Optical-Microwave Entanglement Paves the Way for Distributed Quantum Computation

Zhi-Gang Hu(胡志刚)[1,2], Kai Xu(许凯)[1,2], Yu-Xiang Zhang(张玉祥)[1,2], and Bei-Bei Li(李贝贝)[1,3*]

[1]*Beijing National Laboratory for Condensed Matter Physics, and Institute of Physics, Chinese Academy of Sciences, Beijing 100190, China*
[2]*University of Chinese Academy of Sciences, Beijing 100049, China*
[3]*Songshan Lake Materials Laboratory, Dongguan 523808, China*

(Received 25 September 2023; accepted manuscript online 28 November 2023)

DOI: 10.1088/0256-307X/41/1/014203

Over the past few years, quantum computation based on superconducting circuits has achieved remarkable progress. A milestone occurred in 2019 when Google released *Sycamore*, a processor with 54 qubits, and claimed quantum supremacy by performing in just 100 s a specific computation which would take a classical supercomputer, as stated by Google's team, 10000 years to complete.[1] In 2021, a strong quantum advantage was demonstrated by Pan and his colleagues from the University of Science and Technology of China, using a quantum processor named *Zuchongzhi*, which has 66 functional qubits.[2] This year, the record of the number of quantum qubits has been lifted to 127 qubits.[3] Indeed, the number of qubits is limited to a few hundreds due to the finite space of dilution refrigerators, where the superconducting qubits must be placed to be isolated from thermal noise. However, this number is still several orders of magnitude away from the requirement of quantum error correction, which is essential for general-purpose quantum computers.[4–8]

To overcome this hurdle, networking small-size quantum processors that are cooled individually, i.e., distributed quantum computation, becomes an important avenue to a large-scale quantum computer. However, the superconducting qubits work in the microwave regime. Due to the large thermal noise of microwave photons at room temperature, transmitting faithfully the microwave photons carrying fragile quantum information to a distant node is extremely inefficient. Despite the absorption by the materials, maintaining the communication channel in a cryogenic environment is already technically challenging. In contrast, fiber-based communication in the optical regime is much more convenient. On the one hand, the energy scale of an optical photon is much higher than $k_{\mathrm{B}}T$ (with k_{B} and T being the Boltzmann constant and the temperature) at room temperature, rendering the thermal noise negligible. On the other hand, it is well known that photons at the wavelength of 1550 nm have minimal fiber loss. Therefore, bridging the gap between microwave and optical regimes is of great importance and has become a high-profile research topic.

One promising solution is to use a coherent quantum transducer, which aims at directly mapping an input microwave photon to an optical photon. Various strategies have been employed to realize quantum transducers, including those using the electro-optic effect,[9] atomic-optic interaction,[10] a combination of piezoelectric and optomechanical effects,[11,12] and the electro-optomechanical effect.[13] However, this deterministic transduction has demanding requirements in terms of conversion efficiency and added classical noise, which have yet to be fully met. If the conversion efficiency falls below the required threshold, deterministic state transfer becomes unachievable.[14]

Quantum teleportation, an important application of the non-local character of quantum entanglement, provides an alternative approach to quantum state transfer. As depicted in Fig. 1(a), suppose that a pair of particles denoted by A and B prepared in a Bell state have been distributed to Alice and Bob, respectively. Alice measures particle A and the input state jointly along the basis of four Bell states. Then she sends the measurement outcome to Bob through a classical communication channel. According to her message, Bob performs a unitary operation on particle B, the state of which is thus made exactly the same as the input state possessed by Alice. In this way, quantum state transfer is realized by transmitting the quantum information, rather than the matter carrying this information.[15] Quantum teleportation is not restricted only to two-level qubits or finite-level systems, and can also be extended to continuous variable systems which have an infinite-dimensional Hilbert space, for example, electromagnetic field modes described by position and momentum quadrature operators. In this case, the entangled resource shared by Alice and Bob can be a two-mode squeezed state, also known as the Einstein–Podolsky–Rosen (EPR) state.[16]

Nowadays, generating Bell states or the EPR state in the optical regime is more or less a lab routine.[17] Remarkably, in a recent work of Fink's group at the Institute of Science and Technology Austria, entangled pairs of optical photons at about 193 THz and microwave photons at about 9 GHz, with an energy gap of four orders of magnitude between them, has been successfully prepared[18] and verified in the continuous-variable domain. Such optical-microwave entanglement provides an elegant solution for a quantum network based on supercon-

*Corresponding author. Email: libeibei@iphy.ac.cn
© 2024 Chinese Physical Society and IOP Publishing Ltd

ducting circuits, in which distant superconducting qubits can communicate with each other by optical channels using this teleportation-based protocol: The role of particle A of Fig. 1(a) will be played by the microwave photon, which has the same frequency as the superconducting qubits so that efficient Bell state measurement is feasible; meanwhile, the optical photon playing the role of particle B is convenient for fiber-based long-distance communication. Moreover, such optical-microwave pairs can be used for establishing remote entanglement between two microwave photons via quantum repeaters.

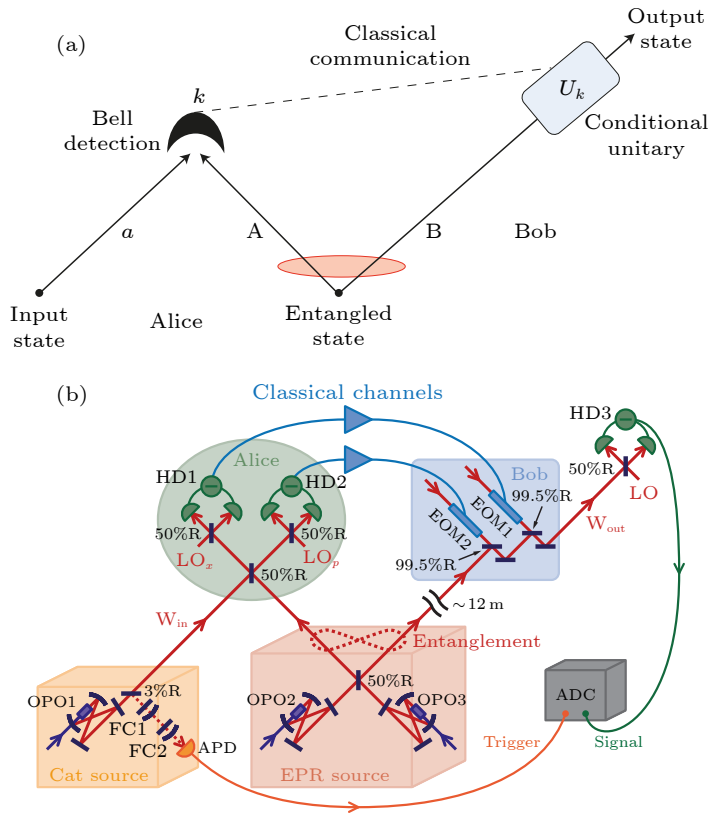

Fig. 1. (a) Basic protocol of quantum teleportation, (b) setup of a full continuous variable teleportation experiment with optical modes, taken from Refs. [15,17], respectively.

In comparison to quantum transducers, the quantum teleportation-based approach offers an advantage through the modularization of settings. Due to inherent imperfections, the distribution of standard remote entanglement is probabilistic, necessitating numerous repetitions and even entanglement distillation to establish perfect entanglement. The distribution of quantum entangled pairs can be implemented separately from the quantum computer that generates the input state. In contrast, transducers also operate probabilistically, but a failure would require repeating the entire quantum computing process itself.

In the work reported by Fink's group, a lithium niobate whispering gallery mode (WGM) optical microcavity with a diameter of 5 mm and a thickness of 150 µm was employed to achieve optical-microwave entanglement. To achieve a strong interaction between the optical and microwave modes, the microcavity was placed within an aluminum microwave cavity in a dilution refrigerator operating at 7 mK. The interaction between the two modes was mediated by the electro-optic effect, which allowed for frequency down-conversion and up-conversion through the conservation of energy and momentum. To optimize the coupling efficiency, the resonant frequency of the microwave mode was tuned to match the free spectral range (FSR) of the optical cavity, as depicted in Fig. 2(b). Figure 2(c) illustrates the pulse sequence used for entanglement generation and detection in a single experimental run. In this sequence, an optical pulse (pulse 1) with a pump power of 154 mW was applied at the frequency $\omega_{\rm p}$, which amplified the vacuum fluctuations in both the microwave and optical modes, thus generating spontaneous parametric down-conversion signals where the entanglement between the optical and microwave fields occurred. After a delay of one microsecond, a second optical pump with about one-tenth power was applied, along with a coherent microwave pulse at the frequency $\omega_{\rm e}$. The output optical and microwave signals were filtered or amplified respectively before they were down-converted with two local oscillators for heterodyne measurement. Note that the second optical pump together with the microwave drive was used for phase-alignment between the two local oscillators. The microwave pulse can stimulate the optical pump to down-convert, producing a coherent pulse in the optical mode $\hat{a}_{\rm o}$, which was used to extract slow local oscillator phase drifts in each experimental run.

The optical-microwave entanglement was verified in the continuous-variable domain using dimensionless quadrature pairs X_j and P_j (where $j = {\rm o}$ and e denote

optical and microwave fields, respectively) instead of the single photon basis, to show that the entanglement was established deterministically. Researchers performed joint heterodyne measurements to obtain these four quadrature components of both the optical and microwave photons for each frequency, between which the correlations can be calculated to obtain the covariance matrix $V_{ij} = \langle \delta u_i \delta u_j + \delta u_j \delta u_i \rangle / 2$, where $\delta u_i = u_i - \langle u_i \rangle$ and $u \in \{X_e, P_e, X_o, P_o\}$. Figure 2(d) displays the results of the covariance matrix for $\omega_p = \omega_o + \omega_e$ based on about one million measurements, where the nonzero off-diagonal elements indicate the non-local correlations between the two propagating modes. Further, the quasiprobability Wigner function was calculated from the measured covariance matrix to obtain an intuitive visualization of the two-mode squeezing. The entanglement was finally verified according to the Duan–Simon criteria,[19,20] by illustrating that the two-mode squeezing is below the vacuum level, i.e., $\Delta^-_{\rm EPR} = \bar{V}_{11} + \bar{V}_{33} - 2\bar{V}_{13} < 1$. The value of $\Delta^-_{\rm EPR}$ shown in Fig. 2(e) breaks the classical limit ($\Delta^-_{\rm EPR} = 1$) by $> 5\sigma$, demonstrating that the output optical and microwave photons were indeed entangled, with a bandwidth close to the effective microwave linewidth.

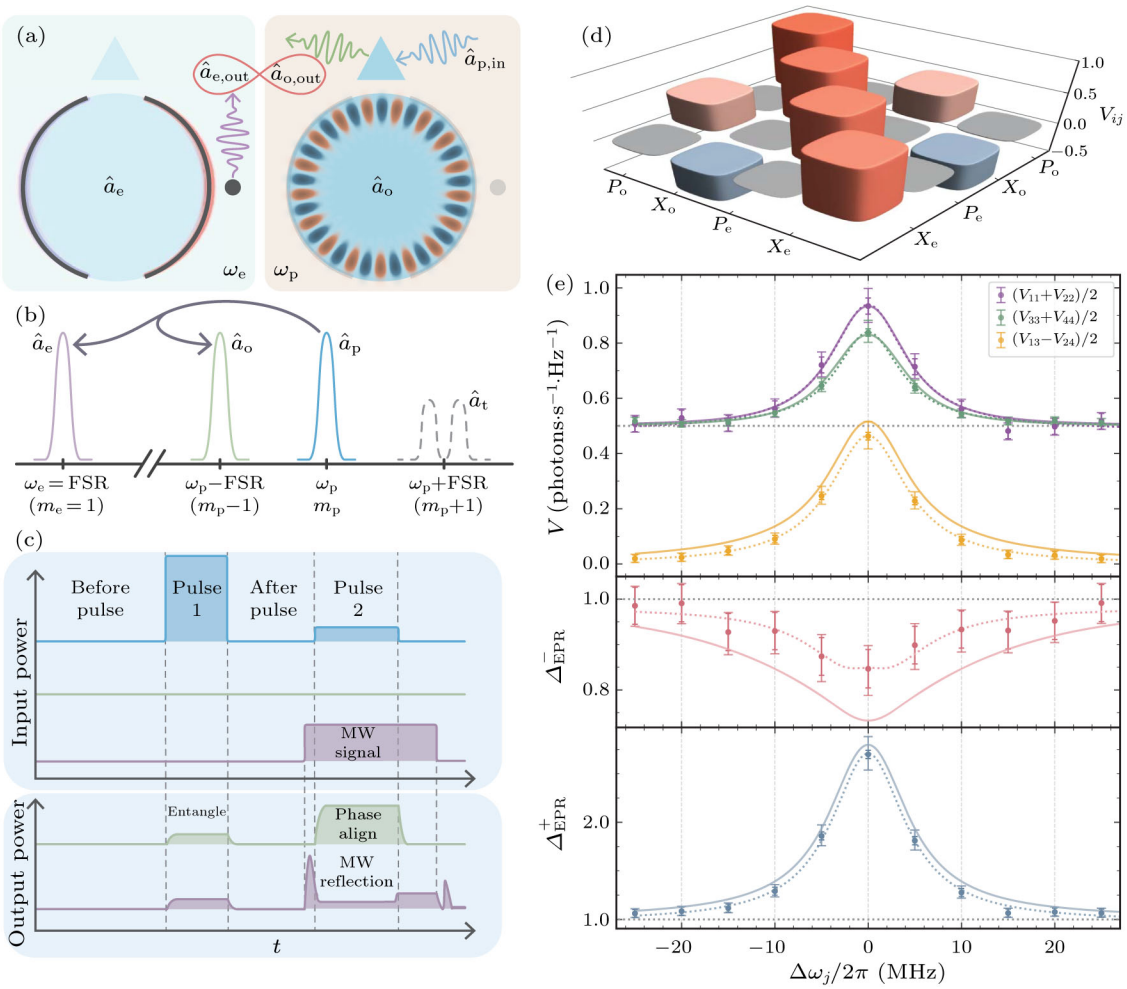

Fig. 2. (a) Simulated microwave (left) and optical (right) mode field distribution. (b) Sketch of the density of states of the relevant modes. (c) Schematic time sequence of a single measurement. (d) Measured covariance matrix V_{ij} in its standard form. (e) Top panel, measured average microwave output noise $\bar{V}_{11} = (V_{11} + V_{22})/2$ (purple), average optical output noise $\bar{V}_{33} = (V_{33} + V_{44})/2$ (green), and $\bar{V}_{13} = (V_{13} - V_{24})/2$ (yellow) as a function of measurement detunings. The middle (bottom) panel denotes the two-mode squeezing (anti-squeezing) in red (blue) calculated from the top panels as $\Delta^{\pm}_{\rm EPR} = \bar{V}_{11} + \bar{V}_{33} \pm 2\bar{V}_{13}$. Taken from Ref. [18].

In conclusion, the Fink group has achieved deterministic quantum entanglement between propagating optical and microwave photons, through a parametric down-conversion process using a lithium niobate electro-optic microcavity. The achieved entanglement rate of 0.11 ebits/200 ns-long pulse in the experiment is in practice limited by the low pulse repetition rate. The entanglement rate can be further improved by increasing the quality factors of the optical and microwave cavities and the electro-optic coupling efficiency. Coupling efficiency improvements will also allow for higher levels of two-mode squeezing and facilitate deterministic entanglement distribution schemes to qubits, teleportation-based state transfer, and quantum-enhanced remote sensing. This is a very promising way to realize distributed quantum computation and thus to scale up superconducting qubits for general-purpose quantum networks. This achievement not only paves the way for entanglement between superconduct-

ing circuits and telecom wavelength light, but also has a wide range of applications for hybrid quantum networks in the context of modularization, scaling, sensing, and cross-platform verification.

Acknowledgments. The authors thank Gang-Qin Liu for useful discussions and acknowledge funding support from the National Natural Science Foundation of China (Gant Nos. 62222515 and 12174438), the Basic Frontier Science Research Program of Chinese Academy of Sciences (Gant No. ZDBS-LY-JSC003), and CAS Project for Young Scientists in Basic Research (Gant No. YSBR-100).

References

[1] Arute F, Arya K, Babbush R, Bacon D, Bardin J C, Barends R, Biswas R, Boixo S, Brandao F G S L, and Buell D A 2019 *Nature* **574** 505
[2] Wu Y L, Bao W S, Cao S R, Chen F, Chen M C, Chen X, Chung T H, Deng H, Du Y, and Fan D 2021 *Phys. Rev. Lett.* **127** 180501
[3] Kim Y, Eddins A, Anand S, Wei K X, van den Berg E, Rosenblatt S, Nayfeh H, Wu Y, Zaletel M, Temme K, and Kandala A 2023 *Nature* **618** 500
[4] Shi Y H, Yang R Q, Xiang Z C, Ge Z Y, Li H, Wang Y Y, Huang K, Tian Y, Song X H, Zheng D G, Xu K, Cai R G, and Fan H 2023 *Nat. Commun.* **14** 3263
[5] Clarke J and Wilhelm F K 2008 *Nature* **453** 1031
[6] Fan H 2023 *Chin. Phys. Lett.* **40** 070305
[7] Pan X Z, Song P T, and Gao Y Y 2023 *Chin. Phys. Lett.* **40** 110303
[8] Xu S B, Sun Z Z, Wang K *et al.* 2023 *Chin. Phys. Lett.* **40** 060301
[9] Hease W, Rueda A, Sahu R, Wulf M, Arnold G, Schwefel H G L, and Fink J M 2020 *PRX Quantum* **1** 020315
[10] Kumar A, Suleymanzade A, Stone M, Taneja L, Anferov A, Schuster D I, and Simon J 2023 *Nature* **615** 614
[11] Hönl S, Popoff Y, Caimi D, Beccari A, Kippenberg T J, and Seidler P 2022 *Nat. Commun.* **13** 2065
[12] Jiang W T, Sarabalis C J, Dahmani Y D, Patel R N, Mayor F M, McKenna T P, van Laer R, and Safavi-Naeini A H 2020 *Nat. Commun.* **11** 1166
[13] Andrews R W, Peterson R W, Purdy T P, Cicak K, Simmonds R W, Regal C A, and Lehnert K W 2014 *Nat. Phys.* **10** 321
[14] Wu J, Cui C, Fan L, and Zhuang Q 2021 *Phys. Rev. Appl.* **16** 064044
[15] Pirandola S, Eisert J, Weedbrook C, Furusawa A, and Braunstein S L 2015 *Nat. Photon.* **9** 641
[16] Braunstein S L and Loock P V 2005 *Rev. Mod. Phys.* **77** 513
[17] Lee N, Benichi H, Takeno Y S, Takeda S, Webb J, Huntington E, and Furusawa A 2011 *Science* **332** 330
[18] Sahu R, Qiu L, Hease W, Arnold G, Minoguchi Y, Rabl P, and Fink J M 2023 *Science* **380** 718
[19] Duan L M, Giedke G, Cirac J I, and Zoller P 2000 *Phys. Rev. Lett.* **84** 2722
[20] Simon R 2000 *Phys. Rev. Lett.* **84** 2726