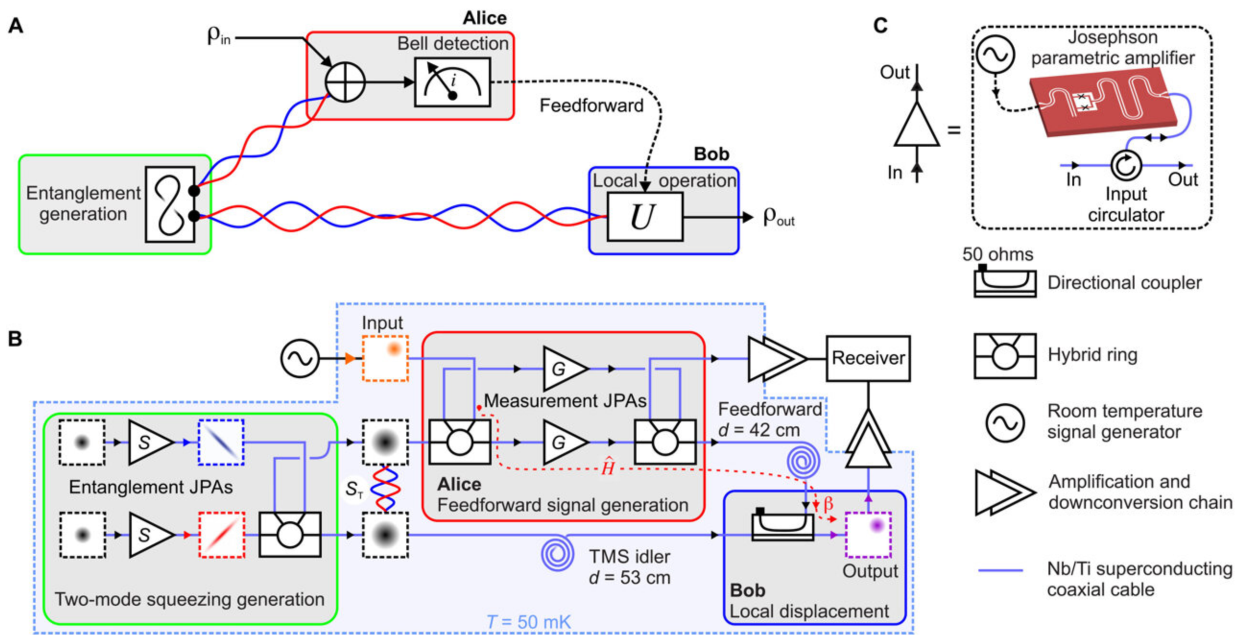
Experimental quantum teleportation of propagating microwaves

January 4 2022, by Thamarasee Jeewandara

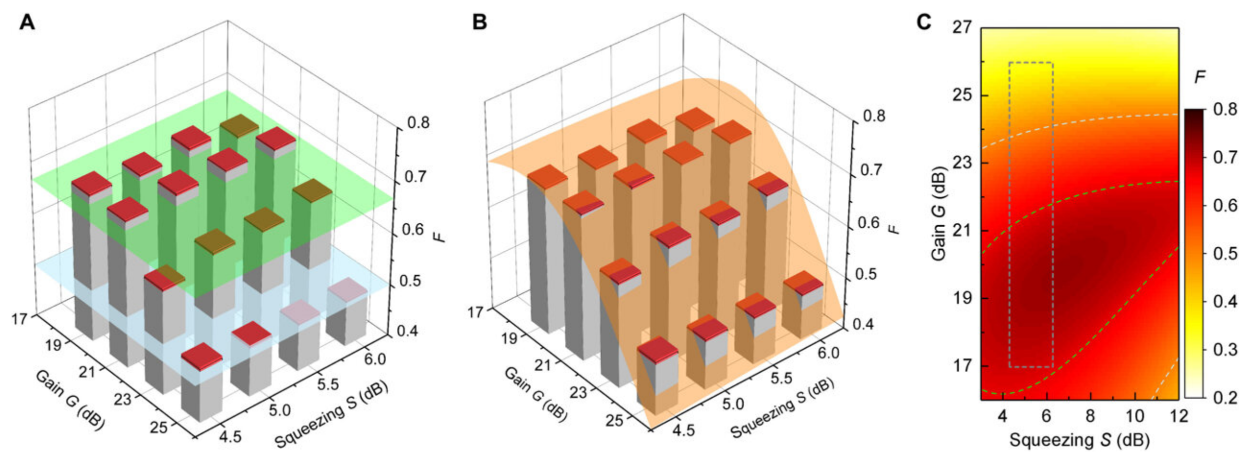


Quantum teleportation (QT) of propagating microwaves: concept and implementation. (A) General concept. (B) Our experimental implementation of QT with propagating quantum microwaves and analog feedforward (also see note S1 for the full technical schematics). Here, an unknown input coherent state is teleported from Alice to Bob by exploiting quantum entanglement characterized by the two-mode squeezing level ST ≲ S. The feedforward signal is generated by the measurement JPAs with the degenerate gain G, in combination with two hybrid rings and a local displacement operation on Bob's side. The latter is implemented with a directional coupler with the coupling β = −15 dB. Plots in dashed boxes represent quantum states in the quasi-probability Wigner phase space spanned by field quadratures p and q. Red dashed line marks a particular input signal path corresponding to operator Hˆ . (C) Details and labels of various experimental elements. Credit: *Science Advances*, DOI: 10.1126/sciadv.abk0891

The field of experimental quantum communication promises ways of efficient and unconditional secure information exchange in quantum states. The possibility of transferring quantum information forms a cornerstone of the emerging field of quantum communication and quantum computation. Recent breakthroughs in quantum computation with superconducting circuits trigger a demand for quantum communication channels between superconducting processors separated in space at microwave length frequencies. To pursue this goal, Kirill G. Fedorov, and a team of scientists in Germany, Finland and Japan demonstrated unconditional quantum teleportation to propagate coherent microwave states by exploring two-mode squeezing and analog feedforward across a distance of 0.42 m. The researchers achieved a teleportation fidelity of F= 0.689±0.004, which exceeded the asymptotic no-cloning threshold, preventing the use of classical error correction methods on quantum states. The quantum state of the teleported state was preserved to open the avenue towards unconditional security in microwave quantum communication.

Quantum teleportation (QT).

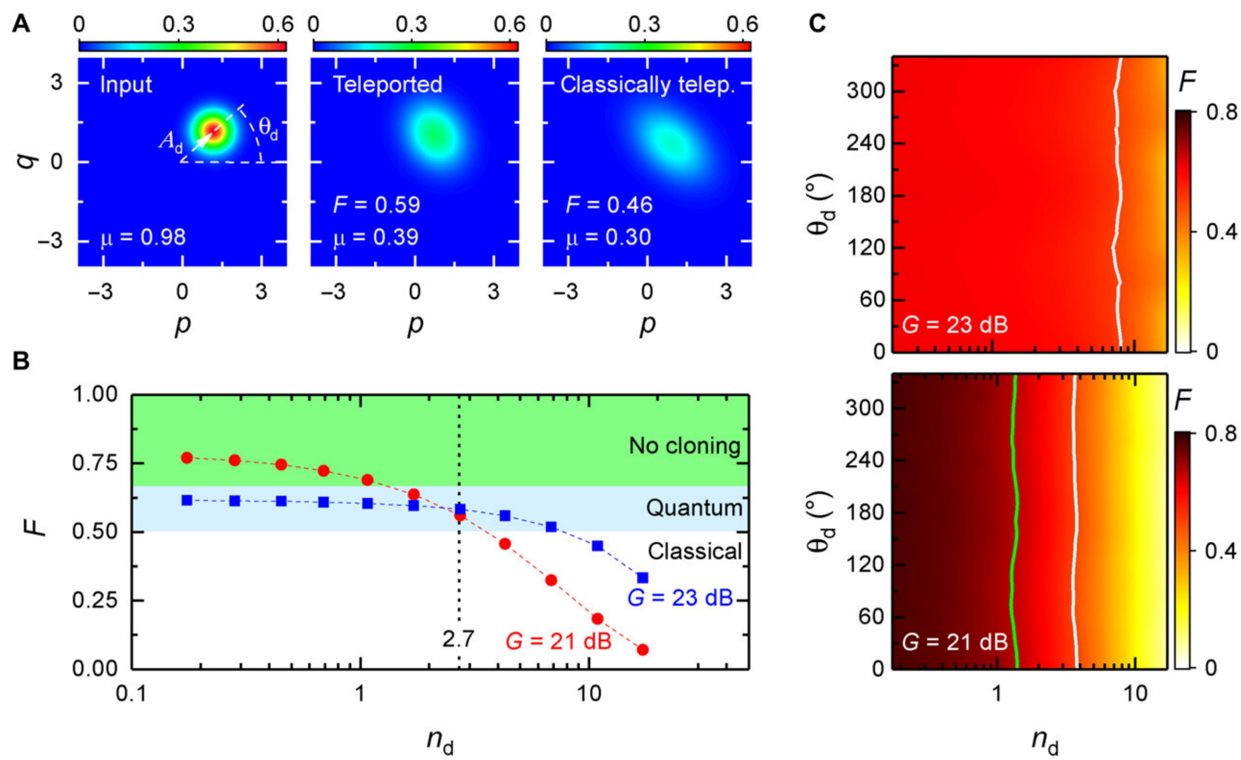
The promise of quantum communication is based on the delivery of efficient and unconditionally secure ways to exchange information by exploring the quantum laws of physics. Quantum teleportation (QT) is an exemplary protocol that stands out to allow the disembodied and safe transfer of unknown quantum states using quantum entanglement and classical communication as resources. Recent progress in quantum computation with superconducting circuits has led to quantum communication between spatially separated superconducting processes functioning at microwave length frequencies. Methods to achieve this communication task includes the propagation of [two-mode squeezed](#) (TMS) microwaves to entangle remote qubits and teleport microwave states to interface between remote superconducting systems. Fedorov et al. demonstrated the deterministic QT of coherent microwave states by exploring two-mode squeezing and analog feedforward across a distance of 0.42 m to provide a key feature for future microwave quantum local area networks and modular quantum computing.



Fidelity thresholds and theory model. (A) Experimental QT fidelities F as a function of the measurement gain G and squeezing S for nd = 1.1 photons. Red bars denote SD of the experimental data. Light blue plane corresponds to the fidelity threshold F = 0.5 between quantum and classical regimes, while green plane denotes the no-cloning limit Fnc = 2/3. The experimental data violate the no-cloning limit for G = 21 dB in the whole range of squeezing levels. (B) Same data with the fitted theory model (orange plane). (C) Extended view over the expected QT performance for the same model, where dark gray dashed box outlines the area presented in (B). This theory plot demonstrates that further improvement of teleportation fidelities requires an increase of both the measurement gain G and squeezing level S. Credit: *Science Advances*, doi: 10.1126/sciadv.abk0891

Transport of an unknown quantum state

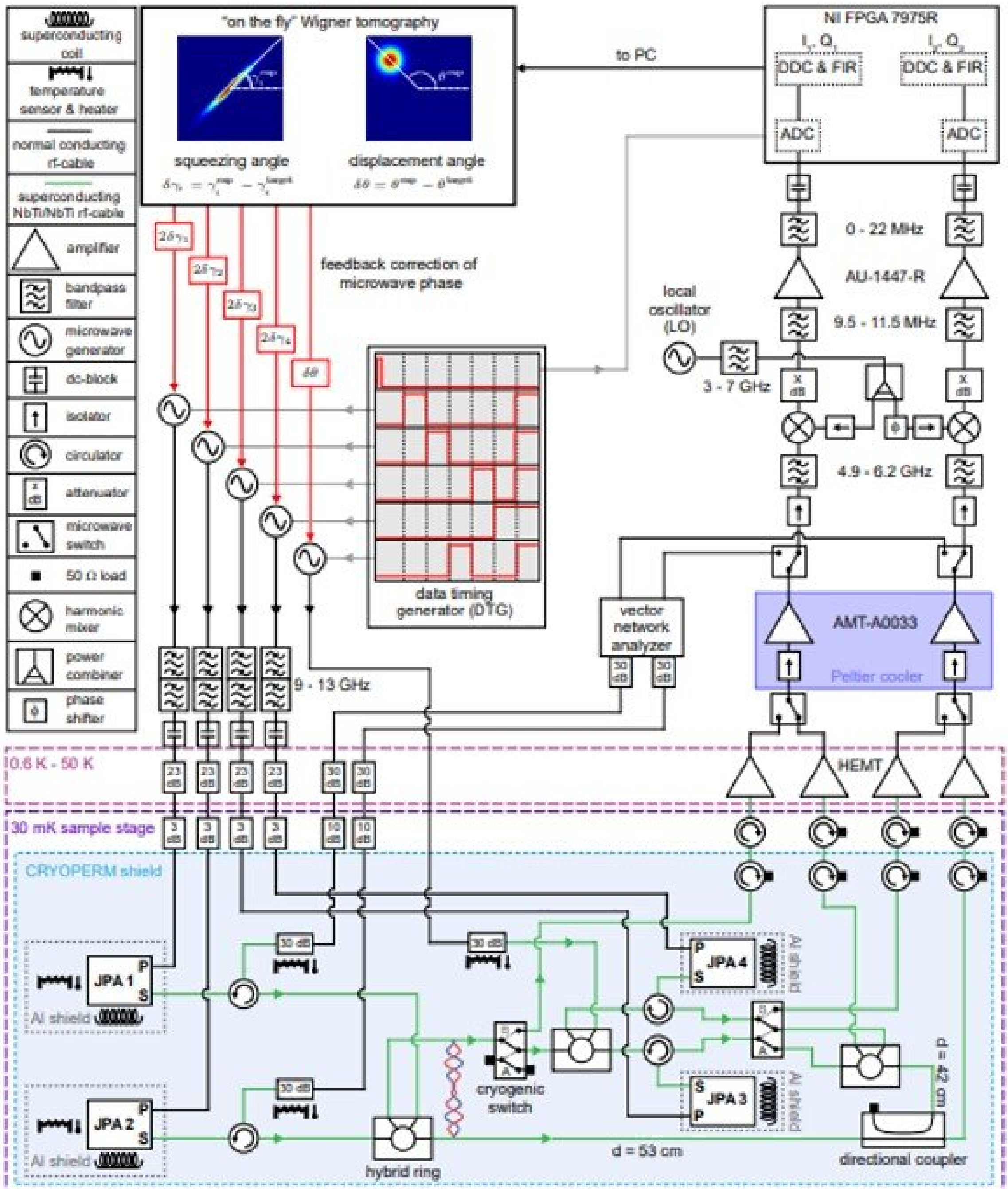
The process of quantum computing aims to achieve the classically impossible goal of transferring an unknown quantum state from one place to another without direct transfer. The task is typically quantified with a known teleportation fidelity to express the overlap in the phase space between an unknown input state and a teleported output state. By exceeding the classical fidelity threshold, researchers can thereby experiment transitions to the quantum realm via nonclassical correlations such as quantum entanglement. The precise value of the classical fidelity threshold is a subject of many scientific discussions depending on the teleported states and the respective Hilbert space dimension (the dimensional analysis of communication through a quantum channel). For instance, the value for a specific task of teleporting coherent quantum states that differs from the threshold for qubit states can be experimentally overcome with superconducting qubits. Furthermore, the teleportation of continuous-variable Gaussian states has many technical advantages compared with discrete variable states, where the experimental generation and control of weak coherent tones are significantly due to their origin from conventional microwave generators. Researchers can generate continuous-variable entangled states, in the form of two-mode squeezed light via weakly nonlinear superconducting devices including various Josephson parametric devices , to generate deterministic entanglement for higher communication bit rates compared to the frequently used non-deterministic entanglement generation schemes.



Tomography and fidelity measurements. (A) Reconstructed Wigner functions of an input state, teleported state, and classically teleported state for the squeezing level S = 4.5 dB, the displacement photon number of the input state nd = 2.7, and the measurement gain G = 23 dB. Inset values represent the QT fidelity F and purity μ. (B) Fidelity F as a function of nd for two characteristic values of G. Black dashed line marks the operating point illustrated in (A). The statistical error is smaller than the symbol size. (C) Fidelity F as a function of nd and displacement angle θd for two characteristic values of G. Light blue and green lines mark the classical and no-cloning limits, respectively. Credit: *Science Advances*, doi: 10.1126/sciadv.abk0891

Experimental protocol and setup

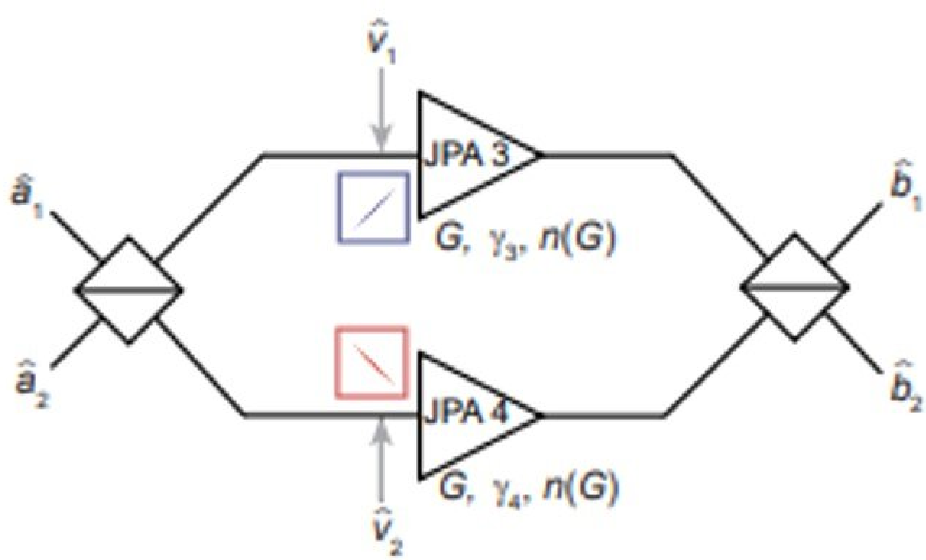
The experimental protocol of quantum teleportation contained several steps, including (1) entanglement generation and distribution between communication parties, usually named Alice and Bob. (2) Local operations on Alice's side aimed at generating a feedforward signal. (3) Feedforward and a local unitary operation on Bob's side, resulting in teleportation of the unknown quantum state by combining the feedforward signal with the entangled resource state. To accomplish this, Fedorov et al. used two entanglement Josephson parametric amplifiers (JPAs) in combination with a hybrid ring (microwave beam splitter) to generate path-entangled two-mode squeezed microwave states at the output of the hybrid ring. When superimposed at the hybrid ring, these states produced outputs that typically look like classical thermal noise. Due to the propagation of the two-mode squeezed states, they straightforwardly distributed the entangled states between Alice and Bob using superconducting niobium-titanium coaxial cables to implement step (1) of QT protocol, where the cables were shaped as half-wavelength waveguide resonators. On Alice's side, they used another hybrid ring to entangle a weak coherent state that served as the unknown input state with the shared two-mode squeezed state. The scientists guided the outputs of the second hybrid ring into a pair of measurement JPAs to perform strong phase-sensitive amplification along orthogonal amplification angles and superimposed the outputs of measurements at the third hybrid ring to produce the feedforward signal and conclude step (ii). During the final part of the QT protocol, the resulting feedforward application to Bob's part of the two-mode squeezed state implemented teleportation of the input state at the output of the directional coupler. This concluded step (iii) of the protocol.



Experimental scheme of microwave quantum teleportation protocol with propagating states. The two cryogenic switches allow for quantum teleportation (switch position A) or characterization measurements (switch position B). The intertwined lines between the outputs of the hybrid ring symbolize the entanglement. Credit: *Science Advances*, doi: 10.1126/sciadv.abk0891

Quantum teleportation (QT) measurements

The experimental results of the microwave QT protocol showed the corresponding quantum-teleported output states and classically teleported output states. Fedorov et al. defined classical teleportation as the identical QT protocol without an entangled resource available to the communicating parties (Alice and Bob), implemented by switching off the pump tones of entanglement Josephson Parametric Amplifiers (JPAs), while the rest of the experimental protocol remained unaltered. However, the teleportation of a specific coherent state was not sufficient for general purposes of quantum communication. It is also important to demonstrate the successful teleportation of a set of quantum states to form a communication alphabet or codebook, where the orthogonality of quantum states forming the communication codebook are not required.



Josephson mixer scheme. The frequency-degenerate Josephson mixer consists of JPA 3 and JPA 4 in combination with two symmetric microwave beam splitters to realize the Bell detection. Credit: *Science Advances*, doi: 10.1126/sciadv.abk0891

Outlook

In this way, Kirill G. Fedorov and colleagues succeeded to implement a quantum teleportation (QT) protocol with propagating microwaves in a cryogenic environment across a distance of 0.42 m. During the experiments, they relied exclusively on conventional aluminum-niobium superconducting parametric devices to generate and control quantum microwave signals that made them fully compatible with other quantum superconducting circuits, relative to frequencies and fabrication technology, including quantum memory cells or superconducting quantum processors. The QT results developed in the study combined with technical advances could bring quantum area networks between superconducting computers within reach. These experiments will pave the way in the convenient microwave regime toward superconducting quantum supercomputers to explore advantages of secure quantum communication.

More information: Kirill G. Fedorov et al, Experimental quantum teleportation of propagating microwaves, *Science Advances* (2021). DOI: 10.1126/sciadv.abk0891

Dik Bouwmeester et al, Experimental quantum teleportation, *Nature* (2002). DOI: 10.1038/37539