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Chip-to-Chip High-Dimensional Teleportation via A Quantum Autoencoder

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Abstract

Quantum teleportation transfers unknown quantum states from one node in a quantum network to another. It is one of the crucial architectures in quantum information processing. The teleportation of high-dimensional quantum states remains challenging due to the difficulties in executing high-dimensional Bell state measurement. Here, we propose a Quantum Autoencoder-Facilitated Teleportation (QAFT) protocol for high-dimensional quantum teleportation, and report the first demonstration of QAFT on qutrits using an integrated photonic platform for future scalability. The key strategy is to reduce the dimension of the input states by erasing redundant information and reconstruct its initial state after chip-to-chip teleportation. Machine learning is applied in training the autoencoder to facilitate the teleportation of any state from a particular high-dimensional subspace and achieve the reconstruction of the unknown state (by the decoder) with high fidelities (~ 0.971). Experimentally, we teleport unknown qutrits by generating, transferring and manipulating photons, and training quantum autoencoders on a silicon chip. A teleportation fidelity of ~ 0.894 is demonstrated. Our scheme opens pathway towards quantum internet and cryptography to transfer unmeasured states in a quantum computer. It also lays the groundwork for machine learning technologies in quantum networks and quantum computations.

Introduction

Data compression is a ubiquitous processing that we use daily to transfer large audio and video files. Autoencoder serves as an efficient means for large dataset compression^{1,2}, by learning an encoder map from an input data to a latent space and a decoder map from the latent space to the input space, over a training set. Moving to the quantum regime, there are some fundamental differences between classical and quantum information. The amount of information that one can extract from a classical system matches the amount of information needed for a complete description of the state of the system. However, in a quantum system, the complete description of a quantum state strictly requires an infinite amount of information. Nevertheless, one can devise quantum compression protocol based on Schur-Weyl transformation³. The quantum autoencoder⁴⁻⁷ is also proposed to efficiently compress a particular dataset of quantum states using machine learning, and its concept has been demonstrated using bulk optics^{8,9}.

Through data compression, quantum autoencoder can become a useful tool for transferring high-dimensional quantum information between remote parties (*e.g.*, chip-to-chip teleportation), reducing the quantum memory, quantum communication channels and the size of quantum gates. Quantum teleportation¹⁰⁻¹² is a crucial protocol for the physical implementation of many quantum communication and quantum computation schemes, including quantum relays¹³, quantum repeaters¹⁴ and linear optics quantum computing^{15,16}. Quantum teleportation enables the moving of a qubit from one place to another without the real need to physically transport the underlying particle where the qubit is attached. To date, quantum teleportation has been experimentally generalized by different physical systems such as photons¹⁷⁻²³, optical coherent states²⁴, atoms²⁵⁻²⁸ and nuclear magnetic states²⁹. However, most controllable teleportation schemes only consider two-dimensional quantum systems, and the teleportation of high-dimensional quantum states still remains challenging.

Bennett et al.¹⁰ first proposed to realize the teleportation of an unknown d -dimensional state by replacing the maximally entangled state of two qubits with that of two entangled qudits, and by replacing the Bell measurement with a generalized measurement involving a set of maximally entangled orthonormal or mutually unbiased bases. Besides the difficulty in generating high-quality qudit entanglement³⁰⁻³⁴, the proposal faces a major obstacle in implementing high-dimensional Bell State measurement (high-D BSM). Due

to the linear optical limitation³⁵, the d^2 Bell states in a complete orthonormal basis cannot be identified, except for $d = 2$. Several theoretical approaches have been developed³⁶⁻³⁹. Recently, two experiments (not integrated) were reported^{40, 41} to teleport a qutrit-by-path. By adopting ancillary photons, Luo et al.⁴⁰ observe specific click patterns of three interfering photons that indicate successful projections into one of the 9 Bell states, at a success probability of 1/81; Hu et al.⁴¹ observe the coincidence events of six photons and use non-maximally entangled state, achieving a success probability of 1/18. Both works exhibit high quality of their proposals, though some concerns present in their scalability, *i.e.*, for a d -dimensional system, they require $(d - 2)$ ancillary photons and $\lceil \log_2(d) - 1 \rceil$ pairs of ancillary photons, respectively. The increment of dimensionality would result in the demand for more ancillary photons, and a decline of success probability.

Here, we propose a quantum-autoencoder-facilitated teleportation (QAFT) protocol, which automatically compresses the high-dimensional quantum states into qubits, further teleports and decodes them at the receiver's end. This protocol does not require ancillary photons and has a success probability of 1/2. We report, for the first time, a silicon photonic chip implementation of quantum autoencoder, and the complete integration and demonstration of QAFT on qutrits. The generation, teleportation and measurement of photon states, as well as the training of encoder are all performed on the silicon chip. Unlike previous universal schemes, our protocol requires separate encoders for separate subspaces. Nevertheless, we are capable of training a universal encoder for any particular subspace of qutrits by taking a finite sample of these qutrits randomly and learning to compress them into qubits. During training, single-shot measurement is carried out to ensure that no qutrit is copied or measured twice. The quantum autoencoder achieves almost lossless compression on the qutrit to qubit, with a reconstruction fidelity of ~ 0.971 . After training, we can teleport any further states and reconstruct them at the receiver chip. A high teleportation fidelity of ~ 0.894 between the input qutrit and the teleported qutrit is achieved. The integrated silicon photonics technology endows the implementation of QAFT with high stability and easier scalability. Our scheme will come in handy for quantum internet, cryptography and transferring quantum states by reducing the requirements on quantum memory, quantum communication channels and the size of quantum gates.

The QAFT Protocol and Chip Design

The overarching idea of QAFT is that by training an autoencoder, the input states can be compressed into qubits, teleported, and reconstructed by the decoder as shown in **Figure 1a**. The transmitter and the receiver each hold half of an Einstein–Podolsky–Rosen (EPR) pair. At the transmitter, the initial qutrit is compressed into qubit by the trained encoder, and the BSM is performed. Depending on the result of BSM and the settings of encoder, the receiver will set up the decoder and reconstruct the initial qutrit from the teleported qubit. The training of the autoencoder is crucial to the success of teleportation.

Figure 1b depicts the multi-photon multi-qubit chip, fabricated using the integrated silicon photonics technology, which has manifest itself as a versatile paradigm for quantum information processing and communications^{42–44}. This chip is comprised of two sub-chips with different functions, *i.e.*, the transmitter chip and the receiver chip, which are coherently linked by a 10-m single-mode fiber, by converting path-encoded qubits to polarization-encoded qubits. The transmitter chip consists of a multi-photon generator, an EPR pair generator, an encoder of the quantum autoencoder, and a Bell projector for BSM, all of which are individually controllable and programmable. A single-wavelength pump light is divided and injected into three silicon spiral sources to produce three pairs of signal photons (λ_s) and idler photon (λ_i) photons, via the spontaneous four wave mixing. Asymmetric Mach-Zehnder interferometers (AMZIs) are applied in each pair of photon generation structure, one to filter the pump light and the other to separate the signal and idler photons (see transmission spectra in Fig. S3). The top two pairs of photons in Fig. 1b are encoded as dual-rail qubits. The two signal photons become one qubit, and two idler photons become the other by passing the crossing structure. The two qubits are maximally entangled in the form of Bell state $|\phi^+\rangle$ with fidelities of 0.960 ± 0.004 (see Fig. S3e), of which one qubit is held by the transmitter and the other is held by the receiver. The idler photon of the bottom pair is used to generate a path-encoded qutrit using the linear optical quantum circuit and its signal photon is used for heralding in measurement. The qutrit is compressed by a well-trained encoder. At the transmitter, a Bell state measurement of the EPR qubit and the teleported qubit is performed, yielding one of the four measurement outcomes, which is actually one of the two possible measurement outcomes $|\phi^+\rangle$ and $|\phi^-\rangle$ in our design, while $|\varphi^+\rangle$ and $|\varphi^-\rangle$ are indistinguishable by the measurement results. The

key component is the reprogrammable two-qubit operator, which entangles two qubits (previously never interacted) in Bell projection. The measurement results can be encoded by two classical bits of information.

The EPR qubit is transmitted along a long distance to the receiver chip through the polarization rotator and splitter (PRS) that converts the path state in waveguide to the horizontal (vertical) state in optical fiber (see Supplementary Note 6). The two-bit BSM results, and the encoder settings are transmitted from the transmitter chip to the receiver chip through classical information channel. The EPR qubit held by the receiver will be identical to the teleportee qubit if the BSM result is $|\phi^+\rangle$. Alternatively, it can be fixed up if the BSM result is $|\phi^-\rangle$. Once the qubit is teleported, the decoder integrated on the receiver chip will reconstruct it to the initial qutrit. As the encoder is a unitary transformation, the decoder, which is integrated in the receiver chip, is set up as the inverse of the encoder. The false-colour micrograph of the fabricated chip is shown in **Figure 1c**, in which the transmitter and receiver are integrated onto a single chip that form as a *teleportation transceiver*. If two transceiver chips perform two-way communication, then each transceiver chip can either transmit or receive qubit to the other transceiver chip. The input single pump light is coupled into the chip by a one-dimensional subwavelength grating coupler, as well as the inline monitors on the chip. Output photons are transported to the connecting fibres by the polarization-independent edge couplers, and then detected off-chip by six superconducting single-photon detectors (D1-D6, ~ 0.85 efficiency). Details on the device and setup are provided in Supplementary Note 3.

Implementation of the trainable quantum autoencoder. A quantum autoencoder is employed to compress the quantum state from d -dimension to n -dimension ($d > n$). We implement an efficient autoencoder that reduces qutrits to qubits ($d = 3$ to $n = 2$) with its graphical representation shown in **Figure 2a**. The basic architecture of the autoencoder is shown in **Figure 2b**, which consists of an encoder (E) for compression and a decoder (D) for reconstruction. The encoder is trained by minimizing the occupation probability of the trash mode, retaining all information on qubits modes. Lossless compression is achieved when the trash state is unoccupied, and the initial qutrit can be reconstructed by the decoder. The parameters of the encoder are updated by machine learning algorithms.

Figure 2c depicts the quantum circuit of the autoencoder and our training system. The circuit realizes the functionalities of qutrit generator, encoder (decoder) and quantum state tomography. The qutrit generator produces arbitrary qutrits by programming three optical paths of the input photon using the three linked MZIs with 5 free parameters (θ_{1-2} and ϕ_{1-3}). The trainable encoder can be represented by a unitary matrix that has 8 free parameters (α_{1-3} , θ_{4-6} and ϕ_{4-5}). The on-chip encoder shows a high stability and endows us a simple way of controlling the unitary transformation by modulating the electrical powers of integrated heaters. Given that the encoder is unitary, the decoder is simply the inverse of the encoder. Quantum state tomography (QST) can be versatily applied on input qutrits or reconstructed qutrits to validate the entire process.

An evolutionary optimization algorithm is utilized to iteratively update parameters of the encoder, aiming to compress a subspace of qutrits. Given a training qutrit, the encoder can compress the qutrit into a qubit (that is pending for teleportation), while leaving the trash mode unoccupied. Any probability of finding photons in the trash mode implies an imperfect compression and will result in the failure to reconstruct the initial qutrit when the trash mode is discarded. The photon occupancy is estimated over a series of arbitrary input qutrits via single-shot measurement, *i.e.*, any qutrit will not be copied or sent twice, and the training algorithm will never measure the same qutrit twice because, practically, the qutrit generator does not know what state it produces and the sequence of output states. After training, any further states can be teleported and reconstructed at the receiver's end.

Results and Discussions

Training of quantum autoencoder with single-shot measurements. **Figure 3a** shows the flow chart of the training process. The main components are the individually controllable photon activator, qutrit generator (θ_{1-2} and ϕ_{1-3}) and trainable encoder (α_{1-3} , θ_{4-6} and ϕ_{4-5}). Random qutrits are generated by a rotation matrix that maps random qubits to qutrits such that they belong to the same subspace and can be compressed by a common encoder. An evolutionary genetic algorithm is adopted to update the free parameters of the unitary encoder iteratively. The training starts from the population initialization. Each population has 20 individuals, and each individual $\vec{P}_k = (I_1, I_2, \dots, I_8)$ is composed of 8 free parameters, which are the electrical currents applied on the 8 phase

shifters, forming arbitrary unitary matrices. As an example, when the $\overrightarrow{P_1}$ in the initial population is applied to the encoder, a random qutrit will be generated at once for the evaluation of this individual. A total of 50 random qutrits are used to estimate the photon occupancy with each qutrit measured only once. Each time after generating and measuring a qutrit, we will randomize the qutrit generator such that the next qutrit is a different random qutrit. The trash mode of the encoder is monitored by the counting logic, which outputs the required time (*i.e.*, Δt) until the first click observed at the trash mode, which is inversely proportional to its photon occupancy (longer Δt leads to lower photon occupancy). If Δt is as long as the time required to detect the dark noise (which is denoted as $T = 10^{10}$ ps), we can regard the photon occupancy of the trash mode as close to zero. Accordingly, we design the fitness function of the genetic algorithm as $f \propto 1 - e^{1-\Delta t/T}$, and the training objective as $f \rightarrow 0$. So far, the fitness evaluation of the individual $\overrightarrow{P_1}$ is achieved. Subsequently, the same process is repeated for the remaining individuals in current population. If the fitness values satisfy the stopping criteria, the best individual in current population is returned as the optimal solution. Otherwise, the algorithm continues and the individuals in current population are transformed by the genetic operators (*i.e.*, selection, crossover, and mutation) to generate the offspring (a population of 20 new individuals). The offspring will be re-evaluated until the algorithm converges.

Figure 3b shows the timing diagram of the counting logic. Two signal channels, a laser channel and a photon channel (monitored at the trash mode) are connected to the counting logic. We create a gate that starts at one of the laser pulses with a period of 10^{10} ps, which is the minimum required time to detect the dark noise. If no photon signal is detected during this period, the photon signal is regarded as a dark noise. The gated stream in recording is composed of clicks in both laser channel and photon channel. The output of the time tagger is the time difference between the first photon click and the first laser click, *i.e.*, $\Delta t = t_{\text{photon}} - t_{\text{laser}}$. The photon clicks after the first click will be discarded. If a photon click appears before the first laser click, the photon will also be discarded.

Figures 3c-3g report the results of training the quantum autoencoder under single shot measurements. **Figure 3c** shows the evolution of the time spent until the first click is observed in the trash mode, showing that the time for the beginning-generation individuals to get the first click is usually very short. The final generation spends much longer time,

mostly approaching 10^{10} ps, which is the count level of the dark noise. The box plot in Figure 3d shows the statistics of time spent in each generation until the first click. On each box, the central mark indicates the median, and the bottom and top edges of the box indicate the 25th and 75th percentiles, respectively. Occasionally, a good individual appears in an early generation, but we do not regard this as “convergence”. For example, the first good individual (*i.e.*, $\Delta t \approx \Delta t_{\text{dark noise}}$) is observed around the 10th generation. However, most of other individuals cannot meet this level, showing large statistical fluctuations. On the contrary, in the final convergence, the variations of the time spent by each individual is greatly reduced, whereby we consider a convergence is reached. **Figure 3e** shows the evolution of the best fitness value and average fitness value within each generation. The fitness value approaches 0 when Δt approaches $\Delta t_{\text{dark noise}}$. The fitness value of the final best encoder is 0.016, and the average fitness of the final population is 0.082. The contrast of the initial and the final generation with regard to the time spent until the first click and the fitness values are shown in **Figures 3f** and **3g**, respectively. The statistic information of the 20 individuals in the initial and the final generation is shown in **Figure 3h**. Most individuals in the final generation have almost the same current value, with a standard deviation of 0.016 mA, implying a high-quality convergence. With the trained encoder, random qutrits are sent over for compression. Different encoders can be trained for different subspaces, through the same training process that relies on a finite number of training samples (see Fig. S2). As seen from the tomography results of the initial qutrits and the compressed states (Fig. S2), the device achieves a high-quality compression from initial qutrits to the compressed states, reducing the occupation probability of the trash mode to 0.023 ± 0.011 . When we reconstruct the qutrit by using the decoder (*i.e.*, the inverse of the trained encoder), the fidelity $F = \langle \varphi | \rho | \varphi \rangle$ between the initial qutrit $|\varphi\rangle$ and the reconstructed density matrix ρ is reported to be 0.971 ± 0.013 .

Bell Projection and teleportation of qutrits. In the teleportation protocol, an unknown quantum state can be transmitted to another location by locally collapsing the state and remotely reconstructing it. This requires the access to Bell states and Bell measurements. A Bell projector is employed to entangle initially separable qubits and measure qubits in the Bell basis. The schematic diagram for the Bell projector devised for dual-rail qubits is

depicted in **Figure 1b** (and Fig. S8). We denote the three generated photons from top to bottom as “the 1st qubit”, “the 2nd qubit”, and “the 3rd qubit”, and denote the four detectors of the BSM from top to bottom as “D1”, “D2”, “D3” and “D4”. By deliberately designing the circuitry, $\hat{O}_{Bell}$ can distinguish the Bell states $|\phi\rangle^\pm$ from the others, as shown in **Table S1**. We distinguish $|\phi\rangle^+$ when observing joint clicks in $\{D_1, D_2\}$ or $\{D_3, D_4\}$ and distinguish $|\phi\rangle^-$ when observing joint clicks in $\{D_2, D_3\}$ or $\{D_1, D_4\}$.

Chip-to-chip teleportation is implemented while ensuring the preservation of coherent teleportation between two chips. The $|\phi\rangle_{1,2}^+$ is created on the transmitter chip, and the 1st qubit is distributed to the receiver chip via a 10-m optical fiber. The $\hat{O}_{Bell}$ measurement is performed at the 2nd qubit and the 3rd qubit, projecting the state into the $|\phi\rangle^+$ basis. This process achieves the teleportation of the 3rd qubit’s state to the 1st qubit. We remark that the states of the entangled channel after distribution remain highly coherent with negligible degradation of fidelity. $\hat{O}_{Bell}$ is carried out on the transmitter chip. We first validate the chip-to-chip teleportation by implementing teleportation of several single qubit states (*i.e.*, $|H\rangle, |V\rangle, |D\rangle, |A\rangle, |R\rangle, |L\rangle$) between the transmitter and receiver chips and show the experimental data in **Figure 4a**. The quantum state tomography on the teleported qubits reports average fidelities of $\bar{F}_1 = 0.914 \pm 0.022$. This high fidelity manifests the feasibility of the chip in achieving chip-to-chip teleportation.

Finally, we demonstrate the QAFT with the chip-to-chip teleportation by teleporting several randomly generated qutrits. The initial arbitrarily prepared qutrit is compressed by a well-trained encoder to a qubit, and the qubit is teleported from the 3rd qubit to the 1st qubit. Then, at the receiver chip, the teleported 1st qubit is reconstructed to the qutrit by the decoder. The decoder is built based on the encoder, whereby the information of which is classically transmitted from the transmitter chip to the receiver chip. The mean fidelity between the density matrices of the initial qutrit and the transported qutrit is $\bar{F}_2 = 0.894 \pm 0.026$ as shown in **Figure 4b**. One of the reasons of the degradation in the teleportation fidelity from $\bar{F}_1$ to $\bar{F}_2$ can be attributed to the reconstruction ability of the encoder. Nevertheless, the high fidelity proves that the QAFT can successfully compress the input qutrits using a trained encoder and reconstruct them through the decoder after a long-distance teleportation.

Conclusion

We propose and demonstrate a QAFT protocol on a silicon photonic quantum chip that teleports arbitrarily generated qutrits by training a quantum autoencoder that compresses the input qutrits to qubits. The proposal is generic, and it is possible to extend the scheme to higher dimensions. The generation, teleportation and measurement of photon states, as well as the training of encoder are all performed on a single silicon chip. The encoder is trained by minimizing the photon occupancy of the trash mode. During training, the qutrits are arbitrarily generated from a subspace, and each qutrit undergoes only a single measurement. After the training, the encoder achieves almost lossless compression from the qutrit to qubit, with a reconstruction fidelity of ~ 0.971 . Different encoders can be trained for qutrit from different subspaces. The transmitter chip and receiver chip are coherently linked using path-polarization conversion techniques. After teleportation, the initial qutrit is reconstructed from the teleported qubit by the decoder (which is set up as the inverse of the encoder) at the receiver chip. A teleportation fidelity of ~ 0.894 is achieved between the initial input qutrit and the teleported qutrit. The quantum autoencoder that allows data compression is beneficial to quantum communication, by reducing the requirements on quantum memory, quantum communication channels and the size of quantum gates. Our scheme uses an autoencoder for the teleportation of quantum states: it will come in handy for quantum internet, cryptography and transfer quantum computer states. Our work also paves way for an interdisciplinary quantum machine learning⁴⁵ and large-scale integrated photonic quantum technology⁴⁶ for the quantum communication and quantum computing with high complexities.

Methods

Experimental setup. The chip is wire-bonded to a printed circuit board, providing independent control of each phase shifter by an electronic current driver with 1-kHz frequency and 12-bit resolution (QontrolTM). Laser pulses are generated by an Ultrafast Optical Clock device (PtiTel) with a repetition rate of 500 MHz, central wavelength of

1550.12 nm and bandwidth of 2 nm. The laser pulses are amplified by an Erbium-doped fibre amplifier and filtered off chip via a wavelength-division multiplexer (WDM, > 100 dB extinction ratio, 0.8 nm bandwidth) and a Filter Wavelength Division Multiplexer (FWDM) which passes wavelength at 1550 ± 1 nm. The pump, signal and idler photons are located at $\lambda_p = 1550.12$ nm, $\lambda_s = 1544.53$ nm and $\lambda_i = 1555.75$ nm, respectively. The input single pump light is coupled into the chip by a one-dimensional subwavelength grating coupler. A polarization controller is utilized to maximize the coupling efficiency of the fibre to chip. The input power is monitored via a photodetector placed at the reflection port of the FWDM. Output photons are coupled out of the chip via an 8-mode edge coupling fibre array and filtered via a FWDM and a WDM. The purpose of the filtering operation is to remove the residual pump photons and enhance the photon indistinguishability. The output photons enter an 8-channel SNSPDs (Photon SoptTM, 100 Hz dark counts, 85% efficiency). Polarization controllers are placed before the SNSPDs. Swabian InstrumentTM GmbH is used as the counting logic that counts the single photon events and processes them on fly. The counting device supports more than 40 million events per second. A Peltier controlled by Thorlabs TED200C is used to stabilize the temperature of the chip and reduce the heat fluctuations caused by the ambient temperature and the heat crosstalk within the chip.

Characterization of phase shifters. The phase shifters are utilized extensively to control the AMZIs and MZIs. The power dissipation caused by applying electrical power to the TiN heater will heat the underneath optical waveguide to change the refractive index and induce a phase shift. The I-V characteristics of each heater was calibrated to observe the equivalent resistance. The characterisation of each phase shifter was done by varying the applied current while measuring the optical power at the output port. The collected measurement data were fitted with a cosine function. An average *R*-square value of 0.99 was achieved in the fittings, and the average visibility was 99.85%. In this chip fabrication, the process of deep-etched trances is adopted, and the heating efficiency is significantly improved. For heaters on MZIs, 3 mA electrical current is sufficient for a phase shift range of 3π . For heaters on AMZIs, 7.5 mA induces a shift of more than one free-spectral range in the transmission. The free spectral ranges for the pump filter (FSR_{pump}) and the

signal/idler filter ($\text{FSR}_{\text{signal}}$) are 11.62 nm and 23.40 nm, respectively. The average extinction ratio for AMZI is over 25 dB.

The polarization rotator and splitter. The on-chip polarization rotator and splitter (PRS) is deliberately designed to realize the conversion of dual-rail qubit on chip to polarization encoding in optical fiber. The path state $|0\rangle(|1\rangle)$ is first converted and combined to the transverse electric (magnetic) mode $|TE0\rangle(|TM0\rangle)$ in a single waveguide, and then to the polarization state $|H\rangle(|V\rangle)$ in the optical fiber (See Fig. S10 and Supplementary Note 6 for the structure of PRS and the detailed working principle). Since the waveguide cross section is designed for $|TE0\rangle$ mode propagation, $|TM0\rangle$ mode would experience a slightly higher loss. The phase shifter connected to PRS is thus calibrated by observing the interference fringe of intensity at the combined waveguide output. Suppose the ratio ($|TM0\rangle/|TE0\rangle$) of propagation loss is α , the intensity at the combined output is $\frac{1}{2}(1 + \alpha^2) - \frac{1}{2}(1 - \alpha^2)\cos\theta$, where θ is the phase shifter. According to the measured fringe of MZI for PRS on the encoder and decoder chips, the visibilities $V_{\text{en}} = 3.0\%$ and $V_{\text{de}} = 5.6\%$ are achieved respectively, and the ratio α is estimated to be 0.97. To couple the two propagation modes simultaneously, we adopt the spot size converter (SSC) as the polarization-independent edge coupling structure. The one-dimensional grating coupler is not adoptable here because it rejects the TM mode at an extinction ratio of ~ 20 dB. A polarization controller is placed between the transmitter chip and the receiver chip, and the polarization alignment of the two chip is done by sending $|0\rangle$ and $|1\rangle$ as the calibration references.

Data availability. The data that support the findings of this study are available from the corresponding authors on reasonable request.

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Author contributions

H.Z., L.W., W.K.M., T.H., L.C.K. and A.Q.L. jointly conceived the idea. H.Z., L.W. and H.C. designed the chip and built the experimental setup. H.C., G.Q.L., B.D., X.H.L. and D.L.K. fabricated the silicon photonic chip. H.Z., L.W. performed the experiments. W.K.M., T.H., and F.K.M. assisted the set-up and experiment. W.K.M., T.H., S.A., M.S.K. and L.C.K. assisted with the theory. All authors contributed to the discussion of experimental results. L.C.K. and A.Q.L. supervised and coordinated all the work. H.Z., L.C.K. and A.Q.L. wrote the manuscript with contributions from all co-authors.

Competing interests

The authors declare no competing interests.

Additional information

Supplementary information is available for this paper.

Figures

a

b

c

Figure 1

The schematic diagram of the Quantum Autoencoder-Facilitated Teleportation (QAFT) protocol in high dimensions. a, The overview of the QAFT protocol. The transmitter and the receiver each hold one half of an EPR pair. An initial qutrit is compressed to a qubit by the well-trained encoder. The transmitter interacts the qubit with its half of EPR pair and measures the two qubits in its possession. The classical channel transfers the BSM result and the settings of the encoder, and based on which, the receiver will reconstruct the initial qutrit by the decoder. b, The design of a silicon photon chip that demonstrates QAFT. The transmitter chip consists of multi-photon generator, entanglement generator, the encoder, and the Bell projector for BSM. The receiver chip integrates the decoder. The two sub-chips are coherently linked by a

single mode fiber. Three pairs of non-degenerate photons are generated. AMZIs are employed to filter the pump light and separate the signal and idler photons. A Bell state is produced by the waveguide routing. The idler photon of the third pair is used for generating a qutrit-by-path. The qutrit is compressed by the trained encoder to a qubit. At the transmitter, a Bell measurement of the EPR pair qubit and the teleported qubit is performed. At the receiver, the initial qutrit state can be reconstructed from the teleported qubit by the decoder. c, The false coloured micrograph of the QAFT chip. The input single pump light is coupled to the chip by a one-dimensional subwavelength grating coupler. Output photons (D1-D6) are coupled by spot size converters (SSCs) as edge couplers, and then detected off-chip by eight superconducting single-photon detectors (0.85 efficiency). Specifically, B1 and B2 are connected by a 10 m fibre, and a polarization rotator and splitter (PRS) are utilized to convert the path state in waveguide to the horizontal (vertical) state in optical fibre.

Figure 2

Implementation and training of the quantum autoencoder on silicon chip. a, The graphical representation of the 3-2-3 quantum autoencoder. The aim of the autoencoder is to represent higher-dimensional data in a lower-dimensional space. If the compression is lossless, the original input can be recovered through a decoding process. b, The architecture of the quantum autoencoder that consists of an encoder (E) for compression and a decoder (D) for reconstruction, respectively. The encoder is trained by minimizing the occupation probability of the trash mode, retaining all the information on qubits modes. Lossless compression is achieved when the trash state is unoccupied. The parameters of the encoder are trained using machine learning algorithms. c, The programmable circuit implementing the trainable encoder and on-chip training process. An evolutionary optimization algorithm is executed on the classical hardware for the updating of the free parameters of the encoder. Both the qutrit and the trainable encoder is independently supplied with electrical control signals. The qutrit generator is randomized each time after the last qutrit is measured. The photon occupancy is estimated over a series of unrepeated qutrits and is employed in the evaluation of the optimization algorithm. Different colors of MZIs are marked for the implementation of different functionalities, including the qutrit preparation (red), encoder (blue) and quantum state tomography (gray). 5 free parameters (θ_{1-2} and φ_{1-3}) are used for qutrit preparation, and 8 free parameters (α_{1-3} , θ_{4-6} and φ_{4-5}) are used for implementing the encoder.

Figure 3

Training of the quantum autoencoder with single-shot measurement. a, The flowchart of training the autoencoder with random qutrits. The training follows genetic algorithm and starts from the population initialization. The individuals are evaluated on chip by observing the photon occupancy of the trash mode, according to the time spent (i.e., Δt) until the first click in the photon channel. The longer the Δt , the lower the photon occupancy at the trash mode. Suppose the time required to detect dark noise is T , the fitness function is defined as $f = 1 - e^{-\Delta t/T}$, with a training target of $f = 0$. For each individual, 50 random qutrits are used for fitness value estimation, with each qutrit measured only once. The algorithm uses genetic operators (i.e., selection, crossover, and mutation) to generate new populations (a new set of 20 individuals), until the algorithm converges. b, The timing diagram of the counting logic. Two signal channels, the laser channel and the photon channel that is connected to the trash mode, are monitored. A gate with a period of 1010 ps (i.e., the time required to detect dark noise) is created from one of the laser pulses. The time difference between the first photon click and the first laser click, i.e., $\Delta t = t_{\text{photon}} - t_{\text{laser}}$, are returned as the output of the counting logic. c, The evolution of the time spent until the first click at the trash mode, which intuitively shows the convergence. The time cost of most individuals in the final generation reaches the count level of the dark noise. d, The statistics of the time spent until first click in each generation, showing in a box plot. e, The evolution of the best fitness value and average fitness value within each generation. The fitness value of the final best encoder is 0.016, and the average fitness of the final population is 0.082. f, The contrast of the first photon detection time in the initial and the final generation. g, The contrast of the fitness value in the initial and the final generation. h, The statistics of the 20 individuals contained in the initial and the final generation, respectively. As observed from the result, most individuals in the final generation have almost the same current value, with a standard deviation of 0.016 mA.

Figure 4

Bell state measurement, and quantum state tomography results for chip-to-chip teleportation. a, Chip-to-chip teleportation results. A total six elementary states were teleported from the transmitter to the receiver, respectively. The density matrices of the six states were constructed by full quantum state tomography on the receiver chip. Reconstructed density matrices are shown along with the measured fidelities, reporting a mean fidelity of 0.914 ± 0.022 . b, Qutrit encoding and decoding. The teleported qubit was decoded to reconstruct the initial generated qutrit on the receiver chip. The decoder is built according to the classical information transmitted to the receiver chip. Full quantum state tomography is applied to reconstruct the density matrix and report a mean fidelity of 0.894 ± 0.026 .

Supplementary Files

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