Quantum communication with itinerant surface acoustic wave phonons

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Surface acoustic waves are commonly used in classical electronics applications, and their use in quantum systems is beginning to be explored, as evidenced by recent experiments using acoustic Fabry-Pérot resonators. Here we explore their use for quantum communication, where we demonstrate a single-phonon surface acoustic wave transmission line, which links two physically-separated qubit nodes. Each node comprises a microwave phonon transducer, an externally-controlled superconducting variable coupler, and a superconducting qubit. Using this system, precisely-shaped individual itinerant phonons are used to coherently transfer quantum information between the two physically-distinct quantum nodes, enabling the high-fidelity node-to-node transfer of quantum states as well as the generation of a two-node Bell state. We further explore the dispersive interactions between an itinerant phonon emitted from one node and interacting with the superconducting qubit in the remote node. The observed interactions between the phonon and the remote qubit promise future quantum optics-style experiments with itinerant phonons.

INTRODUCTION

Quantum communication is of significant interest for the generation of remote entanglement and the secure transmission of information, as well as for distributed quantum computing [1–7]. There are several demonstrations of long-distance quantum communication protocols using optical methods, in parallel with demonstrations of similar protocols using microwave-frequency photons, including Bell state entanglement of remote qubits as well as the transmission of multi-qubit entangled states [8–16]. Microwave-frequency phonons, as opposed to photons, can also be used for quantum communication as well as for coupling hybrid quantum systems [17–20], in the latter case taking advantage of the strong strain coupling in some optical as well as atomic-scale systems. Microwave-frequency acoustic resonators may be able to serve as very long-lived quantum memories [21]. Quantum communication protocols implemented with phonons are thus of significant scientific as well as practical interest. Recent advances in the quantum control of phonons include the creation and measurement of stationary phonon quantum states [22–24], the emission and absorption of phonons in an acoustic resonator [25], and the generation of entangled phonons in a phonon-mediated quantum eraser experiment [26].

Here we report the experimental realization of a phonon-based quantum communication channel, enabling the communication of quantum states via traveling phonons linking two physically-distinct quantum nodes. The phonons are emitted in the communication channel as short-duration acoustic pulses, sufficiently brief that the extent of the acoustic pulses is significantly less than the length of the channel, such that the phonons travel in a particle-like fashion along the channel, which we term itinerant.

The experimental system is shown schematically in Fig. 1, with the physical setup in Fig. 1**a** and the circuit schematic in Fig. 1**b**. The 2 mm-long phonon communication channel (500 ns single-trip time) is terminated at each end by a specially-designed unidirectional interdigitated transducer, which is in turn connected to a superconducting qubit via a superconducting tunable coupler. The unidirectional transducers (UDTs) differ from conventional acoustic transducers, here emitting itinerant phonons in only one direction, as opposed to more standard bi-directional transducers, which emit excitations equally in two opposing directions (see Supplementary Note 1; a related but distinct design appears in [27]). We note this device differs from the experimental construction in e.g. Ref. [25], which uses a single bidirectional transducer in a Fabry-Pérot cavity. In that experiment, a single phonon comprises acoustic excitations that travel in two opposing directions to distant acoustic mirrors, from which the excitations reflect and return to interfere constructively at the emitting transducer, where the excitation can be intercepted by one of two qubits. In the experiment here, two distinct unidirectional transducers are used to link two physically separate nodes. Each transducer is constructed to emit an acoustic excitation in only one direction, creating a significantly more flexible and general-purpose design, with physically separate and distinct phonon emitter and receiver.

We use this device to demonstrate two-node quantum state transfers as well as the phonon-mediated deterministic generation of an entangled Bell state, representing a significant advance over prior work, in which a single transducer was coupled to a Fabry-Pérot acoustic cavity formed by two acoustic mirrors [22–26]. We also realize a single-phonon interferometer, using one qubit to emit and detect a traveling phonon, where the phonon is used to probe the state of the second qubit, effectively demonstrating the dispersive interaction of a photon (localized in the remote qubit) and a traveling phonon. Finally, we demonstrate a Ramsey interferometer, using the second qubit to detect the presence of a traveling phonon emitted by the first qubit, thus interchanging the roles of the qubits in the previous experiment and demonstrating the versatility of this architecture.

RESULTS

Phonon-mediated quantum state transfer

We first probe the interaction between the qubits and the phonon channel, as shown in Fig. 2**a**. We excite Q_1 with a π pulse, then set its coupler G_1 to an intermediate coupling, sufficient that Q_1's relaxation is dominated by phonon emission. We set Q_2's coupler G_2 off during this measurement, so that Q_2 does not interact with the traveling phonon. For frequencies inside the transducer's active band, from 3.87 to 4.01 GHz, where the emission is almost entirely unidirectional itinerant phonons, we observe a time-delayed revival of qubit Q_1's excited state population $P_e^{Q_1}$ at times that are multiples of the phonon round-trip time $\tau_{\mathrm{RT}} \sim 1\,\mu\mathrm{s}$, each revival corresponding to the traveling phonon reflecting off the other transducer before re-exciting Q_1. Outside the unidirectional band, we see a complex structure in P_e as a function of frequency and interaction time, with broad swings of width $\sim 150\,\mathrm{MHz}$ superposed with narrow oscillations of width $\sim 7\,\mathrm{MHz}$. The broad swings and finer details are in accordance with expectations (see Supplementary Note 1) [29].

The itinerant phonon experiments are performed at the working frequency $\omega_{Q_{1,2}}^{\mathrm{uni}}/2\pi = 3.976\,\mathrm{GHz}$, inside the unidirectional band. By working outside this band, we can explore the regime where the transducers are effectively bidirectional, using the second working frequency $\omega_{Q_{1,2}}^{\mathrm{bi}}/2\pi = 4.102\,\mathrm{GHz}$. These frequencies are marked by the dashed white and red lines, respectively, in Fig. 2**a**.

To maximize the efficiency of phonon-mediated quantum state transfers, we need to carefully shape the emission and absorption of the phonon wave packet, which is done by time-dependent control of the coupling between the qubit and its transducer [11–15, 25, 30]. We experimentally optimize the transfer efficiency, with results shown in Fig. 2**b** for both the unidirectional (left) and bidirectional (right) regimes. The transfer starts with the shaped emission of a phonon, shown by the decrease of Q_1's excited state population with the expected time dependence. Both qubits then remain in their ground states until the phonon reaches Q_2, which absorbs the itinerant phonon, following the expected time dependence, and ultimately reaching a plateau once the transfer is complete. The total transfer takes $\sim 700\,\mathrm{ns}$, including the $\sim 500\,\mathrm{ns}$ phonon travel time. The final Q_2 population reaches a maximum of $68\,\%$ for the unidirectional transfer, limited mostly by phonon loss in the channel. For the bidirectional transfer, the final Q_2 population reaches $15\,\%$, 4.5 times less than the unidirectional population, which is $12\,\%$ higher than the ideal value, demonstrating good agreement with theory and excellent unidirectionality for the transducer design. We simulate the transfer process using a cascaded quantum input-output model [25] (solid green line). From this model we estimate that phonon loss reduces the final unidirectional transfer efficiency by 27%, and the finite Q_1 and Q_2 coherence times reduce the fidelity by $1\,\%$ and $2\,\%$, respectively. We note that an equivalent photon travel time would require a $\sim 100\,\mathrm{m}$ long coaxial cable, illustrating the very long delays achievable with phonon-based quantum channels.

In Fig. 2**c**, we show quantum process tomography for both regimes. For the unidirectional process, we find a process fidelity of $\mathcal{F}^{\mathrm{uni}} = (82.0 \pm 0.3)\,\%$, while for the bidirectional regime, the process fidelity is limited to $\mathcal{F}^{\mathrm{bi}} = (39.0 \pm 0.3)\,\%$. We compare these experimental process fidelities with predictions, and find trace distances $d = \sqrt{\mathrm{Tr}\,(\chi_{\mathrm{exp}} - \chi_{\mathrm{sim}})^2} = 0.07$ and 0.3 for the unidirectional and bidirectional regimes. The contrast in fidelities and trace distances underlines the importance of the unidirectional transducers.

Traveling phonon-mediated remote entanglement

We further explore the capabilities of itinerant phonon communication by performing a phonon-mediated remote entanglement of the two qubits, shown in Fig. 3. The protocol is similar to that for the quantum state transfer, except here we calibrate the emission pulse to only emit Q_1's excitation as a phonon with a probability of 1/2, meaning that immediately following the 'half-emission,' with qubit Q_2 in the ground state, the system is ideally in the state $(|e0g\rangle + |g1g\rangle)/\sqrt{2}$ (writing the state $|Q_1\,\gamma\,Q_2\rangle$ where γ represents the itinerant phonon). During the time the emitted 'half-phonon' travels along the phonon channel, Q_1's remaining excitation decays following Q_1's intrinsic T_1 time, with Q_1's coupling to the channel set to zero. The traveling half-phonon is then captured by Q_2, generating a Bell state $|\psi\rangle = (|eg\rangle + e^{i\varphi}|ge\rangle)/\sqrt{2}$ between the two qubits, with φ a relative phase.

Figure 3**a** shows the time-dependent qubit state populations P_e for each qubit, which agree well with a master equation simulation. Following capture of the half-phonon, we perform quantum state tomography at time $t_{\mathrm{m}} = 750\,\mathrm{ns}$; these measurements are used to reconstruct the two-qubit density matrix ρ shown in Fig. 3**b**. We find a Bell state fidelity $\mathcal{F}_{\mathrm{Bell}} = \mathrm{Tr}\ (\rho_{\mathrm{ideal}} \cdot \rho) = 72\,\%$ and a concurrence $\mathcal{C} = 0.53$, close to the master equation simulation results, with a trace distance $d^{\mathrm{Bell}} = \sqrt{\mathrm{Tr}\ (\rho_{\mathrm{exp}} - \rho_{\mathrm{sim}})^2} = 0.13$.

Phonon-qubit dispersive interaction

Sensing traveling phonons without absorbing them would provide a highly useful capability, as would being able to use a traveling phonon as a probe of a remote quantum system, which we explore in a pair of related experiments. First, we use a traveling phonon as a probe of a remote quantum two-level system, shown in Fig. 4**a**. We use qubit Q_1 as the emitter and receiver of a "half-phonon" that is detected interferometrically [25, 26] when returning to Q_1. This allows us to measure how the phase of the traveling phonon is affected by interacting dispersively with qubit Q_2, which serves as a stand-in for a generic quantum system.

The pulse sequence for this state detection is shown to the right in Fig. 4**a**: We first prepare Q_1 in its excited state, and emit a half-phonon, which reflects from the distant transducer, whose coupling to Q_2 is turned on during the reflection process, and the half-phonon interacts with Q_1 on its return. During the half-phonon transit, we briefly shift Q_1's frequency so that Q_1's excited state acquires a relative phase φ, yielding an interferometric interaction with the returning half-phonon, either interfering constructively to return Q_1 towards its excited state, or destructively and having Q_1 emit its remaining energy and relax to its ground state. In Fig. 4**a**, we show the final Q_1 population as a function of the phase φ (blue points), showing a characteristic interference pattern with a visibility of $32\,\%$.

We repeat the experiment with Q_2 excited by a π pulse at the beginning of the experiment, with experiment otherwise unchanged; the results are shown in Fig. 4**a** (salmon points). There are three effects on the oscillation pattern: A slight increase in the oscillation minima, attributed to a decrease of the phonon coherence [25] in its interaction with Q_2; a more marked reduction of visibility attributed to an inadequate absorption of the phonon wave packet; and, most significantly, a phase shift of $\Delta\varphi_{\mathrm{exp}} = 0.40\pi$ attributed to the dispersive interaction between Q_2 and the traveling half-phonon, close to our fit-free simulated value of $\Delta\varphi_{\mathrm{sim}} = 0.41\pi$ (see Supplementary Note 9). This last effect points to the interesting possibility of using phonons as dispersive probes of other quantum systems.

In a separate experiment, shown in Fig. 4**b**, we swap the roles of the qubits, so Q_2 is now used as a dispersive probe for the phonon released by Q_1, using a Ramsey fringe measurement of Q_2. The pulse sequence is shown to the right in Fig. 4**b**, where Q_2 is placed in the state $(|g\rangle + e^{\mathrm{i}\theta}|e\rangle)/\sqrt{2}$ by the initial $\pi/2$ rotation, performed about an axis rotated in the $x - y$ plane of the Bloch sphere by θ, and the θ-dependent evolution of Q_2 is compared for where Q_1 is not excited (no probe phonon) to where Q_1 is excited and Q_2 interacts with the subsequently-released traveling phonon. In the latter case the Ramsey fringe visibility is reduced, which we attribute to leakage from Q_2 into the phononic channel, but we again observe a significant phase shift, here as high as $\Delta\theta_{\mathrm{exp}} = 0.95\,\pi$ close to our simulation $\Delta\theta_{\mathrm{sim}} = 0.99\,\pi$.

DISCUSSION

In conclusion, we demonstrate controlled phonon-mediated quantum state transfer and remote entanglement between two quantum nodes, each node comprising a superconducting qubit with a time-variable coupler, using individual itinerant SAW phonons traveling in an acoustic transmission line after a controlled, on-demand release, followed by capture. Using this architecture, we also demonstrate the dispersive interaction between an itinerant phonon and a superconducting qubit. These results have been made possible by the integration of broadband, highly unidirectional transducer in a 2 mm long phonon communication channel, as well as the use of a quantum state protocol requiring tunable coupling to each qubit node [2]. Achieving a quite impressive quantum state transfer fidelity of $(82.0 \pm 0.2)\,\%$, limited by the loss in the phonon channel, this platform paves the way for quantum-optics-like experiments realized with individual phonons instead of photons.

METHODS

Device fabrication and characterization

The device used in these experiments comprises two dies, a sapphire die with the two superconducting qubits (Q_1 and Q_2), and their associated tunable couplers (G_1 and G_2, respectively), as well as control and readout wiring, and a lithium niobate die with the phononic channel and the two unidirectional transducers. The two dies are fabricated separately then flip-chip assembled [31]. The full circuit schematic is shown in Fig. 1**b**,

The acoustic die is fabricated using a single layer of $\sim 25\,\mathrm{nm}$ thick aluminium patterned by PMMA liftoff on a $\mathrm{LiNbO_3}$ wafer, $500\,\mu\mathrm{m}$ thick. The central part of the acoustic device is the $\ell = 2\,\mathrm{mm}$-long phononic channel, with width $W = 150\,\mu\mathrm{m}$, terminated at each end by a unidirectional transducer ($\mathrm{UDT}_{1,2}$).

The unidirectional transducers (UDTs) are described more completely in Supplementary Note 1. Briefly, the two (nominally identical) unidirectional transducers (UDTs) each comprise a standard bi-directional interdigitated transducer (IDT) combined with an acoustic mirror (a reflective grating). The IDT emits equal-amplitude acoustic excitations in opposite directions, one towards and the other away from the second UDT. The acoustic mirror, placed immediately adjacent to the IDT on the side opposite the second UDT, reflects its incident excitation back towards the second UDT, such that it interferes constructively with the other excitation. Each UDT is coupled inductively to one of the two qubits.

We have separately characterized similar IDT-mirror designs, where in the frequency band from about 3.85 to 4 GHz, excellent directionality is achieved, with emission from the UDT almost entirely directed away from the mirror. Typical directivities are greater than 20 dB. Outside this unidirectional band, the mirrors are less effective and the devices emit more strongly in both directions [27].

The superconducting qubit die is fabricated on $430\,\mu\mathrm{m}$-thick sapphire using standard lithographic processing [15]. The qubits $Q_{1,2}$ are tunable xmon-style qubits [32, 33], where each qubit's frequency is controlled by a flux line $Q_{\mathrm{z1,z2}}$, and excited using a capacitively-coupled microwave line $Q_{\mathrm{xy1,xy2}}$. Each qubit is coupled to the SAW chip through a superconducting tunable coupler $G_{1,2}$, whose coupling is controlled [34] using external flux lines $G_{\mathrm{z1,z2}}$. Qubit states are inferred from standard dispersive measurements using a separate readout resonator for each qubit. The readout resonators are connected to a common readout line; more details are given in the Supplementary Note 1.

The qubits are characterized with their couplers turned off (see Supplementary Notes 6 and 7). At the qubit idle frequency $\omega_{\mathrm{idle}}/(2\pi) \sim 4.3\,\mathrm{GHz}$, we find the qubits have an energy relaxation time $T_1 = 57\,\mu\mathrm{s}$ (Q_1) and $38\,\mu\mathrm{s}$ (Q_2), with a coherence time $T_2^{\mathrm{Ramsey}} = 1.11\,\mu\mathrm{s}$ (Q_1) and $0.88\,\mu\mathrm{s}$ (Q_2) (most likely limited by flux noise as the qubits are tuned far away from their flux-insensitive point). These times demonstrate the potential for excellent qubit coherence when using a flip-chip assembly [31].

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request. Correspondence and requests for materials should be addressed to A. N. Cleland (anc@uchicago.edu).

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COMPETING INTERESTS

The authors declare no competing financial or non-financial interests.

AUTHOR CONTRIBUTIONS

É.D. designed, and fabricated the devices. É.D. performed the experiment and analyzed the data. K.J.S., G.A.P. and M.-H.C. participated to the design process of the unidirectional transducer. É.D., K.J.S., A.B., H.-S.C., J.G., Y.P.Z. developed the fabrication process of the superconducting circuit. É.D., K.J.S. and A.B. wrote code to model surface acoustic wave. A.N.C. advised on all efforts. All authors contributed to discussion and production of the manuscript.

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FIGURE LEGENDS

FIG. 1. Quantum delay line. **a** Schematic representation of the two quantum communication nodes and the phononic quantum channel. Each node comprises a superconducting qubit, a tunable coupler that allows shaping phonon release and capture, and a unidirectional phonon transducer. Details in the Methods section. **b** Circuit diagram of the assembled device. Each qubit Q_j is excited through its dedicated $Q_{xy\ j}$ microwave line and frequency-controlled through a separate $Q_{z\,j}$ flux-bias line, and each tunable coupler G_k is controlled via its associated $G_{z\,k}$ flux-bias line.

FIG. 2. Phonon-mediated quantum state transfer and process tomography. **a** Measured Q_1 excited state population $P_e^{Q_1}$ as a function of time and Q_1 bare frequency, with coupler G_1 at an intermediate coupling $\kappa_1/2\pi = 2.4\,\mathrm{MHz}$ (measured at 3.976 GHz) and G_2 set to zero coupling. In this configuration, Q_1's energy relaxation is dominated by phonon emission via UDT_1, followed by traveling phonon dynamics. The white and red dashed lines indicate the unidirectional and bidirectional working frequencies, respectively (see text); inset shows the qubit excitation and measurement pulse sequence. **b** Quantum state transfer via a traveling phonon at the unidirectional (left) and bidirectional (right) operating frequencies. Q_2's final population is 4.5 times smaller for the bidirectional transfer compared to the unidirectional transfer, in line with simulations. Green solid lines are from a master equation simulation. Inset: Pulse sequence. For either process, Q_1's emission rate is set to $\kappa_c^{\mathrm{uni|bi}}/2\pi = 10|6\,\mathrm{MHz}$, corresponding to a $81|138\,\mathrm{ns}$ full-width-at-half-maximum (FWHM) phonon wavepacket. **c** Quantum process tomography for the unidirectional and bidirectional regimes, with process fidelities of $\mathcal{F}_{\mathrm{uni}} = \mathrm{Tr}\,(\chi_{\mathrm{exp}} \cdot \chi_{\mathrm{ideal}}) = 82 \pm 0.3\,\%$ and $\mathcal{F}_{\mathrm{bi}} = 39 \pm 0.3\,\%$, respectively. Red solid lines show values expected for an ideal transfer; black dashed lines show master equation simulations, taking into account finite qubit coherence and phonon channel losses. Uncertainties are standard deviations from the mean.

FIG. 3. Phonon-mediated Bell state generation. **a** Inset: Pulse sequence for Bell state generation. Main panel: Excited state probabilities for Q_1 (red) and Q_2 (blue) as a function of time. Green lines are results from a master equation simulation. The final state is analyzed at $t_m = 725\,\mathrm{ns}$ (gray dashed line). **b** Bell state density matrix, absolute values, without readout correction, measured at t_{m}. Red solid lines show values expected for an ideal Bell state; black dashed lines show simulation results including qubit coherence and phonon channel losses.

FIG. 4. Phonon interferomeric probe. Dispersive state-dependent interferometric probe. **a** Schematic roles played by each element. **b** Blue (salmon) points show the φ dependence of Q_1's final P_e when Q_2 is in $|g\rangle$ ($|e\rangle$), showing a dependence of the phonon phase on Q_2's state, with a shift of $\sim 0.4\pi$ rad. **c** Qubit pulse sequences (see text for details). **d** Schematic roles played by each element for the dispersive phase-dependent interferometric probe. **e** Ramsey interference in Q_2 (blue circles) reveals Q_2's dependence on the relative phase with the phonon. When repeating the same protocol with no initial π pulse on Q_1, we measure the Ramsey interference of Q_2 (salmon squares), shifted by π compared to the first measurement. Blue (salmon) points show the φ dependence of Q_1's final P_e when Q_2 is in $|g\rangle$ ($|e\rangle$), showing a dependence of the phonon phase on Q_2's state, with a shift of $\sim 0.4\pi$ rad. **f** Qubit pulse sequences, similar to **c** except Q_2 is always placed in $(|g\rangle + e^{\mathrm{i}\theta}|e\rangle)/\sqrt{2}$ and the θ-dependent P_e^{Q2} is measured.