Storage of 1650 modes of single photons at telecom wavelength

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To advance the full potential of quantum networks one should be able to distribute quantum resources over long distances at appreciable rates. As a consequence, all components in the networks need to have large multimode capacity to manipulate photonic quantum states. Towards this end, a multimode photonic quantum memory, especially one operating at telecom wavelength, remains a key challenge. Here we demonstrate a spectro-temporally multiplexed quantum memory at 1532 nm. Multimode quantum storage of telecom-band heralded single photons is realized by employing the atomic frequency comb protocol in a 10-m-long cryogenically cooled erbium doped silica fibre. The multiplexing encompasses five spectral channels - each 10 GHz wide - and in each of these up to 330 temporal modes, resulting in the simultaneous storage of 1650 modes of single photons. Our demonstrations open doors for high-rate quantum networks,
which are essential for future quantum internet.

Introduction
Multimode capacity is an essential requirement to achieve high data rates in modern communication networks. Towards a future quantum network\textsuperscript{1–4} compatible with existing telecom infrastructure, this requirement must also be applied\textsuperscript{5,6}. One challenge in pursuing such a quantum network is to develop a multimode quantum memory\textsuperscript{7–11}, which is able to simultaneously store and process multiple modes of single photons in various degrees of freedom, such as in temporal degree\textsuperscript{12–26}, spectral degree\textsuperscript{27–29}, spatial degree\textsuperscript{30–38}, or any combination of these\textsuperscript{39,40}. In addition to the usual figures-of-merit for quantum memories, i.e., efficiency and fidelity, the multimode performance of a quantum memory is also important, which is mainly determined by the number of storage channels, storage time, and storage bandwidth. The storage channel could be implemented in the spectral or spatial domain. The storage time and storage bandwidth of each channel determine an upper bound of temporal mode number in each channel.

On the quest to reach large multimode quantum storage capacity, the use of multiple spatial channels has yielded good results, with a channel number up to 665 realized in gaseous atomic ensembles\textsuperscript{37} based on Duan–Lukin–Cirac–Zoller (DLCZ) protocol\textsuperscript{41}. Further improvements to the multimode capacity of such memory could be achieved via increasing the number of stored temporal modes in each of these channels. However, the simultaneous storage of multiple temporal modes remains challenging in atomic gas ensembles due to limitations of the applied storage protocols\textsuperscript{41–43}. Specifically, the number of temporal modes that can be stored is related to the optical depth (OD) of the storage media\textsuperscript{44}. Fortunately, the atomic frequency comb (AFC)-based quantum memory with rare-earth ion-doped (REID) materials does not feature any constraint in terms of OD for simultaneous temporal storage, and, thus, is promising for developing highly multimode photonic quantum memory using several photonic degrees of freedom\textsuperscript{45}. Multiple storage channels have been demonstrated with the AFC protocol in the spatial domain\textsuperscript{34} and in the spectral domain\textsuperscript{27–29}, which is facilitated by the inhomogeneous broadening in REID materials. Storage of multiple temporal modes in one spectral channel has also been achieved, for instance the storage of 1250 temporal modes in Yb\textsuperscript{3+}:Y\textsubscript{2}SiO\textsubscript{5} at 979 nm\textsuperscript{46}. Furthermore, the storage of multiple temporal modes in multiple channels has been reported, including storage of 12
spectro-spatial-temporal modes and 130 spectro-temporal modes in Pr\(^{3+}\):Y\(_2\)SiO\(_5\) at 606 nm. Despite these important advances, a quantum memory with large multimode capacity at telecom wavelength has yet to be demonstrated, as an essential step towards a future quantum network compatible with existing telecom infrastructure.

In this paper, we present the multimode storage of 1650 modes of single photons at telecom wavelength with a 10-m-long cryogenically cooled erbium doped silica fibre (EDF). In our demonstration, five individual AFC spectral channels - each with 10 GHz bandwidth and separated by 5 GHz isolation - are prepared by using an optical frequency comb and frequency chirping method. Up to 330 temporal modes of heralded single photons generated from cascaded second-order nonlinear process are stored in each spectral channel. Our achievements pave the way towards developing future quantum internet by utilizing multimode quantum memory compatible with the infrastructures of fibre-based communication.

Results

Multimode storage scheme. Based on the inhomogeneous broadening in REID materials, an \(N \times M\) multimode quantum memory can be realized by using \(N\) spectral channels and \(M\) temporal modes in each spectral channel (see Fig. 1(a)). Through spectral tailoring of the inhomogeneous broadened absorption line of REID materials, AFC channels with a number of \(N\) in the spectral domain are prepared. In each spectral channel, a train of single photons in \(M\) temporal modes are stored, with the maximum value of \(M\) determined by the time-bandwidth product of the AFC-based memory. By doing so, a total number of \(N \times M\) modes of single photons are stored, simultaneously. To develop such a quantum memory with multimode capacity at telecom wavelength, a promising REID material is low doping concentration EDF, which has a telecom-band transition wavelength and THz-wide inhomogeneous broadening (see Figs. 1(b), (c)).

Experimental setup. The experimental setup is composed of an AFC-based EDF quantum memory with five spectral channels, a heralded single photon source at telecom wavelength, and a coincidence detection system, as illustrated in Fig. 2(a). The experimental time sequences are also shown in Fig. 2(b) (see Methods).

We prepare an AFC-based quantum memory with five spectral channels in a 10-m-long EDF cooled to a temperature of 10 mK and exposed to a magnetic field of 2000 Gauss (see Fig. 2(a)(1) and Methods for details). More precisely, through frequency-selective optical
pumping of Er\(^{3+}\) ions into a long-lived auxiliary level (see Fig. 1(c)), the five individual AFCs - each with a bandwidth of 10 GHz - are prepared at central wavelengths of 1532.11 nm, 1532.00 nm, 1531.88 nm, 1531.76 nm and 1531.65 nm, labeled as channels of 1, 2, 3, 4, and 5. Figure 1(d) depicts a typical AFC (channel 2) in our experiment, and all the five AFCs are shown in Supplementary Information note 1. Note that instead of using five individual lasers or sequentially tuning the laser frequency to generate each AFC, we utilize a single laser followed by an intensity and phase modulator to generate an optical frequency comb, such that five AFCs can be prepared simultaneously by the frequency chirping method (see Supplementary Information note 1 for more details on preparing five AFCs). When five spectral distinct photons - spectra matching with the five AFCs - are absorbed by the five AFCs respectively, five collective atomic excitation states can be generated. The state in one of the channels, e.g., in channel 1, can be expressed as:

\[
|\Psi_1\rangle = \frac{1}{\sqrt{W_1}} \sum_{j=1}^{W_1} c_j e^{i2\pi \delta_j t} e^{-ikz_j} |g_1 g_2 ... e_j ... g_W_1\rangle,
\]

where \(W_1\) is the total atom number constituting the AFC in channel 1, the amplitude \(c_j\) depends on both the resonance frequency and position of the \(j_{th}\) atom, \(\delta_j\) is the detuning of the \(j_{th}\) atom with respect to the photon carrier frequency, \(k\) is the wave number of the input photon, \(z_j\) is the position of the \(j_{th}\) atom, \(|g_j\rangle\) and \(|e_j\rangle\) represent ground and excited states of the \(j_{th}\) atom, respectively. Following the creation of the collective atomic excitation, the different terms in the collective excitation state \(|\Psi_1\rangle\), having different detunings, begin to accumulate different phases. Due to the periodic nature of AFC, i.e., \(\delta_j = m_j \Delta\) (\(m_j = 0, \pm 1, \pm 2, \ldots\) and \(\Delta\) is the teeth spacing of AFC), at the time \(t = 1/\Delta\) all terms in the state acquire phases equal to an integer multiple of \(2\pi\), which are all equivalent to 0. This process of rephasing leads to the re-emission of input photon in its original quantum state.

To characterize the five spectral channels of quantum memory, we generate heralded single photons at telecom wavelength in a fibre pig-tailed periodically poled lithium niobate (PPLN) module\(^{48-50}\), as shown in Fig. 2(a)(II). The light from a continuous-wave (CW) laser (PPCL300, PURE Photonics) operating at 1540.60 nm is modulated to light pulses and subsequently sent into the PPLN module. The cascaded second-harmonic generation (SHG) and spontaneous parametric down conversion (SPDC) processes result in correlated photon-pairs centred at 1540.60 nm with a bandwidth of ~60 nm. After efficient filtering, the central wavelengths of signal and idler photons are 1531.88 nm and 1549.32 nm with a
bandwidth of $\sim$100 GHz. The signal photons are sent into the five AFC spectral channels. It is worth noting that AFC itself is both a filter and a memory, in the sense that the spectral modes that do not match the storage bandwidth will be either absorbed and re-emitted spontaneously (with a decay time of $\sim$10 ms) or pass through the memory, in which case they can be discriminated by their arrival time. Then, recalled signal photons from different AFCs are selected by a tunable fibre Bragg grating (FBG). The idler photons corresponding to different recalled signal photons are further selected by another FBG. The two FBGs enable the selective detection of different frequency modes employed in spectral multiplexing (see Supplementary Information note 2 for more details of heralded single photon source).

Finally, we establish a coincidence detection system consisting of superconducting nanowire single photon detectors (SNSPDs, P-CS-6, PHOTEC Corp.) and a time-to-digital converter (TDC, quTAG, qutools), as shown in Fig. 2(a)(III) (see Methods for details of the SNSPDs). All SNSPD detection signals are delivered to the TDC to perform coincidence measurements. The system storage efficiency can be calculated by the ratio of the counts of recalled heralded photons to that of the input heralded photons. The second-order cross-correlation function ($g_{s,i}^{(2)}(0)$) between signal and idler photons after/before storage is calculated as:

$$g_{s,i}^{(2)}(0) = \frac{p_{si}}{p_s \cdot p_i},$$

where $p_{si}$ is the probability of 3-fold coincidence detections of trigger signal, idler photons, and signal photons, $p_s$ ($p_i$) is the probability of coincidence detections of trigger signal and signal (idler) photons, respectively. Note that the coincidence detection in our experiment with trigger signal enables us to select the recalled photons by their arrival time, thus reducing the noise photon from the residual spontaneous emission. According to the Cauchy-Schwarz inequality, a non-classical field satisfies $g_{s,i}^{(2)}(0) > 2$. More details of measuring $g_{s,i}^{(2)}(0)$ through coincidence counts are given in Methods.

**Measurement.** First, we investigate the performance of the five AFC spectral channels. To this end, we vary the storage time from 5 ns to 230 ns by programming the tooth spacing from 200 MHz to 4.35 MHz. For each case, we map heralded single photons onto each of the five spectral channels, and subsequently collect coincidence statistics of the recalled photons to gauge storage performance in terms of storage time, efficiency, and preservation of quantum properties manifested in the $g_{s,i}^{(2)}(0)$ values. According to the measured results, the system storage efficiency of each channel with different storage times ranges from 0.1%
to 1%. The $g_{s,i}^{(2)}(0)$ still remains above 25 for the maximum storage time of 230 ns (see Table I), demonstrating strong non-classical properties for all storage times (see Supplementary Information note 3 and 4 for more analysis of the storage efficiency and $g_{s,i}^{(2)}(0)$ for five individual AFCs). Furthermore, these measurements demonstrate that our memory, in principle, is able to perform quantum storage of 2300 (10 GHz × 230 ns) temporal modes of telecom-band single photons in each channel, for five parallel channels amounting to a total of 11500 modes.

Second, to examine the effect of crosstalk between different spectral channels, we measure the $g_{s,i}^{(2)}(0)$ between recalled signal photons and heralding idler photons corresponding to different spectral channels$^{36}$. If there is no crosstalk between different spectral channels, the measured $g_{s,i}^{(2)}(0)$ between uncorrelated channels should be around 1. On the other hand, with increasing crosstalk, the value of $g_{s,i}^{(2)}(0)$ would also increase (the relationship between crosstalk and $g_{s,i}^{(2)}(0)$ is shown in Supplementary Information note 5). To eliminate the crosstalk between spectral channels, a sufficiently large separation between adjacent AFCs is required$^{27}$ - in our case we choose 5 GHz separation. We first assess the crosstalk resulting from the source and detection system without the quantum memory. For the crosstalk characterization, we label the signal photons corresponding to channels 1 to 5 as $S_1$, $S_2$, ..., $S_5$, and similarly, the idler photons as $I_1$, $I_2$, ..., $I_5$. The choice of which signal and idler channels to detect is determined by the tunable FBG filter settings. Measuring coincidences between $S_m$ and $I_n$, where $m, n \in \{1, 2, 3, 4, 5\}$, we calculate a $5 \times 5$ matrix of $g_{s,i}^{(2)}(0)$. The measured average $g_{s,i}^{(2)}(0)$ is $27.90 \pm 0.18$ for 5 pairs of correlated spectral modes ($m=n$) and $1.07 \pm 0.02$ for the 20 pairs of uncorrelated spectral modes ($m \neq n$), where error bars are acquired through Monte Carlo simulation. The detailed values are shown in Supplementary Information note 6. The results indicate that the crosstalk between different spectral channels is negligible. Next, we evaluate whether the multimode memory induces additional crosstalk. To that end, we send the signal photons into the five AFC spectral channels with the storage time of 200 ns. The recalled signal photons from different channels are indexed as $R_1$, $R_2$, ..., $R_5$. Measuring coincidences between $R_m$ and $I_n$, we obtain the recalled signal photons from five channels (see Fig. 3(a)), and again calculate the $5 \times 5$ array of $g_{s,i}^{(2)}(0)$ values as shown in Fig. 3(b). The measured average $g_{s,i}^{(2)}(0)$ between recalled photons and idler photons is $25.48 \pm 1.05$ for five correlated spectral modes and $1.01 \pm 0.10$ for 20 pairs of uncorrelated spectral modes. The results confirm that the crosstalk between different spectral channels is negligible in our quantum memory.
Third, to quantify the multimode capacity of our quantum memory, we create a train of heralded single photons - with pulse durations of and spaced by 300 ps - for simultaneous storage in all five spectral channels. With the storage time of 200 ns, 330 temporal modes are simultaneously stored in each spectral channel (see Fig. 3(c)). The total stored mode number is, thus, up to 1650. Furthermore, to assess the crosstalk between different temporal modes, we obtain $1650 \times 1650$ values of $g^{(2)}_{s,i}(0)$ through measuring cross-correlation function between different idler photons and recalled signal photons. Figure 3(d) presents parts of $g^{(2)}_{s,i}(0)$ corresponding to different temporal modes in channel 2 (the full $1650 \times 1650$ array of $g^{(2)}_{s,i}(0)$ is shown in Supplementary Information note 7). The average $g^{(2)}_{s,i}(0)$ between correlated signal and idler photonic modes (1650 pairs) is $22.92 \pm 0.07$, verifying that the non-classical correlations are intact. For uncorrelated modes the $g^{(2)}_{s,i}(0)$ is $1.01 \pm 0.01$ on average with error bar from Monte Carlo simulation, confirming the negligible crosstalk between different temporal modes. In addition, we conclude the key metrics of our multimode quantum memory in Table II, which also includes the state-of-the-art of multimode quantum storage of non-classical light based on REID materials.

Discussion

An important feature of our demonstration is the large multimode capacity of quantum memory for storage of single photons at telecom wavelength. Yet there are clear avenues to further advance the multimode capacity. First, by making use of the entire THz-wide inhomogeneous broadening of the EDF, at least seventy individual 10-GHz-wide AFCs could be generated with a separation of 5 GHz. Generating that many large-bandwidth channels, requires a broader optical frequency comb, which can be achieved by a nonlinear broadened comb, Kerr soliton microcomb, and mode-locked fibre laser comb etc. Second, by increasing temporal mode number in each channel to the upper bound determined by the time-bandwidth product of the AFC, a total number of spectro-temporal modes of $10 \text{ GHz} \times 230 \text{ ns} = 2300$ can be realized in each channel, where 230 ns is the measured storage time in our experiment. Combining these improvements, the multimode capacity would exceed $70 \times 10 \text{ GHz} \times 230 \text{ ns} \approx 160000$. In addition, we note that the multimode capacity of our quantum memory could be further increased via adapting multiplexing in the spatial degree.

A number of upgrades are required to make our multimode quantum memory suitable for future quantum networks. A pressing limitation of our system is its low storage efficiency and short storage time. With regards to the efficiency, the main reason it reaches no
more than about 1%, is the presence of the non-zero background absorption, i.e., residual atoms that cannot be removed from the AFC troughs. The first factor is the insufficient lifetime of the Zeeman sublevels compared to that of the excited level. During the 200 ms waiting time, which is set to avoid spontaneously emitted photons, the population of the Zeeman sublevels has also decayed, filling the AFC troughs. The second factor is the small branching ratio for atoms decaying to a different Zeeman sublevel, which leads to incomplete population transfer among the sublevels. It is possible to increase the storage efficiency by lowering the erbium concentration to obtain the longer lifetimes of the Zeeman sublevels. In addition, spin mixing and stimulated emission during preparation of AFC are expected to further decrease the background absorption. The coherence time is a more limiting factor for the storage time, and is highly affected by coupling to two-level systems (TLSs) - both magnetic and non-magnetic. At very low temperatures this interaction is reduced significantly as the phonon energies needed to activate the TLSs become unavailable. Indeed, based on previous characterizations on similar fibres, the expectation of coherence time at 10 mK exceed the memory lifetime we observe. This could point to differences between fibres due to erbium concentrations. Hence, we assert that we could further increase the optical coherence time and by appropriately decreasing the doping concentration. In general, the optical coherence times exhibited in crystals are longer than those in amorphous materials. This is owing to that the crystal host materials have ordered structures at the atomic level, forming a single crystal field, in which the phonon-assisted tunneling is negligible. Conversely, disordered structures in amorphous materials lead to increased disorder and complexity of the environment. When ions in such environment absorb or emit phonons, the interactions with dynamic fluctuations in the environment can be intensified, thereby exacerbating decoherence. However, doping with different co-dopants in amorphous materials can change their internal environment, potentially improving the optical coherence time. Furthermore, employing zero first-order Zeeman (ZEFOZ) magnetic field and dynamical decoupling can further increase the coherence time. By doing so, in Eu³⁺:Y₂SiO₅ crystals spin coherence time up to six hours has been measured and optical storage time can surprisingly achieve one hour. To improve the coherence time of the EDF, continued studies and better understanding of the fundamental interactions which limit the coherence time are required. Yet, we note that not all applications of quantum memory require long storage time. It remains attractive in conjunction with quantum processors that also operate at the same low temperatures
and provide a pathway for quantum transducers from microwave to telecom wavelength photons.

Despite our quantum memory having a pre-set storage time, it can still be employed in repeater schemes for which multiplexing relies on mode-mapping in other degrees of freedom, such as spectral shifting. However, for some applications, on-demand storage may be necessary. One promising option to enable this feature is spin-wave storage, which allows optical coherence to be mapped onto a long-lived spin state, such as the hyperfine level. Nevertheless, it remains challenging due to the complex energy-level structure in EDF.

Furthermore, this method would result in a reduction in memory bandwidth - affected by the small nuclear spin levels splitting - but if these levels have long coherence, the multimode capacity of memory is not affected significantly. Another possibility is to utilize the controllable Stark shift, which, for instance, could inhibit the rephasing of the collective excitation by applying one electric-field pulse during the time interval \([0, 1/\Delta]\), and lead to the recovery of the original photon at the time \(n/\Delta\) by applying a second electric-field pulse in the time interval \([(n - 1)/\Delta, n/\Delta]\), where \(n\) is an integer.

In conclusion, we have demonstrated a multimode quantum memory that is suitable for storage of spectro-temporal modes of single photons at telecom wavelength. A quantum memory with five 10-GHz-wide AFC channels in a 10-m-long cryogenically cooled EDF is prepared, and 330 temporal modes of heralded single photons are stored in each channel leading to the multimode capacity up to 1650. The key method introduced here is the combination of an optical frequency comb with frequency chirping to prepare large-bandwidth multi-channel AFCs, thus, enabling the large multimode capacity of our memory. Our works pave the way for constructing future quantum internet compatible with current telecom infrastructure.

**Methods**

**Erbium doped silica fibre.** The experiment utilizes a 10-m-long, single-mode, commercial EDF with Er\(^{3+}\) ions doping concentration of 200 ppm, co-doped with Al, Ge, and P. The fibre is spooled to a home-made copper cylinder with a diameter of 4 cm and fixed in the dilution refrigerator (LD400, Bluefors), in which the temperature can be cooled below 10 mK. The measured absorption at 1532 nm is 0.35 dB/m at T=10 mK. The EDF is fused with single-mode fibres for each end and exposed to 2000 Gauss magnetic field provided by a superconducting magnet. The loss of the whole fibre sample is about 2.5 dB, including
bending, splicing, and transmission loss.

**Experimental time sequences and procedures.** The time sequences are shown in Fig. 2(b). During the preparation time of 300 ms, the pump light from a CW-laser operating at 1531.88 nm is prepared into an optical frequency comb with frequency spacing of 15 GHz by an IM and a PM, both of which are driven by 15 GHz microwave signals. The optical frequency comb is sent to another PM, which is driven by an arbitrary waveform generator (AWG) to continuously generate frequency chirping light on each comb ranging from -5 GHz to 5 GHz (total span of 10 GHz). Then the prepared pump light is modulated into 300-ms-long light pulses by an OS, and sent into the EDF to prepare quantum memory with five spectral channels. The setting 200 ms waiting time is to decrease the influence of spontaneously emitted photons from excited ions on the recalled photons from the AFC (see Supplementary Information note 8 for more details). During the storage time of 500 ms, another OS turns on. The light from a CW-laser operating at 1540.60 nm is modulated into a light pulse with pulse duration of 300 ps and the repetition rate of 1 MHz (for multiple temporal modes storage, the laser is modulated to 330 light pulses within one cycle of 1 \( \mu \)s, i.e., \( T_{\text{period}}=1 \ \mu \)s) and sent to PPLN module for the generation of correlated photon-pairs with a bandwidth of \( \sim 60 \) nm. By utilizing DWDMs, signal photons at 1531.88 nm and idler photons at 1549.32 nm with a bandwidth of 100 GHz are filtered out. The signal photons are sent into five-channel quantum memory to filter and to store. After the storage time of \( T_{\text{storage}} \), the signal photons are recalled from AFCs. Finally, the idler photons and recalled signal photons corresponding to different channels are selected by FBGs and detected by SNSPDs, subsequently performed coincidence analysis in the TDC.

**Superconducting nanowire single photon detectors.** All detections of single photons are carried out by a set of SNSPDs system provided by PHOTEC Corp. The system consists of SNSPD devices, cryostat system, and electronic control system. The niobium nitride (NbN) SNSPDs, manufactured by Shanghai Institute of Microsystem and Information Technology (SIMIT), operate at \( \sim 2.2 \) K in the cryostat system with a dark counting rate of \( 100 \) Hz and a time jitter of \( \sim 100 \) ps. All detectors have a dead time of less than 50 ns and a detection efficiency of \( \sim 60\% \).

**Calculation of cross-correlation function** \( g_{s,i}^{(2)}(0) \). Considering the counting effective events in \( m \) experimental trials, we record the total 3-fold coincidence counts \( C_{si} \) of the trigger signal, idler and signal photons, the coincidence counts \( C_s \) (\( C_i \)) between signal (idler) photons and trigger signals. With the photon detected probability in each trial calculated...
as $p_{si} = C_{si}/m$, $p_s = C_s/m$, $p_i = C_i/m$, the second-order cross-correlation function $g^{(2)}_{s,i}(0)$ is calculated by

$$g^{(2)}_{s,i}(0) = \frac{p_{si}}{p_s \cdot p_i} = \frac{C_{si} \cdot m}{C_s \cdot C_i}. \quad (3)$$

It is a strong indication of quantum correlations for photons-pairs if $g^{(2)}_{s,i}(0) \gg 2$. According to Cauchy-Schwarz inequality, it also indicates that the auto-correlation function of heralded signal photons is $\ll 1$, i.e., these signal photons are denoted as single photons.

For all the coincidence measurements in this paper, the width of coincidence window is 600 ps.

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

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Author contributions
Q.Z. and D.O. conceived and supervised the project. S.W. and B.J. mainly carried out the experiment and collected the experimental data with help of other authors. H.L., L.Y. and Z.W. developed and maintained the SNSPDs used in the experiment. S.W., B.J. and Q.Z. analyzed the data. S.W., B.J., D.O. and Q.Z. wrote the manuscript with inputs from all other authors. All authors have given approval for the final version of the manuscript.

Competing interests
The authors declare no competing interests.
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FIG. 1: Spectro-temporal multimode quantum storage of single photons at telecom wavelength. (a) General scheme for storage of $N \times M$ modes of single photons. A train of $M$ temporal modes are stored into the AFCs with $N$ spectral channels, resulting in storage of $N \times M$ modes of single photons. (b) The absorption profile of $^4I_{15/2}$ to $^4I_{13/2}$ transitions of Er$^{3+}$ ions in the EDF at 10 mK. The inhomogeneous broadening is up to 2 THz (only 1 THz are shown here). In the section of inhomogeneous broadening absorption profile (70 GHz wide), we prepare five 10-GHz-wide AFCs with a separation of 5 GHz between the edges of adjacent AFCs. In principle, over seventy such AFCs can be prepared if we make use of the entire inhomogeneous broadening. (c) Simplified energy level scheme of Er$^{3+}$ ions in erbium doped silica fibre. AFCs are prepared through frequency-selective optical pumping that transfers atomic states from the ground state ($|g\rangle$) to the auxiliary state ($|aux\rangle$) via the excited state ($|e\rangle$), forming AFCs. (d) A typical trace of 10-GHz-wide AFC measured in our experiment (the central wavelength of the AFC is 1532.00 nm, and comb spacing $\Delta$ is 100 MHz, leading to $T_{storage}=10$ ns).
FIG. 2: **Experimental setup and time sequences.** (a) Experimental setup. (I) Preparation of AFC-based memory with five spectral channels. The erbium doped silica fibre (EDF) is cooled to a temperature of 10 mK by a dilution refrigerator and exposed to a magnetic field of 2000 Gauss provided by a superconducting magnet. Light from a continuous-wave laser (CW-laser) is firstly modulated to an optical frequency comb (OFC) by an intensity modulator (IM) and a phase modulator (PM). Then another PM is utilized to generate chirped light on each comb of the OFC. The modulated pump light is sent to the EDF via an optical circulator (Cir). Optical switch (OS) and variable optical attenuator (VOA) are used to control the pump time and intensity. Beam splitter (BS) and optical power meter (OPM) are utilized to monitor the pump light power. Fibre Bragg grating (FBG) is used to select signal photons recalled from different AFCs. (II) Preparation of the heralded single photon source (HSPS). Light from a CW-laser is modulated to 300 ps pulses by an IM and sent to the periodically poled lithium niobate (PPLN) module for generating correlated photon-pairs. By utilizing two dense wavelength division multiplexers (DWDMs), signal photons at 1531.88 nm and idler photons at 1549.32 nm with a bandwidth of 100 GHz are filtered out. FBG is used to select the idler photons corresponding to different spectral channels. Subsequently idler photons are directly sent to the detection system. The signal photons are sent into the EDF for storage. Erbium doped fibre amplifier (EDFA) and VOA are used to adjust the pump power. Polarization controller (PC) and polarizing beam splitter (PBS) are utilized to control the polarization of pump light. (III) Detection system. The idler and recalled signal photons are detected by two superconducting nanowire single photon detectors (SNSPDs). Coincidence measurements are performed by a time-to-digital converter (TDC). PCs are used to control the polarizations of signal and idler photons. (b) Time sequences. The cycle time of the experiment is one second, including 300 ms for AFCs preparation, 200 ms for waiting spontaneously emitted photons from excited states, and 500 ms for storage (more details see Methods).
FIG. 3: Characterization for the multimode quantum memory. (a) Results for spectral-multiplexed storage in five AFC spectral channels with a storage time of 200 ns. (b) Crosstalk between different spectral modes of idler photons and recalled photons. The average measured $g_{s,i}^{(2)}(0)$ between recalled photons and idler photons is $25.48 \pm 1.05$ for 5 correlated spectral modes and $1.01 \pm 0.10$ for 20 uncorrelated modes. (c) Results for storage of 1650 spectro-temporal modes of single photons at telecom wavelength. Heralded single photons with 330 temporal modes are generated and stored into five spectral channels with a storage time of 200 ns, totally, 1650 modes are stored into the five AFCs. (d) Crosstalk between different temporal modes of idler photons and signal photons recalled from channel 2 (mode numbers: 1, 80, 160, 240, 330). The average $g_{s,i}^{(2)}(0)$ between correlated recalled signal and idler photon modes (1650 pairs) is $22.92 \pm 0.07$. For uncorrelated modes, the average $g_{s,i}^{(2)}(0)$ is $1.01 \pm 0.01$. Error bars in Figs. (b) and (d) are calculated by standard deviations of counts which obey Poisson distribution.
TABLE I: Measured crosstalk ($g_{s,i}^{(2)}(0)$) between recalled signal photons and idler photons with different storage time.

| Storage time | Channel 1   | Channel 2   | Channel 3   | Channel 4   | Channel 5   |
|--------------|-------------|-------------|-------------|-------------|-------------|
| 0 ns         | $25.64\pm0.19$ | $27.53\pm0.18$ | $27.91\pm0.18$ | $28.38\pm0.18$ | $28.62\pm0.19$ |
| 10 ns        | $26.13\pm1.45$ | $28.97\pm1.20$ | $26.81\pm1.49$ | $26.10\pm1.05$ | $27.07\pm1.15$ |
| 50 ns        | $26.95\pm1.48$ | $26.72\pm1.32$ | $26.85\pm1.59$ | $26.95\pm1.23$ | $22.99\pm1.11$ |
| 100 ns       | $26.08\pm1.90$ | $25.77\pm1.60$ | $24.48\pm1.92$ | $27.01\pm1.69$ | $25.85\pm1.36$ |
| 230 ns       | $26.22\pm4.32$ | $31.00\pm4.41$ | $26.22\pm4.32$ | $26.59\pm3.81$ | $22.09\pm3.34$ |
TABLE II: Comparison on the time-bandwidth product and multimode capacity of quantum memories for non-classical light based on different REID materials.

| System            | $\lambda$ (nm) | $T_{storage}$ (ns) | BW (GHz) | TBP | $N^e$ |
|-------------------|----------------|--------------------|----------|-----|-------|
| Eu$^{3+}$:Y$_2$SiO$_5$ | 580           | $1\times10^6$     | 0.002    | 2000| 12    |
| Pr$^{3+}$:Y$_2$SiO$_5$ | 606           | 3500               | 0.06     | 210 | 130   |
| Tm$^{3+}$:Ti$^{3+}$:LiNbO$_3$ | 795        | 7                  | 5        | 35  | 1     |
| Tm$^{3+}$:Y$_3$Al$_5$O$_{12}$ | 795         | 100                | 0.5      | 50  | 1     |
| Nd$^{3+}$:YVO$_4$ | 880           | 500                | 0.5      | 250 | 100   |
| Nd$^{3+}$:Y$_2$SiO$_5$ | 883           | 200                | 0.12     | 24  | 10    |
| Yb$^{3+}$:Y$_2$SiO$_5$ | 979           | $2.5\times10^4$   | 0.1      | 2500| 1250  |
| Er$^{3+}$:Ti$^{3+}$:LiNbO$_3$ | 1532         | 48                 | 6        | 288 | 1     |
| Er$^{3+}$:LiNbO$_3$ | 1532         | 100                | 4        | 400 | 147   |
| EDF (this work)   | 1532          | 50                 | 16       | 800 | 6     |

$^a$ $\lambda$ is the wavelength of the stored single photons.

$^b$ $T_{storage}$ is the storage time of AFC quantum memory.

$^c$ BW is the available storage bandwidth of quantum memory.

$^d$ TBP is the time-bandwidth product of quantum memory.

$^e$ Number of stored modes (i.e., multimode capacity).
Supplementary Files

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