Reversible Optical-to-Microwave Quantum Interface

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We describe a reversible quantum interface between an optical and a microwave field using a hybrid device based on their common interaction with a micromechanical resonator in a superconducting circuit. We show that, by employing state-of-the-art optoelectromechanical devices, one can realize an effective source of (bright) two-mode squeezing with an optical idler (signal) and a microwave signal, which can be used for high-fidelity transfer of quantum states between optical and microwave fields by means of continuous variable teleportation.

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Quantum technologies will achieve maturity only when it becomes possible to integrate distinct modules in a single *hybrid* device, achieving a functionality that transcends the capability of any one component [1]. In general, this will require a quantum interface, able to transfer coherently and faithfully quantum information between the modules, without introducing decoherence. A very useful interface would enable communication between superconducting microwave systems and atomic-molecular-optical systems, or indeed between superconducting systems in distinct low temperature environments [2–4].

A number of schemes for a quantum interface between light at different wavelengths have been demonstrated [5–7], and very recently various solutions for interfacing optics and microwaves have been proposed [8–17]. We describe here a reversible quantum interface between optical and microwave photons based on a micromechanical resonator (MR) in a superconducting circuit, simultaneously interacting with an optical and a microwave cavity (MC).

When the cavities are appropriately driven, the MR mediates an effective parametric amplifier interaction, entangling an optical signal and a microwave idler. Such continuous variable (CV) entanglement can be then exploited to implement CV teleportation [18]. The optical output is mixed with an optical *client* field in an unknown quantum state on a beam splitter at the transmitting site (Alice). The two outputs are then subject to homodyne detection (see Fig. 1) and the classical measurement results communicated to the receiving site (Bob). Upon receipt of these results, Bob makes a conditional displacement of the microwave field, again using beam splitters and a coherent microwave source. The resulting state of the output microwave field is then prepared in the same quantum state as the optical input state. The process is entirely symmetric: the Alice and Bob roles can be exchanged and an unknown input microwave field can be teleported onto the optical output field at Alice, realizing therefore a reversible quantum state transfer between fields at completely different wavelengths.

We assume a MR which on the one side is capacitively coupled to the field of a superconducting MC of resonant frequency ω_w and, on the other side, coupled to a driven optical cavity (OC) with resonant frequency ω_c (see

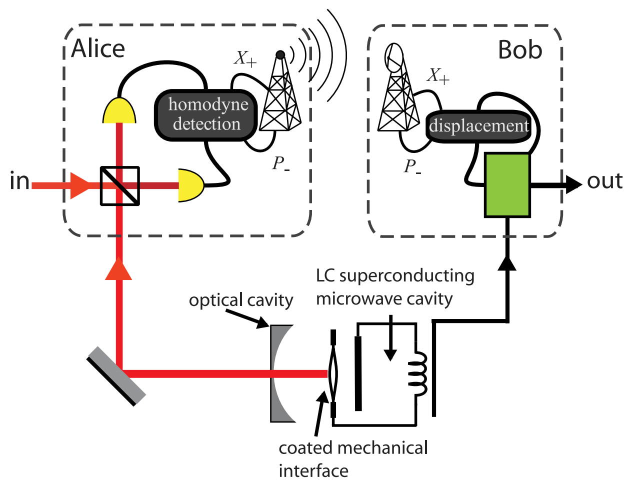

FIG. 1 (color online). Schematic description of the proposed optical-microwave interface. Alice mixes the optical cavity output with the input optical field she has to transfer, and communicates the results of her Bell measurements to Bob. The output state of the microwave field in Bob's hands is a faithful copy of the optical input field state when the optical-microwave cavity outputs are strongly entangled by their common interaction with the mechanical resonator, and Bob correctly displaces its state conditioned to Alice's measurement results. The scheme can be reversed by exchanging the roles of Alice and Bob: Bob performs the Bell measurements on microwave fields and the state of an input microwave field is teleported onto the optical output in Alice's hands after communication of the measurement results and the conditional displacement.

Fig. 1). Such a device could be realized for example by adding an OC to the superconducting circuit system of Teufel *et al.* [19], by depositing an highly reflective coating on the drum-head capacitor of the circuit and driving it with a laser through a standard input mirror. Alternatively one could adopt a membrane-in-the-middle setup [20] in which a metal-coated membrane [21] is capacitively coupled to a MC. The microwave and optical cavities are driven at the frequencies $\omega_{0w} = \omega_w - \Delta_w$ and $\omega_{0c} = \omega_c - \Delta_c$, respectively, where Δ_j, $j = c, w$ are the respective detunings.

The single photon coupling constants between the optical and microwave resonator fields and the MR are small in current experiments so we linearize the equations of motion by expanding around the steady state field amplitudes in each resonator, α_s and β_s (see Supplemental Material [22]). When $|\alpha_s| \gg 1$ and $|\beta_s| \gg 1$, and stability conditions are satisfied, the dynamics around the fixed point can be safely linearized and the effective Hamiltonian, in the interaction picture, is given by [23,24]

$$H = \hbar\Delta_c \hat{a}^\dagger \hat{a} + \hbar\Delta_w \hat{b}^\dagger \hat{b} + \hbar\omega_m \hat{c}^\dagger \hat{c} - \hbar G_c(\hat{a}^\dagger + \hat{a})(\hat{c} + \hat{c}^\dagger) - \hbar G_w(\hat{b}^\dagger + \hat{b})(\hat{c} + \hat{c}^\dagger) \tag{1}$$

where $\hat{a}$, $\hat{b}$, $\hat{c}$ are the (displaced) annihilation operators for the optical, microwave, and MRs, respectively, the optical and microwave driving field amplitudes are E_c, E_w, respectively. The microwave and the optical field must be phase locked, which can be realized by means of frequency-comb techniques [25]; varying this relative phase is equivalent to a local unitary operation which does not modify the entanglement between the two fields, and therefore we have chosen such a phase equal to zero, and taken α_s and β_s real and positive.

Before we present the full analysis, including damping, we can illustrate the key principle. As we describe below, the MR mediates an effective retarded interaction between the optical and cavity modes which is responsible for (i) cavity frequency shift and single mode squeezing for both modes, (ii) excitation transfer between the two modes, and (iii) two-mode squeezing between optical and microwave photons. One can resonantly select one of these processes by appropriately adjusting the cavity detunings. For example, the state transfer schemes of Refs. [9,13–15] choose equal detunings $\Delta_c = \Delta_w$. Instead here we choose opposite detunings $\Delta_c = -\Delta_w \equiv \Delta \simeq \omega_m$, and assume the regime of fast mechanical oscillations, $\Delta \sim \omega_m \gg G_c$, G_w, κ_c, κ_w, so that we are in the resolved sideband regime for both cavities, with red sideband driving for the OC and blue sideband driving for the MC. This choice allows us to neglect the fast oscillating terms at $\sim \pm 2\Delta$. In the case $\Delta_c = -\Delta_w \equiv \Delta \simeq \omega_m$ we can approximate the Hamiltonian by

$$H_a = -\hbar G_c(\hat{a}^\dagger \hat{c} + \hat{a}\hat{c}^\dagger) - \hbar G_w(\hat{b}\,\hat{c} + \hat{b}^\dagger \hat{c}^\dagger). \tag{2}$$

The second term alone is responsible for entangling the microwave resonator with the MR, while the first term alone exchanges the states of the optical and MRs. If these terms are acting together, we anticipate a regime in which the optical and microwave resonators become entangled thereby enabling a CV teleportation protocol to be implemented. This is confirmed in a more detailed analysis including damping.

We include damping and thermal noise by adopting a quantum Langevin equation in which we add to the Heisenberg equations mechanical damping with rate γ_m, the quantum Brownian noise acting on the MR $\hat{\xi}(t)$, cavity decay rates κ_c, κ_w, and the optical and microwave input noises $\hat{a}_{\rm in}(t)$ and $\hat{b}_{\rm in}(t)$ [24].

We now see when the proposed device behaves as a parametric oscillator involving an optical and a microwave mode. It is convenient to move to the interaction picture with respect to $\hat{H}_\Delta = \hbar\Delta_c \hat{a}^\dagger \hat{a} + \hbar\Delta_w \hat{b}^\dagger \hat{b}$, formally solve the dynamics of the MR, and insert this formal solution into the dynamical equations of the two modes. This gives a direct dynamical interaction between the optical and microwave resonators in terms of a convolution integral (here denoted with *) with the mechanical susceptibility $\chi_M(t) = e^{-\gamma_m t/2}\sin\omega_m t$ [24],

$$\dot{\hat{a}} = -\kappa_c \hat{a}(t) + e^{i\Delta_c t}\{\sqrt{2\kappa_c}\hat{a}_{\rm in}(t) + \frac{i}{2}[\chi_M * (G_c\hat{\xi} + G_c^2 \hat{X}_a + G_c G_w \hat{X}_b)](t)\}, \tag{3a}$$

$$\dot{\hat{b}} = -\kappa_w \hat{b}(t) + e^{i\Delta_w t}\{\sqrt{2\kappa_w}\hat{b}_{\rm in}(t) + \frac{i}{2}[\chi_M * (G_w\hat{\xi} + G_w^2 \hat{X}_b + G_c G_w \hat{X}_a)](t)\}, \tag{3b}$$

where the optical and microwave quadrature phase operators are defined by $\hat{X}_a(t) = a(t)e^{-i\Delta_c t} + a^\dagger(t)e^{i\Delta_c t}$ and $\hat{X}_b(t) = b(t)e^{-i\Delta_w t} + b^\dagger(t)e^{i\Delta_w t}$, and where $\hat{\xi}(t)$ is a Langevin thermal force term acting on the MR. The mechanical system acts like a nonlinear medium mixing the two electromagnetic fields. This is analogous to the mechanically mediated electromagnetically induced transparency for optical fields [26]. Note that we have *not* made the rotating wave approximation leading to the dropping of the nonresonant terms as in the approximation in Eq. (2)

As above, we choose opposite detunings $\Delta_c = -\Delta_w \equiv \Delta \simeq \omega_m$, and assume that we are in the resolved sideband regime for both cavities. Under these conditions, the two modes undergo a retarded parametric interaction with a time-dependent coupling kernel $G_c G_w \chi_M e^{i\Delta t}/2$, which is resonantly large only if $\Delta \sim \omega_m$, because otherwise the kernel rapidly oscillates and the interaction tends to average to zero. Therefore, it is convenient to choose one of the two resonant conditions, $\Delta_w = -\Delta_c = \pm\omega_m$, that is, one cavity mode is resonant with the red sideband and the other one with the blue sideband of the respective driving field.

This argument explains how one can entangle the *intracavity* microwave and optical modes [24]. However in quantum communication protocols one manipulates and entangles *traveling output* electromagnetic modes. Therefore we focus on the steady state of the system formed by the two (eventually filtered) cavity outputs, one at optical and the other at microwave frequencies. When such a state is entangled, the proposed device represents an extremely robust resource for any quantum information protocol, owing to the virtually infinite entanglement lifetime.

In experiment the cavity output modes are mixed with a strong local oscillator prior to detection on a photodetector resulting in a homodyne current. This current can then be integrated over some appropriate time window. By appropriately choosing the temporal mode functions of the local oscillator we can thus define the measurement in terms of filtered output modes. By properly choosing the central frequency and the bandwidth of the local oscillator, one can *optimally filter* the entanglement between the two output modes [27]. Other filtering methods, e.g., optoelectronic phase modulation, can also be used [28]. This is analogous to what happens in single-mode optical squeezing [29]: intracavity squeezing is always limited, while one can achieve arbitrary squeezing in an appropriate narrow-bandwidth of the output spectrum.

The measured cavity output modes are defined by the following bosonic annihilation operators [27]

$$\hat{a}_c^{\rm out}(t) = \int_{-\infty}^{t} ds g_c(t-s)\hat{a}^{\rm out}(s), \tag{4a}$$

$$\hat{b}_w^{\rm out}(t) = \int_{-\infty}^{t} ds g_w(t-s)\hat{b}^{\rm out}(s), \tag{4b}$$

where $\hat{a}^{\rm out}(t) = \sqrt{2\kappa_c}\delta\hat{a}(t) - \hat{a}^{\rm in}(t)$, and $\hat{b}^{\rm out}(t) = \sqrt{2\kappa_w}\delta\hat{b}(t) - \hat{b}^{\rm in}(t)$ are the standard input-output relationships for the optical and microwave fields [29], and $g_c(t)$ and $g_w(t)$ are causal filter functions defining the output modes. In fact, $\hat{a}_c^{\rm out}$ and $\hat{b}_w^{\rm out}$ are standard photon annihilation operators, implying the normalization conditions $\int dt|g_c(t)|^2 = \int dt|g_w(t)|^2 = 1$. A simple choice is taking $g_j(t) = \sqrt{2/\tau}\theta(t)e^{-(1/\tau + i\Omega_j)t}$, $j = c, w$, where $\theta(t)$ is the Heaviside step function, $1/\tau$ is the bandwidth of the output modes (equal for the two modes), and Ω_j is the central frequency (measured with respect to the frequency of the corresponding driving field).

The stationary state of the system is a zero-mean Gaussian state because the system is driven by Markovian Gaussian noises $\xi(t)$, $a^{\rm in}$ and $b^{\rm in}$, and we are considering the linearized dynamics of the quantum fluctuations around the semiclassical fixed point [24]. Therefore it is straightforward to quantify its entanglement by computing the corresponding logarithmic negativity E_N [30] (see Supplemental Material [22]). As expected, we find large entanglement (much larger than that between *intracavity* modes [24]) in the limit of narrow-band output modes of the microwave and optical cavities, under the resonant condition $\Delta_w = -\Delta_c = \omega_m$ (see Fig. 2). Large entanglement is achieved only around $\Omega_w = \omega_m$, for fixed central frequency of the optical output mode $\Omega_c = -\omega_m$, and for increasingly narrow output bandwidths. This means that the common interaction with the MR establishes quantum correlations between the microwave and OC outputs, which are strongest between the Fourier components *exactly* at resonance with the respective cavity field.

Equivalently, entanglement is maximum when narrow-band blue-detuned microwave and red-detuned optical output fields are selected, i.e., $\Omega_w = \Delta_w = -\Delta_c = -\Omega_c = \omega_m$. Figure 2 refers to a parameter set representing a feasible extension of the scheme of Ref. [19], i.e., a lumped-element superconducting circuit with a freestanding drum-head capacitor which is then optically coated to form a micromirror of an additional optical Fabry-Perot cavity. Figure 2 shows in practice a very efficient source of two-mode squeezing, in which the idler (signal) is at *optical* frequencies, and the signal (idler) is at *microwave* frequencies.

Such a large stationary entanglement can be exploited for the implementation of CV quantum teleportation [18]. A key role is played by two phase locked local oscillator fields, one for the optical output and one for the microwave output. These local oscillator fields need to be chosen in an

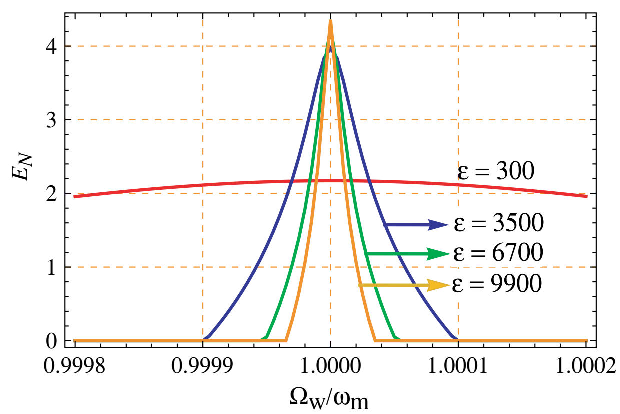

FIG. 2 (color online). E_N at four different values of the normalized inverse of the bandwidth $\epsilon = \tau\omega_m$ vs the normalized frequency Ω_w/ω_m, at fixed central frequency of the optical output mode $\Omega_c = -\omega_m$. The optical and microwave cavity detunings have been fixed at $\Delta_c = -\Delta_w = -\omega_m$, while the other parameters are $\omega_m/2\pi = 10$ MHz, $Q \equiv \omega_m/\gamma_m = 1.5\times10^5$, $\omega_w/2\pi = 10$ GHz, $\kappa_w = 0.04\omega_m$, $P_w = 42$ mW, $m = 10$ ng, $T = 15$ mK, $d = 100$ nm, $\mu = 0.013$, where d and μ are parameters of the equivalent capacitor defined in the Supplemental Material [22]. This set of parameters is analogous to that of Teufel *et al.* [19] for the MC and MR, except that we have considered a lower mechanical quality factor, and a heavier mass, in order to take into account the presence of the coating. We have then assumed an OC of length $L = 1$ mm and damping rate $\kappa_c = 0.04\omega_m$, driven by a laser with wavelength $\lambda_{0c} = 810$ nm and power $P_c = 3.4$ mW.

appropriate temporal mode to affect the required filtering to access the large steady state entanglement produced by the optomechanical interface. An unknown state, the client (Victor) state, of the optical field is prepared and sent to Alice, where it is mixed at a balanced beam splitter with the optical output of the device proposed here and the optical local oscillator with the appropriate temporal mode shape.

Alice performs a balanced homodyne detection at each output port of the beam splitter, effecting a joint measurement of two temporally filtered quadrature phase operators, and sends the results of her measurements to Bob as a classical current. Bob uses the measured homodyne current sent from Alice to effect an appropriate conditional, coherent displacement of the microwave field at his location. This is done by mixing the microwave local oscillator and the microwave output from the interface on an almost perfectly reflecting beam spitter, with the phase and amplitude of the local oscillator chosen according to the measurement current received from Alice. By exploiting only homodyne measurements, conditional coherent field displacements, and the strong entanglement realized by the proposed hybrid device, a quantum state of an optical field can be teleported onto the quantum state of a microwave field. The entire protocol can be reversed; i.e., joint measurement can be performed at the microwave end and conditional coherent displacements performed at the optical end.

The quality of the proposed teleportation protocol is quantified by the fidelity F which, in the case of a pure input state $|\psi_{\rm in}\rangle$ at Victor site, is given by $F = \langle\psi_{\rm in}|\rho_{\rm out}|\psi_{\rm in}\rangle$, where $\rho_{\rm out}$ is the output state at Bob site after the conditional displacement. In terms of the Wigner characteristic functions of the input state $\Phi_{\rm in}(\alpha)$ and of the entangled channel $\Phi_{\rm ch}(\alpha,\beta)$, one has $F = \pi^{-1}\int d^2\alpha|\Phi_{\rm in}(\alpha)|^2\Phi_{\rm ch}(\alpha^*,\alpha)^*$ [31]. We consider a highly nonclassical input state at Victor's site, an even *cat* state $|\psi\rangle = N(|\alpha\rangle + |-\alpha\rangle)$, where $N = \{2+2\exp[-2\alpha^2]\}^{-1/2}$. Various possible threshold fidelities have been suggested for unambiguously distinguishing a successful quantum teleportation from the best classical state transfer strategy [32]. In the case of nonclassical states, however, one can adopt the so-called "no-cloning threshold" $F_{\rm th} = 2/3$ [33], which has the following property: any nonclassical input state (i.e., possessing a negative Wigner function) remains nonclassical at the end of the teleportation protocol, if and only if $F > F_{\rm th}$ [34].

F for the even cat state can be evaluated explicitly (see Supplemental Material [22]), and the results are shown in Figs. 3 and 4. F shows the same behavior of E_N: this fact, although intuitive, is not generally true because F depends upon the protocol details, and is not invariant under local unitary transformations; i.e., it is not an entanglement measure. The similar behavior of E_N and F here is a consequence of the fact that Alice's choice of measuring $\hat{X}_+$ and $\hat{Y}_-$ for her Bell measurement is close to being optimal for the Gaussian entangled state shared by the two parties, because it exploits the subshot noise variance of $\hat{X}_c^{\rm out} + \hat{X}_w^{\rm out}$ and $\hat{Y}_c^{\rm out} - \hat{Y}_w^{\rm out}$. In fact, the selected narrowband microwave and optical output modes possess Einstein-Podolsky-Rosen correlations that can be immediately exploited for teleportation without any need for local optimizations such as those discussed in Refs. [35,36]. This is confirmed by the fact that F is very close to the optimal upper bound achievable for a given E_N, $F_{\rm opt} = (1+e^{-E_N})^{-1}$ [36,37]. Finally Fig. 4 shows F vs the amplitude of the cat state α for different values of the inverse bandwidth τ when the optimal resonance condition $\Omega_w = \omega_m$ is taken.

The teleportation protocol can be reversed, and the role of the optical and microwave output fields can be exchanged, by exploiting the symmetry of the effective parametric interaction mediated by the MR. This means that by exchanging in Fig. 1 the roles of Alice and Bob, one can

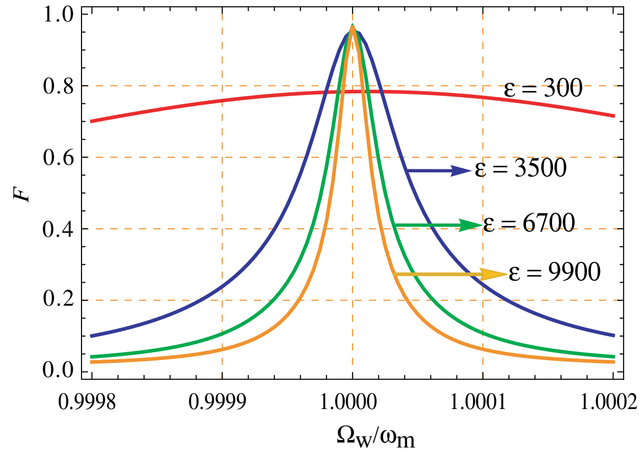

FIG. 3 (color online). Teleportation fidelity F at four different values of $\epsilon = \tau\omega_m$ vs Ω_w/ω_m and for the cat-state amplitude $\alpha = 1$. The other parameters are as in Fig. 2.

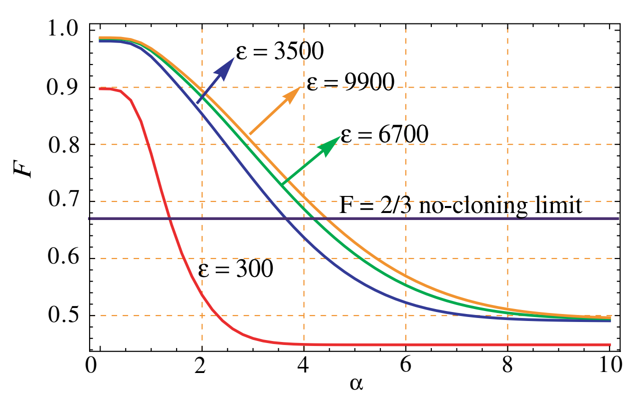

FIG. 4 (color online). Teleportation fidelity F at four different values of $\epsilon = \tau\omega_m$ vs the cat-state amplitude α, at a fixed central frequency of the microwave output mode $\Omega_w = \omega_m$ and fixed temperature $T = 15$ mK. The other parameters are as in Fig. 2.

teleport the state of an input microwave field onto the output optical field at Alice's site. This means mixing and homodyning microwave fields for the Bell measurements at Bob's location, and conditionally displacing the state of the optical field at Alice's location. The only problem in this reversal is technical, because it is presently difficult to achieve as high an efficiency for homodyne detection of microwave fields as it is for optical fields. However single-photon counterdetectors at microwave frequencies are under development, and therefore there is no serious limitation for implementing CV Bell measurements at microwave wavelengths.

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