

OPTICS

A hybrid quantum memory-enabled network at room temperature

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Quantum memory capable of storage and retrieval of flying photons on demand is crucial for developing quantum information technologies. However, the devices needed for long-distance links are different from those envisioned for local processing. We present the first hybrid quantum memory-enabled network by demonstrating the interconnection and simultaneous operation of two types of quantum memory: an atomic ensemble-based memory and an all-optical Loop memory. Interfacing the quantum memories at room temperature, we observe a well-preserved quantum correlation and a violation of Cauchy-Schwarz inequality. Furthermore, we demonstrate the creation and storage of a fully-operable heralded photon chain state that can achieve memory-built-in combining, swapping, splitting, tuning, and chopping single photons in a chain temporally. Such a quantum network allows atomic excitations to be generated, stored, and converted to broadband photons, which are then transferred to the next node, stored, and faithfully retrieved, all at high speed and in a programmable fashion.

INTRODUCTION

A quantum network consisting of a large-scale distribution of quantum nodes and interconnecting channels remains an overarching goal for quantum information science. Such a network could be used for quantum-enhanced technologies that promise to outperform classical systems in the fields of communication, computing, and metrology (1). Unfortunately, quantum channels suffer from exponential loss and high latency (2, 3). In addition, the probabilistic generation of quantum states limits the scale of quantum systems (4, 5). Quantum memories capable of storing quantum states (6) permit quantum communication over long distances with quantum repeaters (7, 8) and avoid the nondeterministic nature of quantum state generation by synchronizing stochastic events (9–13).

Various works have been motivated on quantum memory theory and relevant physical implementations, such as optical delay lines and cavities (14–17), electromagnetically induced transparency (EIT) (18–20), the Duan-Lukin-Cirac-Zoller (DLCZ) protocol (8, 21, 22), photon-echo quantum memory (23, 24), off-resonant Faraday interaction (25), Raman memory (26, 27), and Autler-Townes splitting (ATS) memory (28). To make a quantum memory device practical for scalable and high-speed quantum information processing, the key requirements that have to be satisfied include broad acceptance bandwidth, high efficiency, long lifetime, low noise level, and the capability of running at room temperature.

However, for the past 20 years, it has been proven very challenging to meet all these requirements simultaneously. Considerable efforts have been made in pushing the bandwidth from the kilohertz and

megahertz regime to the gigahertz regime and temperature from near absolute zero to room temperature (18–23, 25–27). At room temperature, EIT and near off-resonant Raman memories suffer from fluorescence noise that is impossible to be filtered out spectrally (29). As for far off-resonant Raman memory, while it eliminates fluorescence noise, a new intrinsic noise related to spontaneous Raman scattering emerges (30).

Recently, we have realized a broadband and room temperature far off-resonance DLCZ (FORD) quantum memory, capable of operating with a high fidelity in the quantum regime (31). Now, we are pursuing a quantum memory that is broadband, room temperature, and more importantly, compatible with the FORD quantum memory for further storing Stokes/anti-Stokes photons (i.e., mapping in) and retrieving them (i.e., mapping out) for controlled durations without any additional noise. Progress toward such a memory has been made by using excited states of atoms (32, 33), albeit with a limited lifetime.

Alternatively, loop architecture has shown the capability to trap and control photons by using ultralow-loss optical elements, which can avoid introducing any additional noise (18, 27, 30, 34). The idea of loop architecture can be traced back to 1993 (14), and although being seemingly straightforward, it is actually very challenging to realize in practice. Continuous efforts have been made to improve its performance and practicability (10, 12, 13, 15–17, 35), and recently, extremely low loss has been achieved, enabling high-efficiency single-photon (10, 13) and multiphoton generation (12). A Loop quantum memory, consisting of an all-optical storage loop and controllable polarization switches, can map broadband flying single photons in and out at room temperature, which thus complements the FORD quantum memory.

Here, we propose and experimentally demonstrate a broadband, room temperature, and hybrid quantum memory-enabled network. The hybrid network combines a broadband FORD memory with a compatible all-optical Loop memory. The network generates nonclassical optical states in a built-in and time-controllable fashion in a warm atomic ensemble and traps these states in an all-optical loop (see Fig. 1A). This hybrid quantum memory system is capable of combining, swapping, splitting, and chopping single

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photons in a chain temporally, as well as finely tuning the time of each individual photon. Some of these tasks have been realized in the frequency domain for coherent light (36) but have never been achieved in the time domain or for genuine quantum light. After traversing the two memory devices successively, the quantum states are observed to be high-fidelity Fock states. We measure the cross-correlation and find that it exceeds the classical Cauchy-Schwarz bound (37) by more than 500 SDs, establishing that our memories would be capable of violating a Bell inequality (38), enabling the detection of nonclassical behavior and that they could be deployed in quantum applications.

RESULTS

The schematic view of the FORD protocol is shown in Fig. 1 (B to D). A strong write/read pulse is incident on an atomic ensemble, creating a Stokes photon via spontaneous Raman scattering, which heralds the successful creation of an atomic excitation (8). After a programmable delay τ_1 , the corresponding anti-Stokes photon is retrieved, where the retrieval efficiency, in principle, can also reach 100% (26). The strong and broadband write/read pulses undergo a much larger detuning than that is usually applied in the standard DLCZ protocol, which makes the acceptance bandwidth very broad for Stokes/anti-Stokes photons. The strong write pulse with a detuning Δ_W

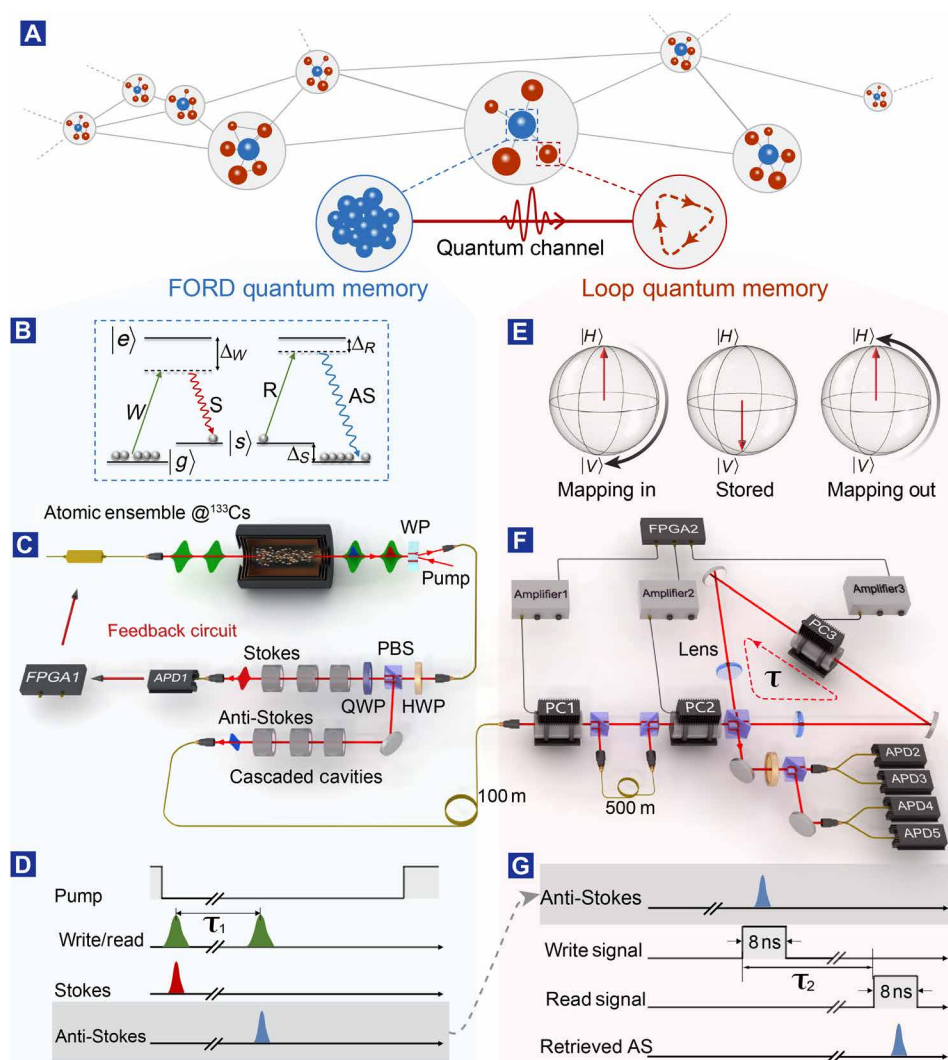


Fig. 1. A schematic diagram and experimental setup for a hybrid quantum memory enabled network. (A) A quantum network consists of two different functional nodes and their interconnections. (B) Write and read processes of FORD quantum memory. Solid lines represent three-level Λ -type configuration of atoms, in which states $|g\rangle$ and $|s\rangle$ are hyperfine ground states of cesium atoms ($\Delta_s = 9.2$ GHz); state $|e\rangle$ is the excited state; dashed lines represent broad virtual energy levels induced by the write and read pulses. (C) Setup of FORD quantum memory. WP, Wollaston prism; PBS, polarization beam splitter; QWP, quarter wave plate; HWP, half wave plate. (D) Time sequences of FORD quantum memory. (E) Polarization switching in the mapping in-and-out processes shown in Bloch spheres. (F) Setup of Loop quantum memory. The Pockels cell in the loop is controlled by write and read electrical signals from two channels of a field-programmable gate array (FPGA) module. A 500-m-long fiber is introduced to coordinate with the Loop memory as another switching path against photon loss. Four avalanche photodiodes (APDs) are used to detect photons in a chain with small time interval. PC, Pockels cells. (G) Time sequences of Loop memory. The time interval τ_2 between write and read signals can be any positive integral multiples of 1 cycle period τ .

creates a broadband Stokes photon, while the atomic ensemble with a single created excitation becomes (8, 39)

$$|\psi\rangle = \frac{1}{\sqrt{N}} \sum_{j=1}^N e^{i(\vec{k}_W - \vec{k}_S) \cdot \vec{r}_j} |g_1 g_2 \dots s_j \dots g_N\rangle \quad (1)$$

where N is the number of atoms, \vec{k}_W (\vec{k}_S) is the wave vector of the write (Stokes) pulse, and \vec{r}_j is the coordinate of the j th atom that is excited to state $|s\rangle$. After a programmable time delay τ_1 , a read pulse with a detuning Δ_R transforms the collective excitation state into a broadband anti-Stokes photon. The measured bandwidth is about 500 MHz, calculated by a convolution-based approach (31).

Connected by an optical fiber, flying anti-Stokes photons are transmitted to the remote all-optical Loop memory. As shown in Fig. 1 (E to G), once the anti-Stokes photon is mapped in the loop, high-speed polarization switches (Pockels cells) are activated. The first control pulse applied to the Pockels cell in the loop switches the photon to be vertically polarized. The photon then cycles counterclockwise for a controllable time τ_2 , until the second control pulse applied to the Pockels cell map sits out by switching its polarization back to horizontal. Then, the retrieved anti-Stokes photon is collected by a fiber coupler, and a standard Hanbury Brown–Twiss experiment can be conducted to study photon statistics with a 50:50 fiber beam splitter and avalanche photodiodes. The bandwidth of our all-optical Loop memory is much higher than tens of terahertz and is only limited by the response bandwidth of linear optical elements, which means that the Loop memory matches the bandwidth of the FORD memory.

The retrieved distributions of anti-Stokes photons triggered by Stokes photons after the FORD memory are illustrated in Fig. 2 (A and B). We attribute the slight decline of retrieval efficiency to be

loss induced by atomic motion. The retrieved distribution of injected photons after the Loop memory is illustrated in Fig. 2 (C and D). The retrieval efficiency of the Loop memory can be obtained by comparing the counts of the mapped-out anti-Stokes photons with the values before being mapped into the loop, which reaches 90% for short storage times. The decrease mainly results from photon loss due to multiple reflection and dispersion from the optical elements in the loop. The red fitted curve in Fig. 2D implies that our current devices (two Pockels cells are being upgraded to a single fast and low-loss one) enable light storage for around 10 cycles in the loop. Insets show that the pulse shapes associated with the broadband nature of the released anti-Stokes photons are well preserved.

The main limitation of the FORD memory's retrieval efficiency here is the lack of another independent laser generation system. In our current experimental setup, since the frequencies of write and read pulses are the same, the detuning of read process is much smaller than that of write process. As a result, the read process may happen immediately after an excitation is created, leading to the limited retrieval efficiency. The problem can be solved by preparing the write and read pulses independently with different lasers. Therefore, the read effect in the write process can be suppressed greatly or can even be ignored, resulting in much higher retrieval efficiency. In addition, other possible solutions include increasing the pulse energy (26), optimizing the pulse shape (40), harnessing cavity enhancement (41), and using a double-pass geometry (42).

Quantum correlations in a hybrid quantum memory network

To evaluate the ability of our memories to preserve quantum correlations, we measure the second-order correlation function $g_{S-AS}^{(2)}(\tau_1, \tau_2)$ between the retrieved anti-Stokes mode and the Stokes mode. The results are presented in Fig. 3 as functions of storage time τ_1 and τ_2 . The decrease of $g_{S-AS}^{(2)}(\tau_1, \tau_2 = 31.2 \text{ ns})$ of the FORD memory (see

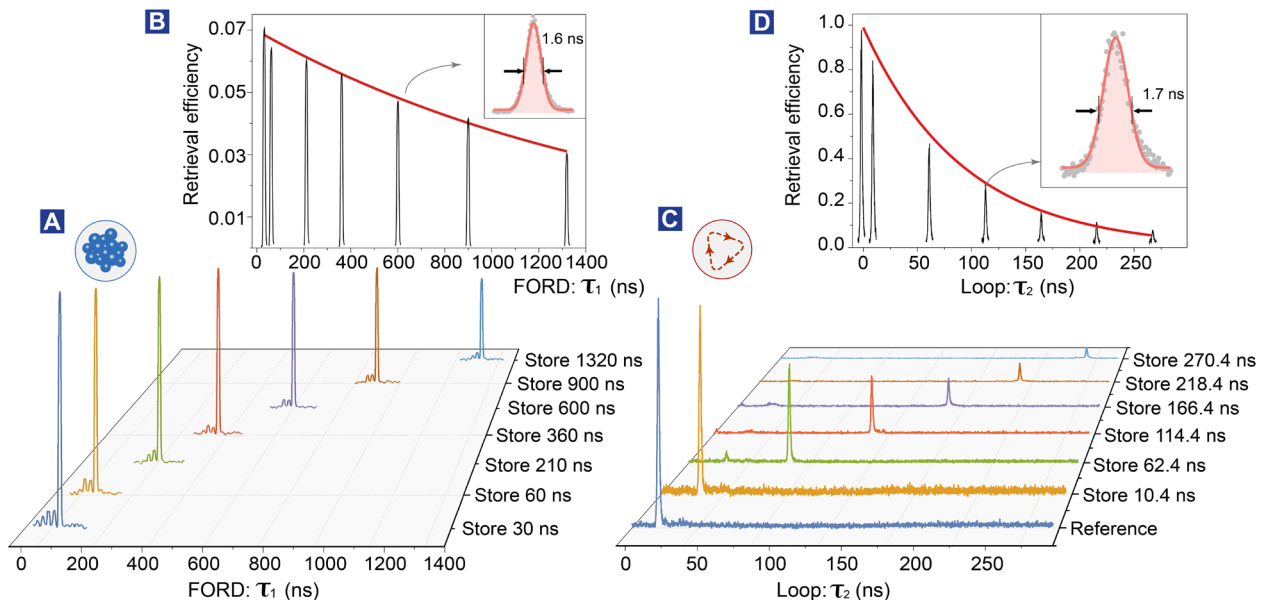


Fig. 2. Retrieval efficiency of FORD and loop memory. (A) Retrieved distribution of anti-Stokes photons triggered by Stokes photons as a function of τ_1 . (C) Retrieved distribution of injected photons as a function of τ_2 with the circulation period τ being 10.4 ns. (B and D) The red solid lines fit the measured retrieval efficiency of the FORD and Loop memories. Insets show the pulses at $\tau_1 = 600 \text{ ns}$ and $\tau_2 = 114.4 \text{ ns}$ with Gaussian fits, giving the duration of the retrieved broadband pulses. Comparing with the duration of 1.6 ns measured before the Loop memory, the pulse shape is well preserved. The transmission per round trip is 90% (two Pockels cell are used in the loop with the same clock rate of 50 kHz and a rise time of 5 ns, and the transmittance for each Pockels cell is 97%).

Fig. 3A) mainly comes from atomic motion (43) and background noise, while the slight drop of $g_{S-AS}^{(2)}(\tau_1 = 30 \text{ ns}, \tau_2)$ of the Loop memory (see Fig. 3B) comes from the decrease of the count rate as the efficiency drops. At the initial values of storage time, the nonclassicality can be revealed by a violation of Cauchy-Schwarz inequality (37)

$$(g_{S-AS}^{(2)})^2 \leq g_{S-S}^{(2)} \cdot g_{AS-AS}^{(2)} \quad (2)$$

by up to 549 SDs (the measured cross- and auto-correlations are $g_{S-AS}^{(2)} = 22.63 \pm 0.93$, $g_{AS-AS}^{(2)} = 1.57 \pm 0.50$, $g_{S-S}^{(2)} = 2.11 \pm 0.25$). The storage time at which the cross-correlation drops to $1/e$ of its maximum value (20, 43) can be viewed as the maximum storage time over which the memories preserve quantum coherence and quantum correlations. This lifetime, for the FORD memory, is $1.45 \mu\text{s}$, while for the loop memory, this lifetime is $1.22 \mu\text{s}$. Note that the retrieval efficiency of the loop memory decays more quickly in time than the FORD memory, but the loop memory is also free of any noise processes such as fluorescence and four-wave mixing, which explains why it is capable of preserving quantum correlations for almost as long as the FORD memory. For a short storage time of 10.4 ns, there is no measurable degradation in the $g_{S-AS}^{(2)}$ cross-correlation between the input and retrieved fields: For the input field, we find $g_{S-AS}^{(2)} = 21.1 \pm 0.8$, and for the retrieved field, we measure $g_{S-AS}^{(2)} = 21.5 \pm 1.3$.

In a hybrid network suitable for quantum applications (Fig. 1A), it should be possible to generate photons and to transfer them individually between quantum memories in a programmable way. Here, we demonstrate one aspect of this functionality, by sequentially writing and then reading photons with intermediate storage times in both memories. As an example, we choose the point shown in the

middle of Fig. 3C, with $\tau_1 = 480 \text{ ns}$ and $\tau_2 = 122.4 \text{ ns}$. The $g_{S-AS}^{(2)}$ is found to be 14.43 ± 0.47 , which is in good agreement with the prediction of 14.47 found using a simple model in which the best fit decay curves presented in Fig. 3 (A and B) are multiplied together. In a large area, including the point (480 and 122.4 ns), the cross-correlations in such a hybrid quantum memory-enabled network all exceed the key boundary of 6. This, as suggested in (38), means that the correlations between the Stokes and anti-Stokes photons are strong enough, in principle, to violate a Bell inequality.

Creation and storage of a fully-operable heralded photon chain state

To better demonstrate the unique features of our hybrid quantum memory system, we further perform the storage of a fully-operable heralded photon chain state. The hybrid quantum memory system is capable of combining, swapping, splitting, and chopping single photons in a chain temporally, as well as finely tuning the timing of each individual photon. To realize this, we add a feedback loop to repeat the spontaneous Raman process in the FORD memory until a Stokes photon is triggered successfully. Such a repeat-until-success scheme enabled by quantum memory increases the excitation rate up to 10 times. Meanwhile, the lifetime of the FORD memory is prolonged from 1.44 to $2.24 \mu\text{s}$ by optimizing the spatial mode of the addressing light to cover the feedback period, which is around $1 \mu\text{s}$. A 500-m-long fiber is introduced as a fixed delay line to coordinate with the Loop memory, which can mitigate the lifetime difference between the FORD and Loop quantum memories, allowing versatile two-memory coordination. Moreover, to store more temporal modes in a single Loop, the circulation period is prolonged from

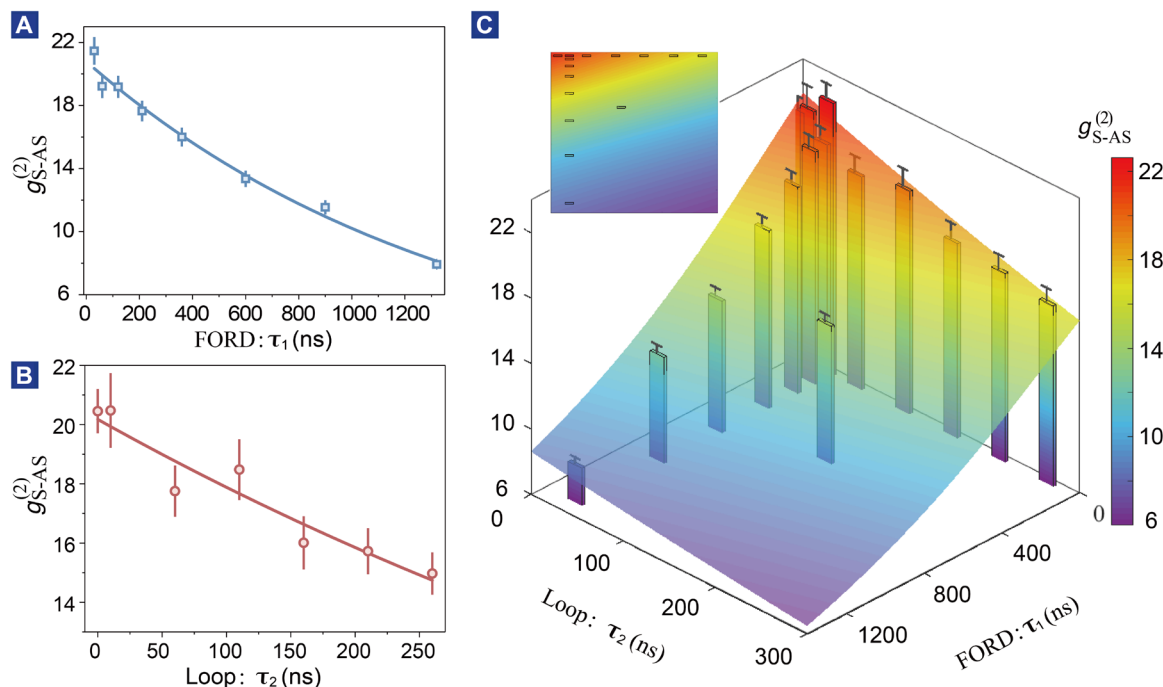


Fig. 3. Measured cross-correlation as a function of storage time. (A) The cross-correlation $g_{S-AS}^{(2)}(\tau_1, \tau_2 = 31.2 \text{ ns})$ is fitted with form $g_{S-AS}^{(2)}(\tau_1) = 1 + C/(1 + A\tau_1 + B\tau_1^2)$, where the quadratic term describes atomic motion, and the linear term comes from background noise. (B) The cross-correlation $g_{S-AS}^{(2)}(\tau_1 = 30 \text{ ns}, \tau_2)$ is fitted with form $g_{S-AS}^{(2)}(\tau_2) = Ae^{-B\tau_2}$, which follows the exponential decay of the memory efficiency. The data are obtained under the condition of a write/read beam waist being $214 \mu\text{m}$ and the detuning $\Delta_R = 4 \text{ GHz}$. Error bars are derived assuming Poissonian statistics of the individual photocounts. (C) Joint cross-correlation of the hybrid quantum memory-enabled network as a function of storage times. The surface is well described by the product of the two decay functions. The inset provides a top view of the measured points.

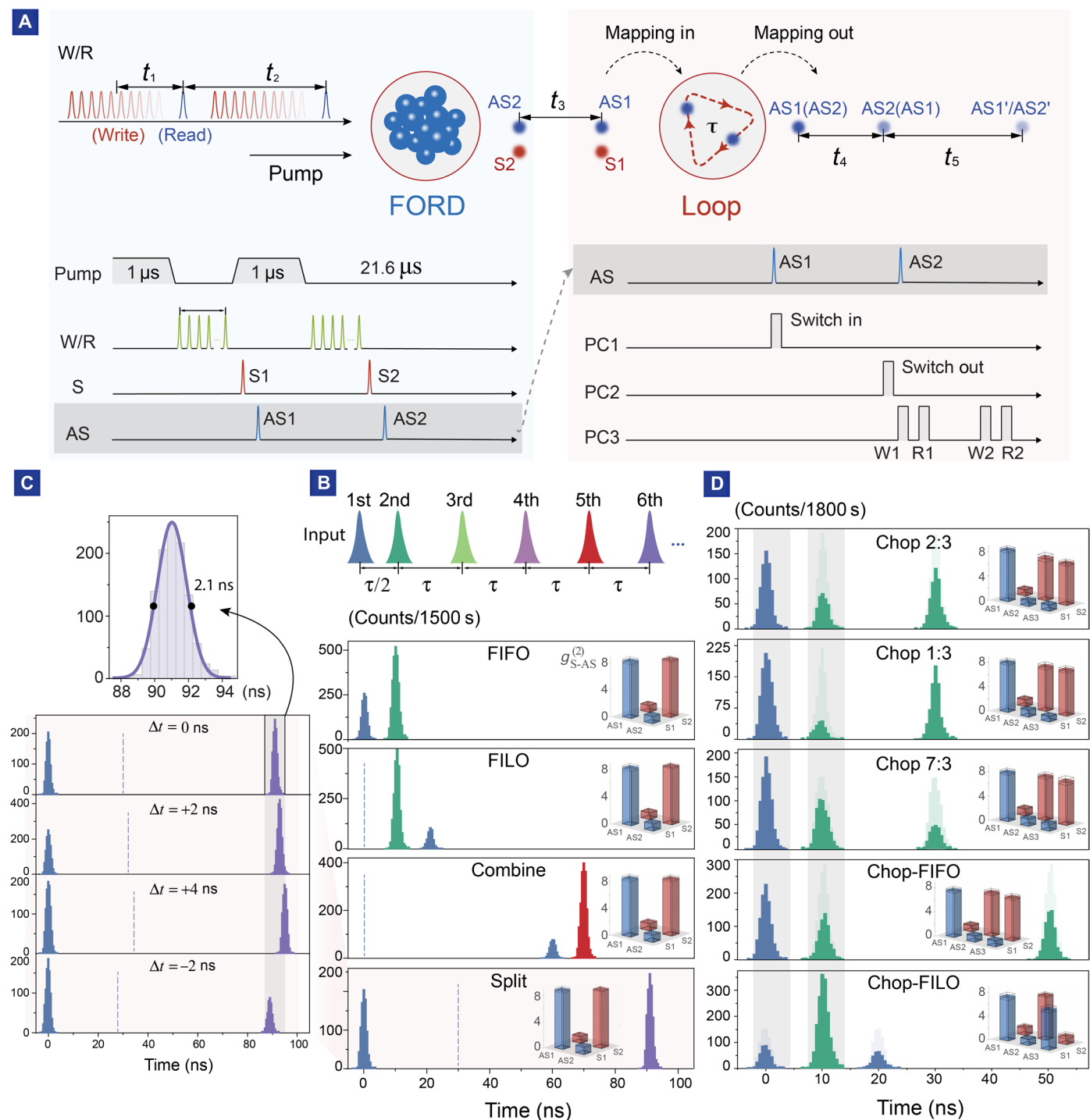


Fig. 4. Experimental creation and storage of a fully operable heralded photon chain state. (A) Schematic diagram of creating a two-photon chain with tunable interval and mapping the chain in and out to various temporal modes. t_1 is the storage time of FORD memory, t_2 is the time interval between two heralded anti-Stokes photons (AS1 and AS2), t_3 is the interval between AS1 and AS2 after a 500-m fiber and two Pockels cells, t_4 represents the interval between AS1(AS2) and the first part of AS2(AS1), and t_5 is the interval between two chopped parts. The circulation period τ here is 20.3 ns, where the transmission rate of the Pockels cell in the loop is 95% with a clock rate of 30 MHz and a rise time of 5 ns. (B) Various temporal modes of anti-Stokes photons are marked in different colors. Heralded photons can be mapped out of the Loop memory to arbitrary temporal modes defined. The transmission rate of anti-Stokes photons between two memories is around 12.4%. FIFO, First in first out; FILO, first in last out. (C) Fine tuning of the mapped-out photons with a step of 2 ns. The inset portrays the shape of the mapped-out anti-Stokes photons. (D) Demonstration of chopping a single photon in a chain, where the probability is continuously tunable by adjusting half-wave voltage of the Pockels cell in the loop. The pulse shadows represent the sum of AS1(AS2) and AS1'(AS2'). Inserted bar graphs are measured cross-correlation values. More detailed values from t_1 to t_5 and cross-correlations can be found in the Supplementary Materials.

10.4 to 20.3 ns. Time sequences are shown as Fig. 4A. More experimental details can be found in the Supplementary Materials.

As shown in Fig. 4B, defining several temporal modes in different colors, two flying anti-Stokes photons in arbitrary input temporal modes can be mapped to any desired output temporal modes, presenting functions as first in first out (FIFO) and first in last out (FILO), combining and splitting two single photons. Furthermore, the time interval between two heralded anti-Stokes photons can be finely tuned by the delay of write pulses in the FORD memory, coordinating with the Loop memory in the temporal control of photons. In particular, as Fig. 4C shows, the temporal mode of anti-Stokes photons can be finely tuned with a step of 2 ns. Apart from temporal mode shifting, each of the single photons in the chain can be chopped into two temporal modes with tunable probability, as shown in Fig. 4D. The observed cross-correlation between two heralded anti-Stokes photons after two memories reaches 8.8, leading to a strong contrast with the measured cross-correlation of noise (1.0) and exceeding the bound of 6 needed to achieve a Bell violation. More measured cross-correlation values are shown in the Supplementary Materials.

DISCUSSION

The technical requirements for a quantum repeater are quite different from what are needed for local synchronization. For a local photonic processor, entangling operations need to be attempted at a high rate, to build up a cluster state or similar, as a resource for quantum computing. Therefore, a memory must be able to store an incident optical mode that is already entangled with a wider system. The system clock rate should be high so that a large entangled state can be built, whereas latency is low. On the other hand, for a quantum repeater, only two parties are connected, so it is sufficient to distribute entanglement over a chain of linear segments. Bandwidth is important but not critical, whereas high signal latencies mean that a system with the potential for long storage times is valuable.

In addition, future photonic quantum processors could be securely connected over distance, provided that the primitive network elements are compatible. While we believe that the FORD quantum memory can be a building block for scalable quantum technologies, a network also requires memories that can store incoming photons, the functionality for which is provided by the Loop memory. Here, we have shown that a Loop quantum memory for arbitrary input states, with high operating bandwidth but limited intrinsic lifetime, can behave as a node constituting a local photonic processor, and a FORD quantum memory, with long lifetime but technically more complex atomic-ensemble system, can serve as a main node linking other local photonic processors for constructing large-scale quantum networks.

In summary, we have proposed and experimentally demonstrated a broadband, room temperature, and hybrid quantum memory-enabled network. The demonstrated building block consists of two different functional quantum nodes: an atomic ensemble-based memory capable of generating and storing quantum states and an all-optical memory for mapping incoming photons in and out, at room temperature, and with high bandwidth. The two types of quantum memory are complementary in functionality and are compatible with each other, both running at room temperature and with broad bandwidth.

Our demonstration may provide a route toward scalable quantum information processing (4–7), which requires the capability to create,

store, and distribute quantum states on demand across a large number of nodes through interconnecting channels (44). The performance of two types of quantum memories can be further improved in the future (12, 13, 45), especially the ultralow loss of loop architecture has been achieved experimentally. The currently achievable lifetime of the two quantum memories is at the microsecond level. However, the enabled hybrid quantum network would already be applicable in building quantum computers and quantum simulators locally.

MATERIALS AND METHODS

Experimental details of FORD quantum memory

We used cesium atoms ^{133}Cs to achieve a large optical depth due to its higher saturated vapor pressure compared with other alkali atoms. The 75-mm-long cesium cell with 10 torr Ne buffer gas was placed into a magnetic shield and was heated up to 61°C to obtain an optical depth of about 5000. A horizontally polarized write/read laser beam creates Stokes and anti-Stokes photons with a programmable time lag. In our FORD memory, write and read pulses were copropagating for maximizing the spin wave lifetime (43). It has been shown that Stokes (anti-Stokes) photons are collinear with write (read) pulses (46) but with orthogonal polarization (47), so we used a Wollaston prism to separate the retrieved photons from the strong addressing light. Meanwhile, since Stokes and anti-Stokes photons were also copropagating under the phase-matching condition, six home-built cavities arranged in a double-pass configuration were used to split Stokes and anti-Stokes photons. The transmission rate of each cavity reaches around 90%, while the extinction rate of each cavity against noise is up to 500:1.

Experimental details of storing a heralded photon chain state

We generated two heralded anti-Stokes (AS1 and AS2) photons successively in the FORD quantum memory in a built-in and time-controllable fashion. To maintain the high nonclassicality, the pump, read, and write pulses were applied each time before an anti-Stokes photon was retrieved. Limited by the response rate of our Pockels cells, the operation period was 21.6 μs , during which two anti-Stokes photons were created. After transmitting through the cavity filters, the first photon AS1 was selected to enter a 500-m-long fiber with an additional 2.5- μs delay, mitigating the fixed time difference caused by the long state preparation period for the two anti-Stokes photons. The second photon AS2 did not pass through the fiber.

Since the circulation period of the Loop memory is 20.3 ns and the rise/fall time of our Pockels cells is 5 ns, a two-photon chain state can be stored in the Loop memory, and each of the photons can be addressed independently in the time domain. In our experiment, we demonstrated several functions that can be realized in such a hybrid quantum network. FIFO: The sequence of two mapped-out photons is conserved. FILO: The sequence of two mapped-out photons is reversed by storing AS1 for a longer time than AS2. Combining: The two anti-Stokes photons with a large gap can be stored successively and retrieved as a two-photon chain state. Splitting: The gap between two anti-Stokes photons is increased by storing AS2 for a longer time than AS1. Chopping: Each single photon in a chain can be mapped out with a tunable probability and into different temporal modes on-demand. Furthermore, the fine tuning of single photons can be realized by adjusting the time delay of the read process in FORD memory. The nonclassicality under all these situations is verified by the measured cross-correlation values. More details can be found in section S3.

SUPPLEMENTARY MATERIALS

Supplementary material for this article is available at <http://advances.sciencemag.org/cgi/content/full/6/6/eaax1425/DC1>

Section S1. Improved lifetime of FORD memory

Section S2. Improved bandwidth match between signal photons and cavity filters

Section S3. Experimental scheme of operating a photon chain state

Fig. S1. Measured cross-correlation as a function of storage time.

Fig. S2. Bandwidth measurement of Stokes (red curves above) and anti-Stokes photons (blue curves below).

Fig. S3. Schematic diagram of creating and storing a photon chain state.

Fig. S4. Measured cross-correlation values for photon chain states.

Fig. S5. Tunable chopping probability of a single photon in the Loop memory.

Fig. S6. Path selection process before photons being mapped into the Loop memory.

Table S1. Measured cross-correlation functions under various operations.

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