langle H| + e^{iQ^A\pi}|-Q^A\rangle_{BC}\langle V|. \quad (8)$$

It clearly shows that Bob's OAM generation is remotely and electrically tunable by Alice and is spin dependent on Carol's photon. Generally, each of four Bell states appears with an equivalent probability of 25%. According to the BSM result sent by Alice via a classical communication channel, Bob is able to convert his OAM generation operator to the one iden-

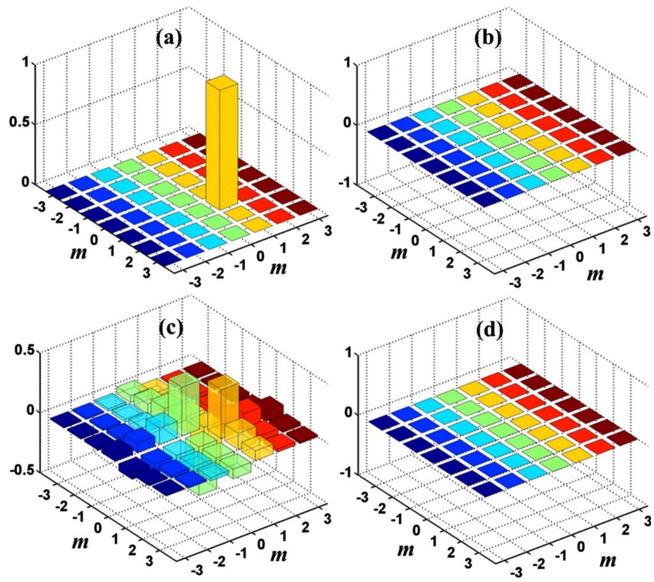

FIG. 3. (Color online) Left and right panels show the theoretical results of real and imaginary parts of Bob's OAM density matrices for Carol's spin state $|\psi\rangle_C = |H\rangle$: (a) and (b) correspond to the case of Alice tuning $Q^A = 1$ while (c) and (d) correspond to $Q^A = 0.5$.

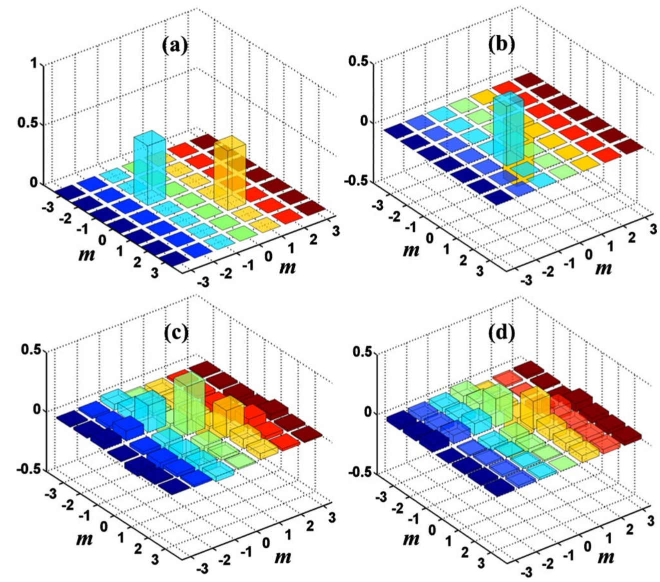

FIG. 4. (Color online) Left and right panels show the theoretical results of real and imaginary parts of Bob's OAM density matrices for $|\psi\rangle_C = |L\rangle$: (a) and (b) correspond to $Q^A = 1$ while (c) and (d) correspond to $Q^A = 0.5$.

tical with $\hat{G}_{Tele}(Q)$ after applying a corresponding local unitary transformation on his own photon's OAM degree, thus completing the process of the teleportation. For easy understanding, we rewrite Eq. (7) in a succinct form as follows:

$$|\Xi\rangle = \tfrac{1}{2}[|\Phi_{AC}^{(+)}\rangle I\hat{G}_{Tele}(Q) + |\Phi_{AC}^{(-)}\rangle \sigma_z^B \hat{G}_{Tele}(Q) + |\Psi_{AC}^{(+)}\rangle \sigma_x^B \hat{G}_{Tele}(Q) + |\Psi_{AC}^{(-)}\rangle i\sigma_y^B \hat{G}_{Tele}(Q)]|\psi\rangle_C, \quad (9)$$

where I is the identical operator and σ_x^B, σ_y^B, and σ_z^B are three Pauli operators acting on the OAM degree of freedom of Bob's photon.

IV. QUANTUM STATE TOMOGRAPHY

The performance of the teleportation process is usually characterized by the method of quantum state tomography (QST) [30]. The QST requires a series of complementary measurements on a large ensemble of identically prepared copies of the system. In our case, the analysis of Bob's OAM states can be made in virtue of spatial mode analyzers consisting of different holograms and a single-mode fiber [31,32]. Without losing generality, here we discuss four cases of ideal tomography. For the first and second cases (see Fig. 3), Carol prepares her photon in the fixed horizontal state $|\psi\rangle_C = |H\rangle$, while Alice tunes the applied voltage to generate unit and half-integer optical vortex charges, $Q^A = 1$ and $Q^A = 0.5$, respectively. From Eq. (8) we know that the corresponding remote OAM state generated on Bob's photon should be $|\psi\rangle_B^{(1)} = -|Q=+1\rangle$ and $|\psi\rangle_B^{(2)} = -i|Q=+0.5\rangle$, respectively. For the third and fourth cases (see Fig. 4), Carol fixed her photon in another polarization, i.e., left-handed circularly polarized state, $|\psi\rangle_C = |L\rangle = (|H\rangle + i|V\rangle)/\sqrt{2}$, and Alice is still with $Q^A = 1$ and $Q^A = 0.5$. Then, Bob's OAM states should be $|\psi\rangle_B^{(3)} = -[|Q=+1\rangle + i|Q=-1\rangle]/\sqrt{2}$ and $|\psi\rangle_B^{(4)} = -[i|Q=+1/2\rangle + |Q=-1/2\rangle]\sqrt{2}$, respectively. One can see from Figs. 3(c) and 4(c) that Alice can remotely prepare Bob's photon with a half-integer optical vortex, which corresponds to an OAM state lying in a high-dimensional Hilbert space [28]. Besides, comparing Fig. 3(b) with Fig. 4(b) or Fig. 3(d) with Fig. 4(d), one can also find that Bob's OAM generation is really not only electrically tunable by Alice, but also remotely spin dependent on Carol's photon.

V. CONCLUSIONS

In conclusion, based on the entanglement transfer from a preliminary OAM-OAM entanglement to a spin-OAM hybrid one, we put forward a scheme for teleporting a controllable OAM generator, via which Alice is able to—according to another independent photon's spin state sent by Carol—electrically control the remote OAM generation on Bob's photon. This process provides us an approach for electrically tele-encoding an arbitrary polarization state onto a remote OAM state. We anticipate that the combination of teleportation with optical angular momentum would show potential applications in future quantum communication and distributed quantum computation.

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