Estimating losses in teleportation schemes using the phenomenological operator approach to dissipation in cavity quantum electrodynamics

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In this paper, we estimate the losses during teleportation processes requiring either two high-Q cavities or a single bimodal cavity. The estimates were carried out using the phenomenological operator approach introduced by de Almeida *et al.* [Phys. Rev. A **62**, 033815 (2000)].

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High-Q cavity is an important scenario for testing the foundations of quantum mechanics [1] as well as for demonstrating quantum information processing [2]. As is well known, the teleportation phenomenon [3], the cornerstone of universal quantum computation [4], has received increasing attention, and a number of protocols have been suggested for its implementation in various contexts, including cavity-QED [5–10]. Experimentally, teleportation has been demonstrated for discrete variables [11–15] and for a single mode of the electromagnetic field with continuous variables [16,17]. More recently, teleportation between matter and light has been announced [18], where matter and light are, respectively, the stationary and flying media. Teleportation processes involving two modes of a single cavity were considered in Refs. [19,20], where the unknown states to be teleported are, respectively, a superposition of zero- and one-photon states and a superposition of coherent states, with the teleportation occurring from one mode to another inside a cavity. In Ref. [21], the scheme of Ref. [19] was simplified so that explicit Bell measurement is not required. In this paper, we estimate the role of losses during teleportation processes, including the losses during the preparation of the state being teleported. The estimates were carried out using the phenomenological operator approach [22,23].

Our proposal requires Ramsey zones, two-level Rydberg atoms interacting off -resonantly with the cavity fields, selective atomic state detectors, and cavities (see Fig. 1). The model we are considering is

$$H_{a,f,\mathcal{E}} = \frac{\hbar\omega_0}{2}\sigma_z + H_{f,\mathcal{E}} + H_{eff}, \quad (1)$$

where ω_0 is the atomic $|e\rangle \rightarrow |g\rangle$ transition frequency, $\sigma_z = |e\rangle\langle e| - |g\rangle\langle g|$, $H_{eff} = \hbar\chi a^\dagger a |e\rangle\langle e|$ is the effective Hamiltonian describing the dispersive interaction between the atom and the field, and $H_{f,\mathcal{E}} = \hbar\omega a^\dagger a + \Sigma_k \hbar\omega_k b_k^\dagger b_k + \Sigma_k \hbar(\lambda_k a^\dagger b_k + \lambda_k^* a b_k^\dagger)$, where $a^\dagger$ and a are, respectively, the creation and annihilation operators for the cavity-field mode of frequency ω; whereas $b_k^\dagger$ and b_k are the creation and annihilation operators for the k*th* environmental oscillator mode, whose corresponding frequency and coupling parameter write ω_k and λ_k, respectively. As shown in Ref. [22], Eq. (1) can be written in the following simplified way in the reduced Hilbert space comprising the field and environment:

$$H_\ell = \hbar\omega_\ell a^\dagger a + \sum_k \hbar\omega_k b_k^\dagger b_k + \sum_k \hbar(\lambda_k a^\dagger b_k + \lambda_k^* a b_k^\dagger), \quad (2)$$

where $\ell = g, e$, $\omega_g = \omega$, and $\omega_e = \omega + \chi$. Note that the problem was reduced to that of the free dissipation of a cavity field whose frequency is ω_ℓ when it interacts with the atomic state $|\ell\rangle$. Also, note that the field frequency is unchanged if the atom enters the cavity in its ground state. The evolutions of both the atom and cavity mode state can be obtained by the following rule [22]:

$$|\ell\rangle|\alpha\rangle|\mathcal{E}\rangle \rightarrow |\ell\rangle|\alpha_{\ell,t}\rangle|\beta_{k\ell,t}\rangle, \quad (3)$$

where

$$\alpha_{\ell,t} = \alpha_o e^{-\Gamma t/2 - i\omega_\ell t}, \quad (4)$$

$$\beta_{ke,t} = \exp(i\chi t)\beta_{k,t}, \quad (5)$$

$$\beta_{kg,t} = \beta_{k,t}, \quad (6)$$

and

$$\langle\{\beta_{k,t}\}| - \{\beta_{k,t}\}\rangle = \exp[-2|\alpha_o|^2(1 - e^{-\Gamma t})]. \quad (7)$$

The scheme described here applies, for example, to two cavities made of a pair of mirrors each, with their symmetry axes perpendicular to each other: two monomodal cavities, the teleportation occurring from one mode of a cavity to

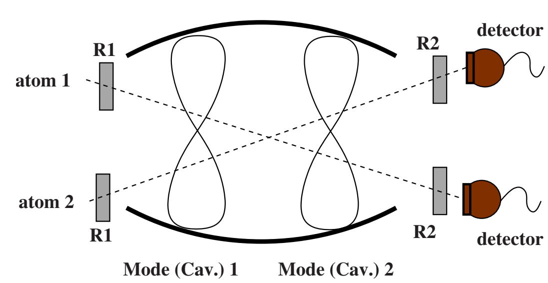

FIG. 1. (Color online) Experimental setup for engineering and teleporting a superposition of coherent states (SCSs) into a single lossy bimodal cavity or between two lossy monomodal cavities. Ramsey zones R_1, R_2 (R_1', R_2') are necessary for preparing (teleporting) the SCS.

another mode of a second cavity, and to two orthogonally polarized modes of a single bimodal cavity. All these foregoing schemes imply that each mode couples with a different reservoir, allowing us to safely use the rule given by Eq. (3) to each mode at a time. Thus, let as assume that the state to be teleported is prepared in mode 1, which can be one of the two orthogonally polarized modes of a bimodal cavity, or a single mode of the cavity 1, in the superposition $|\Psi_{MQSS}\rangle_1 = N(a|\alpha\rangle_1 + b|-\alpha\rangle_1)$, where $N = [1 + (ab^* e^{-2|\alpha_0|^2} + \text{H.c.})]^{-1/2}$ is the normalization constant, and a, b are unknown coefficients obeying $|a|^2 + |b|^2 = 1$. This "Schrödinger cat state" was studied in Ref. [24] to investigate the role of the environment in the transition of the quantum to classical dynamics. Note that the scheme we propose here differs from that of Refs. [20,25] since we consider the coherent-states superposition in each mode evolving under different reservoirs [26]. The atom and the cavity mode fields coupling parameter is $\chi_i = \frac{g^2}{\delta_i}$, where g is the Rabi frequency, τ is the atom-field interaction time, $\delta_i = (\omega_i - \omega_0)$ is the detuning between the field frequency corresponding to mode or cavity $i = 1, 2$, and ω_0 is the atomic $|e\rangle \to |g\rangle$ transition frequency. The evolution outside the cavity occurs with $\chi_i = 0$. As discussed in Ref. [20], having in mind a bimodal cavity, we consider the last term in Eq. (1) involving χ being effective only with one mode at a time. Therefore, while the interaction between an atom and mode 1 [Eq. (2)] of the cavity field is taking place, the relative phase due to the dispersive interaction between the atom and mode 2 [Eq. (1)] of the cavity field is negligible. This will be true provided the difference Δ between the two modes is large enough. In addition, to simplify our estimation of the fidelity of the teleported mesoscopic quantum superposition state (MQSS), we assume that the atom-field coupling is turned on (off) suddenly at the instant the atom enters (leaves) the cavity. With these remarks in mind, let us discuss the ideal process.

The ideal MQSS to be teleported is prepared by injecting a coherent state $|\alpha\rangle_1$ into mode 1, assuming $\lambda_{ik} = 0$ in Hamiltonian (1). Then, a two-level atom 1 is laser excited and rotated in a Ramsey zone R_1 to an arbitrary superposition $a|e\rangle_2 + b|g\rangle_2$. After that, atom 1 crosses the cavity, having been velocity selected to interact off-resonantly with mode 2 such that $\chi\tau = \pi$, where τ is the atom-field interaction time. Atom 1 then crosses a Ramsey zone R_1' undergoing a $\pi/2$ pulse and is detected, inducing a collapse of the cavity field to the even (+) or odd (−) MQSS $N(a|\alpha\rangle_1 \pm b|-\alpha\rangle_1)$. The +(−) sign occurs if the atom 1 is detected in the state $|g\rangle_1(|e\rangle_1)$. From now on, let us suppose that the even MQSS has been prepared. To teleport the MQSS, first atom 2 crosses a Ramsey zone R_2, undergoing a $\pi/2$ pulse, and then interacts off-resonantly with mode 2, assumed previously prepared in the coherent state $|\alpha\rangle_2$, with the coupling parameter adjusted to $\chi\tau = \pi$. As commented, mode 2 can be one of two orthogonally polarized modes of a bimodal cavity or a single mode of a second cavity. When considering a bimodal cavity, after the interaction of atom 2 and mode 2, the Stark shift is switched to a large detuning, thus, freezing the evolution corresponding to mode 2 and, at the same time, initiating the interaction of atom 2 and mode 1 [2]. After crossing the cavity, atom 2 crosses the Ramsey zone R_2' undergoing a $\pi/2$ pulse. By detecting atom 2 and measuring the phase of the field in mode 2, the field state in mode 1 is projected on to one of four possibilities. An appropriate rotation applied on the state in mode 2 thus completes the teleportation process. Let us consider these steps in detail, having in mind the rules given by Eq. (3).

Preparing the MQSS in a dissipative environment. Before atom 1 crosses R_1, the whole state of the system composed by atom 1, modes 1 and 2, and the reservoirs is $|\Psi(0)\rangle = |e\rangle_1 |\alpha(0)\rangle_1 |\alpha(0)\rangle_2 |\mathcal{E}\rangle_{R1} |\mathcal{E}\rangle_{R2}$. After the atom crosses R_1 and before it enters the cavity ($\chi = 0$), this initial state evolves to $|\Psi(0)\rangle \to |\Psi(t)\rangle = (a|g\rangle_1 + b|e\rangle_1)|\alpha(t)\rangle_1 |\alpha(t)\rangle_2 |\beta_{k,t}\rangle_{R1} |\beta_{k,t}\rangle_{R2}$. Next, atom 1 interacts off-resonantly with mode 1, such that $\chi\tau = \pi$, resulting in

$$|\Psi(t)\rangle = \frac{1}{2}[a|e\rangle_1 |-\alpha(t)\rangle_1 |\alpha(t)\rangle_2 |\beta_{e,t}\rangle_{R1} |\beta_{k,t}\rangle_{R2} + b|g\rangle_1 |\alpha(t)\rangle_1 |\alpha(t)\rangle_2 |\beta_{g,t}\rangle_{R1} |\beta_{k,t}\rangle_{R2}]. \tag{8}$$

Atom 1 then crosses R_1', undergoing a $\pi/2$ pulse and, when it is detected in the ground state, the cavity field collapses to the even MQSS in mode 1,

$$|\phi\rangle = N_p[a|\alpha(t)\rangle_1 |\beta_{g,t}\rangle_{R1} + b|-\alpha(t)\rangle_1 |\beta_{e,t}\rangle_{R1}] |\alpha(t)\rangle_2 |\beta_{k,t}\rangle_{R2}, \tag{9}$$

where N_p is the normalization constant. Disregarding mode 2 and its corresponding reservoir in Eq. (9), we have prepared MQSS state,

$$|\Psi_{MQSS}\rangle_1 = N_p[a|\alpha(t)\rangle_1 |\beta_{k,t}\rangle_{R1} + b|-\alpha(t)\rangle_1 |-\beta_{k,t}\rangle_{R1}], \tag{10}$$

where we use $\beta_{g,t} = \beta_{k,t}$ and $\beta_{e,t} = \exp(i\chi t)\beta_{k,t} = -\beta_{k,t}$ from Eq. (5). We remark the straightforward calculation when using the phenomenological operator approach (POA) method.

Teleporting the MQSS in a dissipative environment. After preparing mode 1 in the MQSS given by Eq. (9), atom 2 crosses Ramsey zone R_2 undergoing a $\pi/2$ pulse. The whole state of the system is

$$\frac{1}{\sqrt{2}}(|e\rangle_2 + |g\rangle_2) N_p[a|\alpha(t)\rangle_1 |\beta_{k,t}\rangle_{R1} + b|-\alpha(t)\rangle_1 |-\beta_{k,t}\rangle_{R1}] \times |\alpha(t)\rangle_2 |\beta_{k,t}\rangle_{R2}. \tag{11}$$

Next, atom 2 interacts off-resonantly with mode 2, such that $\chi\tau = \pi$, resulting in

$$\frac{N_p}{\sqrt{2}}[a|e\rangle_2 |\alpha(t)\rangle_1 |\beta_{k,t}\rangle_{R1} |-\alpha(t)\rangle_2 |-\beta_{kt}\rangle_{R2} + b|e\rangle_2 |-\alpha(t)\rangle_1 |-\beta_{k,t}\rangle_{R1} |-\alpha(t)\rangle_2 |-\beta_{k,t}\rangle_{R2} + a|g\rangle_2 |\alpha(t)\rangle_1 |\beta_{k,t}\rangle_{R1} |\alpha(t)\rangle_2 |\beta_{k,t}\rangle_{R2} + b|g\rangle_2 |-\alpha(t)\rangle_1 |-\beta_{k,t}\rangle_{R1} |\alpha(t)\rangle_2 |\beta_{k,t}\rangle_{R2}], \tag{12}$$

where again we have used Eq. (5). After the interaction of atom 2 and mode 2, atom 2 then interacts off-resonantly with mode 1. Considering a bimodal cavity, soon after the interaction of atom 2 and mode 2, which leads to Eq. (12), the

Stark shift must be switched to a large detuning $\delta=(\omega_2-\omega_0)$, thus, freezing the evolution corresponding to the interaction between atom 2 and mode 2 and, at the same time, initiating the off-resonant interaction of atom 2 and mode 1, such that $\chi\tau=\pi$. The result, after this interaction, is

$$\frac{N_p}{\sqrt{2}}[a|e\rangle_2|-\alpha(t)\rangle_1|-\beta_{k,t}\rangle_{R1}|-\alpha(t)\rangle_2|-\beta_{k,t}\rangle_{R2} + b|e\rangle_2|\alpha(t)\rangle_1|\beta_{k,t}\rangle_{R1}|-\alpha(t)\rangle_2|-\beta_{k,t}\rangle_{R2} + a|g\rangle_2|\alpha(t)\rangle_1|\beta_{k,t}\rangle_{R1}|\alpha(t)\rangle_2|\beta_{k,t}\rangle_{R2} + b|g\rangle_2|-\alpha(t)\rangle_1| - \beta_{k,t}\rangle_{R1}|\alpha(t)\rangle_2|\beta_{k,t}\rangle_{R2}]. \quad (13)$$

After crossing the cavities, atom 2 crosses Ramsey zone R_2' undergoing a $\pi/2$ pulse, such that Eq. (13) evolves to

$$\frac{N_p}{2}\{|e\rangle_2|\alpha(t)\rangle_1|\beta_{k,t}\rangle_{R1}[-a|\alpha(t)\rangle_2|\beta_{k,t}\rangle_{R2} + b|-\alpha(t)\rangle_2|-\beta_{k,t}\rangle_{R2}] + |e\rangle_2|-\alpha(t)\rangle_1|-\beta_{k,t}\rangle_{R1}[a|-\alpha(t)\rangle_2|-\beta_{k,t}\rangle_{R2} - b|\alpha(t)\rangle_2|\beta_{k,t}\rangle_{R2}] + |g\rangle_2|\alpha(t)\rangle_1|\beta_{k,t}\rangle_{R1}[a|\alpha(t)\rangle_2|\beta_{k,t}\rangle_{R2} + b| - \alpha(t)\rangle_2|-\beta_{k,t}\rangle_{R2}]|g\rangle_2|-\alpha(t)\rangle_1|-\beta_{k,t}\rangle_{R1}[a|-\alpha(t)\rangle_2| - \beta_{k,t}\rangle_{R2} + b|\alpha(t)\rangle_2|\beta_{k,t}\rangle_{R2}]\}. \quad (14)$$

Finally, detecting atom 2 and measuring the phase of the field state in mode 1, the field state in mode 2 is projected on one of four possibilities allowed by Eq. (14). The phase of the field in mode 1 can be measured by injecting a reference field of known amplitude $\alpha(t)$ at time t into mode 1, which makes the field states $|\alpha(t)\rangle_1$ and $|-\alpha(t)\rangle_1$ in Eq. (14) evolve, respectively, to the states $|2\alpha(t)\rangle_1$ and $|0\rangle_1$. Such states can be distinguished by sending a stream of two-level atoms, all of them in their ground state $|g\rangle_s$, to interact resonantly with mode 1 of the cavity field. Detecting all these atoms in the ground state indicates that mode 1 was in $|-\alpha(t)\rangle_1$ of Eq. (14), while detecting at least one atom in the excited state indicates that mode 1 was in $|\alpha(t)\rangle_1$ state. When atom 2 is detected in the $|g\rangle_2$ state and the field in mode 1 is detected in $|\alpha(t)\rangle_1$, then mode 2 is projected exactly on the desired state,

$$|\Psi_{MQSS}\rangle_2 = N_t(a|\alpha(t)\rangle_2|\beta_{k,t}\rangle_{R2} + b|-\alpha(t)\rangle_2|-\beta_{k,t}\rangle_{R2}), \quad (15)$$

where mode 1 and its corresponding reservoir are neglected. If the measurement results in $|g\rangle_2|-\alpha(t)\rangle_1$, a single atom interacting off-resonantly with mode 2 such that $\chi\tau=\pi$ completes successfully the teleportation process. For measurements revealing the state $|e\rangle_2$ in Eq. (14), no matter what the field state in mode 1 is, the teleportation process cannot be completed unless additional cavities and/or atoms be introduced, thus, overcomplicating the scheme. The probability of success of the present protocol is then 50%. Here, we stress the role of the POA method in simplifying each step of the process. As can be seen from Eq. (14), only the reservoir corresponding to mode 2, which receives the state to be teleported, affects this teleportation protocol. In fact, this is a consequence of different reservoirs existing for each mode. For a treatment of two modes evolving under the same reservoir in state engineering and teleportation processes, see Refs. [20,25]. Also, note that mode 2 and its corresponding environment do not affect the prepared MQSS in mode 1 and vice versa, although both modes are now mixed to their corresponding environments. To calculate the reduced density operator $\rho_{MQSS}(t)$ of the teleported state in mode 2, we only need to trace out mode 1 and its environment,

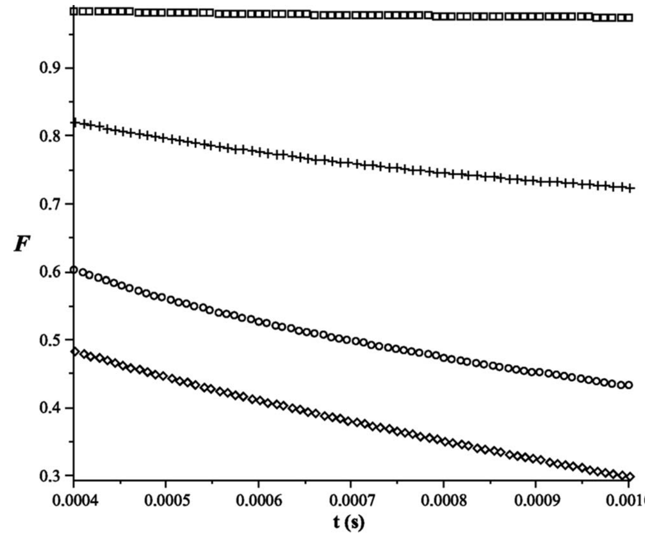

FIG. 2. Fidelity for the teleported MQSS for $\alpha=0.5$ (box), 1.0 (cross), 1.5 (circle), and 2.0 (diamond). The coefficients are $a=b=0.5$, and the experimental damping time is $T_2=0.9\times10^3$ for mode 2.

$$\rho_{MQSS}(t) = N_t^2[|a|^2|\alpha(t)\rangle_{22}\langle\alpha(t)| + |b|^2|-\alpha(t)\rangle_{22}\langle-\alpha(t)| + \mathcal{Z}(t) \times(ab^*|\alpha(t)\rangle_{22}\langle-\alpha(t)| + \text{H.c.})], \quad (16)$$

where $\mathcal{Z}(t)=\langle\{\beta_{k,t}\}|-\{\beta_{k,t}\}\rangle$ is given by Eq. (7), and the normalization constant is $N_t=\{1+[\mathcal{Z}(t)ab^*e^{-2|\alpha(t)|^2}+\text{H.c.}]\}^{-1/2}$. The fidelity of the teleported state is easily computed by $\mathcal{F}_T(t)={}_2\langle\Psi_{MQSS}(0)|\rho_{MQSS}(t)|\Psi_{MQSS}(0)\rangle_2$, where $|\Psi_{MQSS}(0)\rangle_1=\mathcal{N}_E[a|\alpha(0)\rangle_1+b|\alpha(0)\rangle_1]$. In Fig. 2, we present the fidelity for the teleported MQSS [Eq. (16)] for $\alpha=0.5$, 1.0, 1.5, and 2.0. The parameters are taken from recent experiments in cavity-QED [1,2]. Note that a successful realization of the teleportation process is obtained for α ranging from 0.5 to 1.0. For $\alpha=0.5$, the fidelity remains near unity for all times, while for $\alpha=1.0$ the fidelity decays to about 0.85 by the time the teleportation is completed, reaching the lowest value 0.7 for larger times, yet a significantly high value. For $\alpha=1.5$, the fidelity of the MQSS, by the time the teleportation is concluded, is about 0.6, higher than the classical limit 0.5. Regarding nowadays technology, teleportation in cavity fails for $\alpha\geq2.0$. These results are closely related to those of Ref. [25], where two modes of a bimodal cavity evolve under the same reservoir. In Ref. [25], the effective damping rate for each mode is the mean damping rate for the two modes. Here, however, considering two orthogonally polarized modes of a bimodal cavity, the two modes evolve independently of each other. As a consequence of a common reservoir for two modes, at the microwave domain the result obtained from an exact calculation presented in Refs. [20,25]

can be obtained from the rules given by Eq. (3) by simply replacing Γ_1 and Γ_2 with $\bar{\Gamma}=(\Gamma_1+\Gamma_2)/2$.

It is worthwhile to compare the scheme analyzed above with other related recent proposals. For instance, in Ref. [27], a scheme for teleporting a superposition of two coherent states was proposed, which is closely related to one of the protocols that we have analyzed in this paper. However, different from our work, the authors have not either included losses nor analyzed the possibility to realize teleportation inside a single bimodal cavity. In Ref. [28], the authors present a scheme for teleporting an entangled coherent state. Their scheme relies on the use of five high-Q cavities, and the losses are not included. In Ref. [29], the authors propose a similar scheme which uses four cavities. In their scheme, the authors do not analyze the role of the losses, even requiring the excitation of the coherent state to be not small. Also, it is worth to mention that the papers [30–32], dealing with teleportation of atomic states, takes advantage from noise to achieve teleportation, while we consider the noise as a source of errors in our cavity-field states teleportation protocol.

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