Controlled teleportation via photonic Faraday rotations in low-Q cavities

W. P. Bastos · W. B. Cardoso · A. T. Avelar · N. G. de Almeida · B. Baseia

Abstract  This paper presents feasible experimental schemes to realize controlled teleportation protocols via photonic Faraday rotations in low-Q cavities. The schemes deal with controlled teleportation of superposition states and two-particle entanglement of atomic states. The information is encoded in lambda configured three-level atoms trapped inside coupled cavities by optical fibers. Also, we estimate the success probability and the current feasibility of the schemes.

Keywords  Controlled teleportation · Photonic Faraday rotations · Low-Q cavities

1 Introduction

The quantum teleportation was firstly suggested by Bennett et al. [1] and its experimental realizations have been reported from 1997 onwards [2–9]. Teleportation remains a challenge in some contexts yet, such as in trapped wave fields inside high-Q microwave cavities [10–14], in atomic state via cavity decay [15–20], in the single-mode thermal state of light fields [21], in trapped field states inside a single bimodal cavity [22,23], in schemes without the Bell-state measurement [14,24–28], in the angular spectrum of a single-photon field [29], among others.

Since the pioneering work by Bennett et al. [1], several schemes for teleportation that differ from this original protocol have appeared in the literature. As examples, in the experiment of Ref. [2], Boschi et al. explored both the polarization and the state of the photon via two distinct paths to demonstrate teleportation; in Ref. [30], Popescu substituted the nonlocal channel by the mixed Werner states. Entanglements of mixed states as nonlocal channels were further considered in Ref. [31,32]. In Ref. [33],

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Vaidman proposed a “cross measurement” method to achieve a two-way teleportation using a spin state and a system with continuous variable. Related to this topic, Moussa showed in [34] how to implement teleportation with identity interchange of quantum states, a kind of “cross measurement” in the context of QED cavity. In Ref. [35], de Almeida et al. used Greenberger–Horne–Zeilinger (GHZ) states as the nonlocal channel instead of the standard Einstein–Podolsky–Rosen (EPR) states, and in Ref. [36] Agrawal and Pati showed how to achieve perfect teleportation and superdense code using W states as the nonlocal channel. Generation of W states and clusters states in QED cavity was discussed in [37,38]. In Ref. [24], Zheng refers to the approximated teleportation (fidelity $\approx 99\%$) without Bell states measurements of the superposition of zero- and one-photon states from one high-$Q$ cavity to another [39]$^1$. In Ref. [40], also using a GHZ channel, Karlsson and Bourennane showed how to accomplish teleportation controlled by a third party. Controlled teleportations involving many agents were considered in Ref. [41–45]. Since then, controlled operations have found important applications, as quantum secret sharing, introduced by Hillery et al. in Ref. [46], and experimentally reported in [47–50].

Quantum secret sharing was considered further by a number of authors [51–60], including a version of controlled quantum secret [61]. Another important application of controlled operation by a third part is given by partial optimal teleportation, introduced in Ref. [62] by Filip, considered further in Ref. [63–65], and experimentally reported in Ref. [66]. More recently, our group introduced the concept of controlled partial teleportation (CPT) and presented a feasible scheme for its implementation in the trapped ions domain [67,68].

In this paper, motivated by growing applications of controlled operations [40–66], we proposed several schemes to experimentally realize controlled teleportation (CT) as well as CPT in the context of lossy optical cavities connected by optical fibers, taking advantage of the so called photonic Faraday rotations [69]. The main idea is to make use of the Faraday rotation produced by single-photon-pulse input and output process with regard to low-$Q$ cavities [70]. In view of our applications, we revisited the input-output relation for a cavity that coherently interacting with a trapped three-level atom, recently considered in [19,20,69]. Differently from the present proposal, in the Ref. [19] the authors treated a scheme for deterministically teleporting an arbitrary multipartite state, either a product state or an entangled state, and in the Ref. [20] they treated a scheme for deterministically teleporting a pure quantum state, both making use of the Faraday rotation of photonic polarization in cavity QED systems. We consider a three-level atom that interacts with two degenerate cavity-modes of a low-$Q$ cavity pumped by photonic emission of a single photon source via optical fibers. Figure 1 shows the atomic levels of each atom inside one of the cavities. Each transition is governed by the Jaynes-Cummings model.

The paper is organized as follows: in Sect. 2 we present the theoretical model; in Sect. 3 we present several schemes to implement the CT and CPT; the Sect. 4 contains our conclusions.

$^1$ This nonunity fidelity is a consequence of the imperfect discrimination of the Bell states, as required by the original protocol.
Controlled teleportation via photonic Faraday rotations

Fig. 1 Atomic configuration of the three-level atom trapped in each of the low-Q cavities. States \(|0\rangle\) and \(|1\rangle\) couple with a left (L) and a right (R) polarized photon, respectively.

$$\begin{align*}
|0\rangle & \quad |1\rangle \\
L & \quad R
\end{align*}$$

2 Theoretical model

The Hamiltonian that describes a three-level atomic system (Fig. 1) interacting with a single mode of a low-Q cavity is given by [71, 72]

$$H = H_0 + \hbar \lambda (a_L^+ \sigma_L^- + a_L \sigma_L^+) + \hbar \lambda (a_R^+ \sigma_R^- + a_R \sigma_R^+) + H_R,$$

(1)

with

$$H_0 = \frac{\hbar \omega_0}{2} (\sigma_{Lz} + \sigma_{Rz}) + \hbar \omega_c (a_L^+ a_L + a_R^+ a_R),$$

(2)

and

$$H_R = H_{R0} + i \hbar \left[ \int_{-\infty}^{\infty} d\omega \sum_{j=L,R} \alpha(\omega) \left( b_j^+ (\omega) a_j - b_j (\omega) a_j^+ \right) \\
+ \int_{-\infty}^{\infty} d\omega \sum_{j=L,R} \bar{\alpha}(\omega) \left( c_j^+ (\omega) \sigma_j - c_j (\omega) \sigma_j^+ \right) \right],$$

(3)

where \(\lambda\) is the atom-field coupling constant, \(a_j^+ (a_j)\) is the creation (annihilation) operator of the cavity field-mode with \(j = L, R\), \(\omega_0\) (\(\omega_c\)) is the atomic (field) frequency, and \(\sigma_{L-}\) and \(\sigma_{L+}\) (\(\sigma_{R-}\) and \(\sigma_{R+}\)) are the lowering and raising operators of the transition L (R), respectively. The L and R transitions are shown in Fig. 1. \(H_{R0}\) is the Hamiltonian of the free reservoirs, in such a way that the field and atomic reservoirs are given by \(H_{Rc} = \hbar \int_{-\infty}^{\infty} d\omega \omega b_j^+ b_j\) and \(H_{RA} = \hbar \int_{-\infty}^{\infty} d\omega \omega c_j^+ c_j (j = L, R)\), respectively. The reservoirs couple with the field and atomic systems independently, at different values of frequency \(\omega\), with the coupling amplitudes \(\alpha = \sqrt{\kappa / 2\pi}\) and \(\bar{\alpha} = \sqrt{\gamma / 2\pi}\), respectively. \(\kappa\) and \(\gamma\) are the cavity-field and atomic damping rates, \(b_j\) and \(c_j\) (\(b_j^+\) and \(c_j^+\)) are the annihilation (creation) operators of the reservoirs.

Next, due to the presence of a pumping field into the cavity by an optical fiber one can change, in a convenient way, to a rotating frame with respect the pumping field frequency \(\omega_p\) using the following transformation:
\[ H_{\text{eff}} = U^\dagger H U - \left[ \hbar \omega_p (a_L^\dagger a_L + a_R^\dagger a_R) + \frac{\hbar \omega_p}{2} (\sigma_{Lz} + \sigma_{Rz}) \right], \]  

(4)

where \( U = \exp\{-i \sum_{j=L,R} [\omega_p (a_j^\dagger a_j + b_j^\dagger b_j + c_j^\dagger c_j) + \frac{\omega_p}{2} \sigma_{jz}] \} \). At this point, using the Heisenberg equations for the operators \( a_j \) and \( \sigma_{j-} \) (consequently for \( a_j^\dagger \) and \( \sigma_{j+} \)), with \( j=L, R \), we get

\[
\dot{a}_j(t) = - \frac{i}{\hbar} \left[ \omega_c - \omega_p \right] a_j(t) - \frac{\kappa}{2} a_j(t) - \sqrt{\kappa} a_{\text{in},j}(t),
\]

(5)

\[
\dot{\sigma}_{j-}(t) = - \frac{i}{\hbar} \left[ \omega_0 - \omega_p \right] \sigma_{j-}(t) - \sqrt{\gamma} \sigma_{jz}(t) a_j(t),
\]

(6)

The relation between the input and output fields reads \( a_{\text{out},j}(t) = a_{\text{in},j}(t) + \sqrt{\kappa} a_j, j = L, R \). Here, assuming the reservoirs at zero temperature such that \( b_{\text{in},j} \approx 0 \), plus an adiabatic approximation, the foregoing evolution equations lead us to a single relation between the input and output field states in the form \([19,69]\)

\[
r(\omega_p) = \frac{[i(\omega_c - \omega_p) - \frac{\kappa}{2}][i(\omega_0 - \omega_p) + \frac{\gamma}{2}]}{[i(\omega_c - \omega_p) + \frac{\kappa}{2}][i(\omega_0 - \omega_p) + \frac{\gamma}{2}]} + \frac{\lambda^2}{2},
\]

(7)

where \( r(\omega_p) \equiv a_{\text{out},j}(t)/a_{\text{in},j}(t) \) is the reflection coefficient of the atom-cavity system. On the other hand, considering the case of \( \lambda = 0 \) and an empty cavity we have \([71,72]\)

\[
r_0(\omega_p) = \frac{i(\omega_c - \omega_p) - \frac{\kappa}{2}}{i(\omega_c - \omega_p) + \frac{\kappa}{2}}.
\]

(8)

According to \([19,69]\) the transitions \( |e\rangle \leftrightarrow |0\rangle \) and \( |e\rangle \leftrightarrow |1\rangle \) are due to the coupling of two degenerate cavity modes \( a_L \) and \( a_R \) with left (L) and right (R) circular polarization, respectively. For the atom initially prepared in \( |0\rangle \), the transition \( |0\rangle \rightarrow |e\rangle \) will occur only if the L circularly polarized single-photon pulse \( |L\rangle \) enters the cavity. Hence Eq. (7) leads the input pulse to the output one: \( |\Psi_{\text{out}}\rangle_L = r(\omega_p) |L\rangle \approx e^{i\phi} |L\rangle \), with the corresponding phase shift \( \phi \) being determined by the parameter values. Note that an input R circularly polarized single-photon pulse \( |R\rangle \) would only sense the empty cavity; as a consequence the corresponding output governed by Eq. (8) is \( |\Psi_{\text{out}}\rangle_R = r_0(\omega_p) |R\rangle = e^{i\phi_0} |R\rangle \) with \( \phi_0 \) a phase shift different from \( \phi \). Hence, for an input linearly polarized photon pulse \( |\Psi_{\text{in}}\rangle = \frac{1}{\sqrt{2}} ( |L\rangle + |R\rangle ) \), the output pulse is

\[
|\Psi_{\text{out}}\rangle_\ominus = \frac{1}{\sqrt{2}} ( e^{i\phi} |L\rangle + e^{i\phi_0} |R\rangle ).
\]

(9)

This also implies that the polarization direction of the reflected photon rotates by an angle \( \Theta_F = (\phi_0 - \phi)/2 \) with respect to that of the incident photon, an effect known as Faraday rotation \([70]\). If the atom is initially prepared in \( |1\rangle \), then only the R circularly
polarized photon could sense the atom, whereas the L circularly polarized photon only interacts with the empty cavity. So we have,

$$|\Psi_{\text{out}}\rangle_+ = \frac{1}{\sqrt{2}}(e^{i\phi_0}|L\rangle + e^{i\phi}|R\rangle),$$  \hspace{1cm} (10)

where the Faraday rotation is $\Theta_F^+ = (\phi - \phi_0)/2$.

3 Controlled teleportation

In this Section we present two cases of CT. Firstly we will consider CT of superposition states. Next, we present CPT of entangled states.

3.1 Superposition states

Here, we consider the CT of superposition states with one, two, or more controls.

i) One control: in this scheme we deal with three atoms, separately trapped inside three low-Q cavities (A, B, and C), respectively. The atoms are previously prepared in specific states, such that, $|\psi_A\rangle = \frac{1}{\sqrt{2}}(|0\rangle_A + |1\rangle_A)$, $|\psi_B\rangle = \frac{1}{\sqrt{2}}(|0\rangle_B + |1\rangle_B)$, $|\psi_C\rangle = \alpha|0\rangle_C + \beta|1\rangle_C$, where $\alpha$ and $\beta$ are unknown coefficients that obey $|\alpha|^2 + |\beta|^2 = 1$, and the subindex represents the atom trapped in the cavity. Also, we consider a linearly polarized photon in the state $|\psi_p\rangle = \frac{1}{\sqrt{2}}(|L\rangle + |R\rangle)$, where $|L\rangle$ ($|R\rangle$) represents the state with left (right) direction of polarization. The experimental scheme is displayed in Fig. 2. The nonlocal channel is created after the interaction of the photon with the atom inside the cavity A. Due to the low quality of the cavity the photon is lost, escaping through an optical fiber directed to the cavity B. This interaction causes a Faraday rotation in the photonic state [see Eqs. (9) and (10)] leading the entire atom-photon state to

$$|\phi_1\rangle = \frac{1}{2}(e^{i\phi}|L0\rangle_A + e^{i\phi_0}|L1\rangle_A + e^{i\phi_0}|R0\rangle_A + e^{i\phi}|R1\rangle_A),$$  \hspace{1cm} (11)

where the phases $\phi$ and $\phi_0$ are obtained by the reflection coefficients in Eqs. (7) and (8).

After the photon has interacted with the atom of cavity B and considering the adjustments $\omega_p = \omega_c - \kappa/2$, $g = \kappa/2$ and $\omega_0 = \omega_c$ (consisting in $\phi = \pi$ and $\phi_0 = \pi/2$), we have

$$|\phi_2\rangle = \frac{1}{2\sqrt{2}} [(|0\rangle_B [(|L\rangle|0\rangle_A - i|L\rangle|1\rangle_A - |R\rangle|0\rangle_A - i|R\rangle|1\rangle_A] + |1\rangle_B [-i|L\rangle|0\rangle_A - |L\rangle|1\rangle_A - i|R\rangle|0\rangle_A + |R\rangle|1\rangle_A])].$$  \hspace{1cm} (12)
In sequence the photon interacts with the atom of the cavity C leading the whole state as

\[
|\phi_3\rangle = \frac{1}{2\sqrt{2}} \left[ (|0\rangle_B - \alpha(|L\rangle + i|R\rangle)|0\rangle_A|0\rangle_C + i\alpha(|L\rangle - i|R\rangle)|1\rangle_A|0\rangle_C \\
+ i\beta(|L\rangle - i|R\rangle)|0\rangle_A|1\rangle_C + \beta(|L\rangle + i|R\rangle)|1\rangle_A|1\rangle_C \\
+ |1\rangle_B [i\alpha(|L\rangle - i|R\rangle)|0\rangle_A|0\rangle_C + \alpha(|L\rangle + i|R\rangle)|1\rangle_A|0\rangle_C \\
+ \beta(|L\rangle + i|R\rangle)|0\rangle_A|1\rangle_C - i\beta(|L\rangle - i|R\rangle)|1\rangle_A|1\rangle_C \right] \quad (13)
\]

Next, the photon goes through a quarter wave plate (QWP1 in Fig. 2) where it suffers a rotation in its polarization state (Hadamard operation) such that

\[
(|L\rangle + i|R\rangle)\sqrt{2} \rightarrow |L\rangle, \quad (14a)
\]
\[
(|L\rangle - i|R\rangle)\sqrt{2} \rightarrow |R\rangle, \quad (14b)
\]

and after the addition of a Hadamard operation upon the state of the atom C, the entire system state evolves to

\[
|\phi_4\rangle = \frac{1}{2\sqrt{2}} \left[ (|0\rangle_B - |L0\rangle_C (\alpha|0\rangle_A - \beta|1\rangle_A) - |L1\rangle_C (\alpha|0\rangle_A + \beta|1\rangle_A) \\
+ i|R0\rangle_C (\alpha|1\rangle_A + \beta|0\rangle_A) + i|R1\rangle_C (\alpha|1\rangle_A - \beta|0\rangle_A) \\
+ |1\rangle_B [|L0\rangle_C (\alpha|1\rangle_A + \beta|0\rangle_A) + |L1\rangle_C (\alpha|1\rangle_A - \beta|0\rangle_A) \\
+ i|R0\rangle_C (\alpha|0\rangle_A - \beta|1\rangle_A) + i|R1\rangle_C (\alpha|0\rangle_A + \beta|1\rangle_A) \right]. \quad (15)
\]

Then, by measuring the photon polarization state plus the state of the atoms trapped inside the cavities B and C it is possible the reconstruction of the teleported state via appropriated atomic rotations, as summarized in Table 1. Note that the teleportation is concluded if and only if the atomic state in the cavity B is known in terminal A. So, this atom is here treated as an agent that control the teleportation scheme.

ii) Two controls: This scheme is similar to that shown above. Here an atom, which will work as a new control, is added to the new cavity ($B_1$). One atom is previously prepared in the state $|\psi_{B_1}\rangle = \frac{1}{\sqrt{2}}(|0\rangle_{B_1} + |1\rangle_{B_1})$ while the others work as before.
The experimental setup is displayed in Fig. 3. After the successive interactions of the photon with the atoms trapped inside cavities A and B using the same adjustments considered in the previous Section, the state of the system results the same as that in Eq. (12). The next step consists in the interaction of the photon emerging from the cavity B with the atom trapped inside the cavity B1. So, after the photonic Faraday rotation the state of the system is given by

\[
|\phi_3\rangle = \frac{1}{4} \left( |00\rangle_{BB1} (-|L0\rangle_A + i|L1\rangle_A - i|R0\rangle_A + |R1\rangle_A) + |01\rangle_{BB1} (i|L0\rangle_A + |L1\rangle_A + |R0\rangle_A + i|R1\rangle_A) + |10\rangle_{BB1} (i|L0\rangle_A + |L1\rangle_A + |R0\rangle_A + i|R1\rangle_A) - |11\rangle_{BB1} (-|L0\rangle_A + i|L1\rangle_A - i|R0\rangle_A + |R1\rangle_A) \right). \tag{16}
\]

Then, this photon is left to interact with the atom trapped inside the cavity C, in such a way that the whole state of the system takes the form

\[
|\phi_3'\rangle = \frac{1}{4} \left( |00\rangle_{BB1} [\alpha (|L\rangle + |R\rangle)]_A |0\rangle_C - i\alpha (|L\rangle - |R\rangle)]_A |0\rangle_C - i\beta (|L\rangle - |R\rangle)]_A |1\rangle_C - \beta (|L\rangle + |R\rangle)]_A |1\rangle_C \right).
\]
Next, the photon that leaves the cavity $C$ crosses a quarter wave plate ($QWP2$ in Fig. 3) and its state results in

\[ |L\rangle + |R\rangle \sqrt{2} \rightarrow |L\rangle, \tag{18a} \]
\[ |L\rangle - |R\rangle \sqrt{2} \rightarrow |R\rangle. \tag{18b} \]

A Hadamard operation on the state of the atom inside the cavity $C$ furnishes

\[
|\phi_4\rangle = \frac{1}{4} \left( |00\rangle_{BB_1} [ |L0\rangle_{FC} (\alpha |0\rangle_A - \beta |1\rangle_A) + |L1\rangle (\alpha |0\rangle_A + \beta |1\rangle_A) \right. \\
- i |R0\rangle_{FC} (\alpha |1\rangle_A + \beta |0\rangle_A) - i |R1\rangle_{FC} (\alpha |1\rangle_A - \beta |0\rangle_A) \\
+ i |01\rangle_{BB_1} [ - |L0\rangle_{FC} (\alpha |1\rangle_A + \beta |0\rangle_A) - |L1\rangle_{FC} (\alpha |1\rangle_A - \beta |0\rangle_A) \\
- i |R0\rangle_{FC} (\alpha |0\rangle_A + \beta |1\rangle_A) - i |R1\rangle_{FC} (\alpha |0\rangle_A - \beta |1\rangle_A) \\
+ i |10\rangle_{BB_1} [ - |L0\rangle_{FC} (\alpha |0\rangle_A - \beta |1\rangle_A) - |L1\rangle_{FC} (\alpha |0\rangle_A + \beta |1\rangle_A) \\
- i |R0\rangle_{FC} (\alpha |1\rangle_A + \beta |0\rangle_A) + i |R1\rangle_{FC} (\alpha |1\rangle_A - \beta |0\rangle_A) \right) . \tag{19} 
\]

The appropriate operations that correspond to the measurements upon the control systems are summarized in the Table 2.

\textit{iii) Generalization:} A procedure to generalize the number of controls in the scheme of controlled teleportation of superposition states can be done by the adding of atoms trapped in additional cavities and using specific quarter wave plates after the last cavity. In this way, if the number of controls is odd, a QWP1 is required with rotations given by Eqs. (14aa) and (14ab) is necessary; if the control number is even one request a QWP2 with the rotations given by Eqs. (18aa) and (18ab). So, with appropriated rotations we can recover the teleported state with the knowledge of the control results.

3.2 Controlled partial teleportation of entangled states

In our scheme for CPT [67,68] an entangled state that describes particle $A$ (given to Alice) AND particle $B$ (given to Bob), is to be partially teleported. Meanwhile, a quantum channel composed by an entanglement of three particles is shared by Alice ($A'$), Ben ($B'$), and a third part, say Chris (C). If Alice performs a Bell measurement on the states of particle $A$ and $A'$, and Chris performs a measurement on the state of

\[ + |01\rangle_{BB_1} [-i \alpha (|L\rangle - |R\rangle) |0\rangle_A |0\rangle_C - \alpha (|L\rangle + |R\rangle) |1\rangle_A |0\rangle_C \\
- \beta (|L\rangle + |R\rangle) |0\rangle_A |1\rangle_C + i \beta (|L\rangle - |R\rangle) |1\rangle_A |1\rangle_C \\
+ |10\rangle_{BB_1} [-i \alpha (|L\rangle - |R\rangle) |0\rangle_A |0\rangle_C - \alpha (|L\rangle + |R\rangle) |1\rangle_A |0\rangle_C \\
- \beta (|L\rangle + |R\rangle) |0\rangle_A |1\rangle_C + i \beta (|L\rangle - |R\rangle) |1\rangle_A |1\rangle_C \\
+ |11\rangle_{BB_1} [ \alpha (|L\rangle + |R\rangle) |0\rangle_A |0\rangle_C - i \alpha (|L\rangle - |R\rangle) |1\rangle_A |0\rangle_C \\
- i \beta (|L\rangle - |R\rangle) |0\rangle_A |1\rangle_C - \beta (|L\rangle + |R\rangle) |1\rangle_A |1\rangle_C \right) . \tag{17} 
\]
Table 2  Possible results and rotations to complete the controlled teleportation procedure for the case ii)

| MAPS | CS | TS | AO |
|------|----|----|----|
| \([L_0]_{FC}\) | \([00]_{BB_1}\) | \(\alpha|0\rangle_A - \beta|1\rangle_A\) | \(\sigma_z\) |
| \([L_1]_{FC}\) | \([00]_{BB_1}\) | \(\alpha|0\rangle_A + \beta|1\rangle_A\) | \(\uparrow\) |
| \([R_0]_{FC}\) | \([00]_{BB_1}\) | \(\alpha|1\rangle_A + \beta|0\rangle_A\) | \(\sigma_x\) |
| \([R_1]_{FC}\) | \([00]_{BB_1}\) | \(\alpha|1\rangle_A - \beta|0\rangle_A\) | \(\sigma_y\sigma_x\) |
| \([L_0]_{FC}\) | \([01]_{BB_1}\) | \(\alpha|1\rangle_A + \beta|0\rangle_A\) | \(\sigma_x\) |
| \([L_1]_{FC}\) | \([01]_{BB_1}\) | \(\alpha|1\rangle_A - \beta|0\rangle_A\) | \(\sigma_y\sigma_x\) |
| \([R_0]_{FC}\) | \([01]_{BB_1}\) | \(\alpha|0\rangle_A + \beta|1\rangle_A\) | \(\uparrow\) |
| \([R_1]_{FC}\) | \([01]_{BB_1}\) | \(\alpha|0\rangle_A - \beta|1\rangle_A\) | \(\sigma_z\) |
| \([L_0]_{FC}\) | \([10]_{BB_1}\) | \(\alpha|1\rangle_A + \beta|0\rangle_A\) | \(\sigma_x\) |
| \([L_1]_{FC}\) | \([10]_{BB_1}\) | \(\alpha|1\rangle_A - \beta|0\rangle_A\) | \(\sigma_y\sigma_x\) |
| \([R_0]_{FC}\) | \([10]_{BB_1}\) | \(\alpha|0\rangle_A + \beta|1\rangle_A\) | \(\uparrow\) |
| \([R_1]_{FC}\) | \([10]_{BB_1}\) | \(\alpha|0\rangle_A - \beta|1\rangle_A\) | \(\sigma_z\) |
| \([L_0]_{FC}\) | \([11]_{BB_1}\) | \(\alpha|0\rangle_A + \beta|1\rangle_A\) | \(\sigma_z\) |
| \([L_1]_{FC}\) | \([11]_{BB_1}\) | \(\alpha|0\rangle_A - \beta|1\rangle_A\) | \(\uparrow\) |
| \([R_0]_{FC}\) | \([11]_{BB_1}\) | \(\alpha|1\rangle_A + \beta|0\rangle_A\) | \(\sigma_x\) |
| \([R_1]_{FC}\) | \([11]_{BB_1}\) | \(\alpha|1\rangle_A - \beta|0\rangle_A\) | \(\sigma_y\sigma_x\) |

The first column shows the possible results of measurements on the atom C and photon F states. Second and third columns do the same for the two control states (CS) and for the teleported state (TS). Fourth column shows the corresponding Pauli matrices representing unitary operations on the atomic state (AO) required to complete the teleportation process.

Particle C, then when both inform Bob their results, the following interesting result emerges, after the usual rotation performed by Bob: particle B’ takes exactly the role of particle A in the previous entanglement shared by Alice and Bob. As the entanglement between the particles A and B is broken and a new entanglement between the particles B and B’ is created in a different place, depending on the collaboration of both Alice and Chris, this characterizes a CPT.

Next, we describe some schemes for CPT with different number of controls taking into account the low Q cavities scenario combined with Faraday rotations.

i) One control: to perform CPT in this case, four cavities are required as displayed in Fig. 4. Cavities A and B are previously prepared in the superposed states while the cavities C and D are previously prepared in the entangled state that we want to teleport, given by

\[ |\psi\rangle_{CD} = \alpha|01\rangle_{CD} + \beta|10\rangle_{CD}. \]  

Here we will follow the same procedure of the CT-schemes used in 3.1: the photon, previously prepared in a superposed polarization state, enters in the cavity A and interacts with the atom. Next, this photon is sent to interact with the atom trapped in the cavity B. After that, the photon interacts with the atom C in the presence of the same Faraday rotation discussed in Section A. Before any Faraday rotations, the state of the system is written as
polarization detector sent to interact with the atoms inside the cavity B and B1, respectively. After another polarization state, enters the cavity A and interacts with the atom. Next, the photon is PD and stands for a quarter wave plate, QWP inside the cavities, QWP1 stands for a quarter wave plate, and PD is the photon polarization detector.

\[ |\delta_1\rangle = \frac{1}{2\sqrt{2}} \left( |0\rangle_B \left( -\alpha |0\rangle_A |0\rangle_{CD} (|L\rangle + i|R\rangle) + i\alpha |1\rangle_A |0\rangle_{CD} (|L\rangle - i|R\rangle) \right) + i\beta |0\rangle_A |1\rangle_{CD} (|L\rangle - i|R\rangle) + \beta |1\rangle_A |0\rangle_{CD} (|L\rangle + i|R\rangle) \right) 
+ |1\rangle_B \left( i\alpha |0\rangle_A |0\rangle_{CD} (|L\rangle - i|R\rangle) + \alpha |1\rangle_A |0\rangle_{CD} (|L\rangle + i|R\rangle) \right) 
+ \beta |0\rangle_A |1\rangle_{CD} (|L\rangle + i|R\rangle) - i\beta |1\rangle_A |1\rangle_{CD} (|L\rangle - i|R\rangle) \right). \]  

(21)

After a Faraday rotation in the atom in cavity C as well as in the photon state via the QWP1, the state in Eq. (21) goes to

\[ |\delta_2\rangle = \frac{1}{2\sqrt{2}} \left( |0\rangle_B \left( -|L0\rangle_C (\alpha |01\rangle_{AD} - \beta |10\rangle_{AD}) - |L1\rangle_C (\alpha |01\rangle_{AD} + \beta |10\rangle_{AD}) \right) 
+ |R0\rangle_C (\alpha |11\rangle_{AD} + \beta |00\rangle_{AD}) + i |R1\rangle_C (\alpha |11\rangle_{AD} - \beta |00\rangle_{AD}) \right) 
+ |1\rangle_B \left( |L0\rangle_C (\alpha |11\rangle_{AD} + \beta |00\rangle_{AD}) + |L1\rangle_C (\alpha |11\rangle_{AD} - \beta |00\rangle_{AD}) \right) 
+ i |R0\rangle_C (\alpha |01\rangle_{AD} - \beta |10\rangle_{AD}) + i |R1\rangle_C (\alpha |01\rangle_{AD} + \beta |10\rangle_{AD}) \right). \]  

(22)

Then, the controlled teleportation is concluded after the operations described in the Table 3. Note that the knowledge of the atomic state controlling the teleportation is essential to complete the process.

\( ii) \ Two \ controls: \) Now, we will describe CPT of entangled states using two controls. This scheme is similar to that using one control as shown above. Let B1 be the new control as shown in Fig. 5. The atoms C and D share a previously prepared entangled state to be teleported, while B and B1 are the two controls. At the end of this scheme for CPT the partner C of the entangled state composed by C and D will be teleported to A, with A and D becoming the entangled state. To better explaining the procedure we take advantage of the previous scheme in Subsection \( ii) \). Assume the atoms C and D in the state given by Eq. (20). The photon, previously prepared in a superposed polarization state, enters the cavity A and interacts with the atom. Next, the photon is sent to interact with the atoms inside the cavity B and B1, respectively. After another interaction, now with the atom inside the cavity C, a Hadamard operation is applied to the atom C and the photon passes through a QWP2. Thus,
The first column shows the possible results of measurements on the atom C and photon F states. Second and third columns do the same for the control state (C) and for the teleported state (T S). Fourth column shows the corresponding Pauli matrices representing unitary operations upon the atomic state (A O) required to complete the teleportation process.

\[
|\delta_3\rangle = \frac{1}{4} \left[\begin{array}{c}
|00\rangle_{BB_1} \left(|L0\rangle_{FC} (\alpha|01\rangle_{AD} - \beta|10\rangle_{AD}) + |L1\rangle_{FC} (\alpha|01\rangle_{AD} + \beta|10\rangle_{AD})
- i|R0\rangle_{FC} (\alpha|11\rangle_{AD} + \beta|00\rangle_{AD}) - i|R1\rangle_{FC} (\alpha|11\rangle_{AD} - \beta|00\rangle_{AD})\right] \\
+ |01\rangle_{BB_1} \left[-|L0\rangle_{FC} (\alpha|11\rangle_{AD} + \beta|00\rangle_{AD}) - |L1\rangle_{FC} (\alpha|11\rangle_{AD} - \beta|00\rangle_{AD})
- i|R0\rangle_{FC} (\alpha|01\rangle_{AD} - \beta|10\rangle_{AD}) - i|R1\rangle_{FC} (\alpha|01\rangle_{AD} + \beta|10\rangle_{AD})\right]
+ |10\rangle_{BB_1} \left[-|L0\rangle_{FC} (\alpha|11\rangle_{AD} + \beta|00\rangle_{AD}) - |L1\rangle_{FC} (\alpha|11\rangle_{AD} - \beta|00\rangle_{AD})
- i|R0\rangle_{FC} (\alpha|01\rangle_{AD} - \beta|10\rangle_{AD}) - i|R1\rangle_{FC} (\alpha|01\rangle_{AD} + \beta|10\rangle_{AD})\right]
+ |11\rangle_{BB_1} \left[|L0\rangle_{FC} (\alpha|01\rangle_{AD} - \beta|10\rangle_{AD}) + |L1\rangle_{FC} (\alpha|01\rangle_{AD} + \beta|10\rangle_{AD})
- i|R0\rangle_{FC} (\alpha|11\rangle_{AD} + \beta|00\rangle_{AD}) - i|R1\rangle_{FC} (\alpha|11\rangle_{AD} - \beta|00\rangle_{AD})\right]\right].
\]

(23)

To conclude the CPT of entangled states one needs a measurement on the states of the photon and the atom trapped inside the cavity C. Moreover, the states of the controls B and B_1 must be known by Bob. To recover a successful teleportation Bob also needs to perform appropriate rotations given by the Table 4.
The first column shows the possible results of measurements on the atom \( C \) and photon \( F \) states. \( CS \) and \( TS \) columns do the same for the control state \( (BB) \) and for the teleported state \( (AD) \). The fourth column \( (AO) \) shows the corresponding Pauli matrices representing unitary operations upon the atomic state required to complete the teleportation process.

### iii) Generalization
To generalize the number of controls in the scheme one can insert the QWP after the last control as follows: QWP\(_1\) for odd controls and QWP\(_2\) for even controls.

### 4 Conclusions
In summary we presented two schemes to realize controlled teleportation of atomic states via photonic Faraday rotations in lossy optical cavities connected by optical fibers. The schemes only involve virtual excitations of the atoms and considers low-Q cavities, ideal photodetectors, and fibers without absorption. The practical experimental imperfections due to photon loss and inefficient detectors turn the protocol as probabilistic. In this respect we can estimate the success probability of the scheme taking into account the losses mentioned above, based on Ref. [73], e.g., considering the coupling and transmission of the photon through the single-mode optical fiber, given by \( T_f = 0.2 \), the transmission of each photon through the other optical components by \( T_o = 0.95 \), the fraction of photons with the correct polarization \( p_\pi = 0.5 \), the quantum efficiency of the single-photon detector as \( \eta = 0.28 \) [74], \( \Delta \Omega / 4\pi = 0.02 \) as the solid angle of light collection, and a single-photon rate by source given by 75 kHz. So, we estimate the success probability of the CT of superposition and CPT as

\[
P = p_{Bell} \times T_f \times T_o \times p_\pi \times \eta \times \Delta \Omega / 4\pi \simeq 1.33 \times 10^{-4}
\]

(considering \( p_{Bell} = 0.25 \))

---

**Table 4**  Possible results and rotations for completing the controlled partial teleportation for the case ii)

| MAPS | CS  | TS          | AO          |
|------|-----|-------------|-------------|
| \( |L0\)\_FC | \( |00\)_{BB} \_1 \) | \( \alpha |01\)\_AD - \( \beta |10\)\_AD \) | \( \sigma_z \otimes \mathbb{I} \) |
| \( |L1\)\_FC | \( |00\)_{BB} \_1 \) | \( \alpha |01\)\_AD + \( \beta |10\)\_AD \) | \( \mathbb{I} \otimes \mathbb{I} \) |
| \( |R0\)\_FC | \( |00\)_{BB} \_1 \) | \( \alpha |11\)\_AD + \( \beta |00\)\_AD \) | \( \sigma_x \otimes \mathbb{I} \) |
| \( |R1\)\_FC | \( |00\)_{BB} \_1 \) | \( \alpha |11\)\_AD - \( \beta |00\)\_AD \) | \( \sigma_z \sigma_x \otimes \mathbb{I} \) |
| \( |L0\)\_FC | \( |01\)_{BB} \_1 \) | \( \alpha |01\)\_AD + \( \beta |10\)\_AD \) | \( \mathbb{I} \otimes \mathbb{I} \) |
| \( |L1\)\_FC | \( |01\)_{BB} \_1 \) | \( \alpha |11\)\_AD - \( \beta |00\)\_AD \) | \( \sigma_z \otimes \mathbb{I} \) |
| \( |R0\)\_FC | \( |10\)_{BB} \_1 \) | \( \alpha |01\)\_AD - \( \beta |10\)\_AD \) | \( \sigma_z \sigma_x \otimes \mathbb{I} \) |
| \( |R1\)\_FC | \( |10\)_{BB} \_1 \) | \( \alpha |01\)\_AD + \( \beta |00\)\_AD \) | \( \mathbb{I} \otimes \mathbb{I} \) |
| \( |L0\)\_FC | \( |11\)_{BB} \_1 \) | \( \alpha |01\)\_AD - \( \beta |10\)\_AD \) | \( \sigma_z \otimes \mathbb{I} \) |
| \( |L1\)\_FC | \( |11\)_{BB} \_1 \) | \( \alpha |01\)\_AD + \( \beta |00\)\_AD \) | \( \mathbb{I} \otimes \mathbb{I} \) |
| \( |R0\)\_FC | \( |11\)_{BB} \_1 \) | \( \alpha |11\)\_AD + \( \beta |00\)\_AD \) | \( \sigma_x \otimes \mathbb{I} \) |
| \( |R1\)\_FC | \( |11\)_{BB} \_1 \) | \( \alpha |11\)\_AD - \( \beta |00\)\_AD \) | \( \sigma_z \sigma_x \otimes \mathbb{I} \) |
as the probability of the ideal Bell-state measurement without necessity of additional rotations), which results a time spent of 0.1 s for one successful controlled teleportation event. In the experiment of Ref. [73] the author obtained about one successful teleportation event every 12 min. In view of the current experimental feasibility we hope that these schemes can be realized.

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