Coherent Optical Memory
Based on A Laser-written On-chip Waveguide

Tian-Xiang Zhu,1,2 Chao Liu,1,2 Liang Zheng,1,2 Zong-Quan Zhou,1,2,∗ Chuan-Feng Li,1,2,† and Guang-Can Guo1,2
1 CAS Key Laboratory of Quantum Information, University of Science and Technology of China, Hefei 230026, China
2 CAS Center For Excellence in Quantum Information and Quantum Physics, University of Science and Technology of China, Hefei 230026, China
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Quantum memory is the core device for the construction of large-scale quantum networks. For the scalable and convenient practical applications, the integrated optical memories, especially the on-chip optical memories, are crucial requirements because they can be easily integrated with other on-chip devices. Here, we report the coherent optical memory based on a type IV waveguide fabricated on the surface of a rare-earth-ion doped crystal (i.e. Eu3+:Y2SiO5). The properties of the optical transition (7F0 → 5D0) of the Eu3+ ions inside the surface waveguide are well preserved as compared to that of the bulk crystal. Spin-wave atomic frequency comb storage is demonstrated inside the type IV waveguide. The reliability of this device is confirmed by the high interference visibility of 95 ± 1% between the retrieval pulse and the reference pulse. The developed on-chip optical memory paves the way towards integrated quantum nodes.

I. INTRODUCTION

Optical quantum memories (QMs), as a light-matter interface, are enabling techniques for various applications in quantum information science, including the generation of on-demand photons [1, 2], serving as an identity quantum gate in quantum computation [3, 4], and building the quantum repeater for large-scale quantum network [4, 5]. Among various physical systems for the implementation of QMs [6–10], the rare-earth-ion doped crystals, as a solid-state platform, has shown some unique advantages, such as large bandwidth [11, 12], high multimode capacity [13, 14], long-lived coherence [17, 18], and high storage fidelity [19, 20]. For the scalable and convenient applications, great efforts have been devoted to the integrated optical memories based on the waveguide manufactured by various techniques [11, 12, 14, 20, 28]. The femtosecond-laser micromachining (FLM) has been a powerful tool for fabrication of integrated optical memory due to its advantages of high accuracy and low damages to the samples [29–31]. Photonic quantum storage using the FLM waveguides have been implemented with the comparable performances in storage times and storage efficiencies as compared to that based on bulk material [24, 26, 32].

Generally, there are four types of waveguides obtained by FLM [33]. Previous demonstration of integrated QMs based on FLM focus on the structure of type I [25, 32] and type II waveguides [24, 26]. These waveguides are fabricated at a depth of a hundred-micron scale beneath the crystal surface. However, the integrated optical devices should be made on the surface of the substrate to conveniently interface with other on-chip devices such as coplanar electrical structures.

Here, we solve this problem by fabricating a type IV on-chip waveguide in the rare-earth-ion doped crystals and utilize it to conduct a coherent optical memory for the first time. Our type IV waveguides are fabricated in a Eu3+:Y2SiO5 crystal. We carefully characterized the optical transition (7F0 → 5D0) of Eu3+ ions inside the type IV waveguide, including the optical coherence time (T2) and the optical inhomogeneous broadening. We implement spin-wave atomic frequency comb (AFC) storage and observe high interference visibility between the readout echo and a reference pulse. The spin inhomogeneous broadening of the Eu3+ ions inside the waveguide is characterized by analyzing the spin-wave storage dephasing of AFC storage.

II. FABRICATION OF THE TYPE IV WAVEGUIDES

The waveguides fabricated by FLM are classified according to the refractive index changes in the laser-written area, geometric shape and waveguide position of the sample [33]. The type IV waveguide consists of two deep laser-irradiated scores and is located on the surface of the crystal, it is also called as the ridge waveguide. The laser beam can be constrained between the two gaps and propagates through the waveguide.

We use the FLM system from WOPhotonics (Altechna RD Ltd, Lithuania) to fabricate the type IV waveguide on a Eu3+:Y2SiO5 crystal, with a doping level of 0.1% and a dimension of 10 mm × 3.25 mm × 3.25 mm (b×D1×D2). Many parameters affect the results of the fabrication processes, for instance, the wavelength, the pulse duration, the polarization, the repetition frequency, the waist size of the focus spot and the energy of per-pulse of the femtosecond laser [24, 25]. Considering the anisotropy of the Eu3+:Y2SiO5 crystal, the injection direction of the laser beam will also influence the results of FLM [25, 26]. In our experiment, the femtosecond laser beam is focused...
FIG. 1. (a) Experimental setup. The crystal is placed in a cryostat with a base temperature of 3.2 K. The incident laser beam is split into two parts, i.e., the input mode and the preparation & control mode. They are modulated by the independent acousto-optic modulators (AOM), and combined via a beam splitter (BS, with a reflectivity of 8%) and finally coupled into the single-mode fiber. The Gaussian beam is coupled into the type IV waveguide via a 3× beam expander (BE, GBE03-A, Thorlabs) and a lens with a focal length of 75 mm. The output beam is coupled into the single-mode fiber by the lens set, for spatial filtering. Finally, the output beam is sent into a photovoltaic detector after passing through a temporal gate based on AOM3. FC: fiber coupler, PBS: polarization beam splitter. (b) Top view of the type IV Waveguides, in the plane of b×D1 of the crystal. (c) Front view of The type IV Waveguides, in the plane of D2×D1 of the crystal. The scale bar of (b) and (c) is 50.0 µm. The depth of the ridges are 13.0 µm, the width of the ridges is 4.8 µm, and the spacing between the ridges is 15.2 µm.

The laser beam injects along the D2 axis of the crystal and moves along the b axis with a speed of 1 mm/s. To ensure single-mode operation of the waveguide, the distance between the two parallel damage tracks are set as 20 µm. By optimizing the single-mode coupling efficiency of the 580 nm laser polarized along the D1 axis in type IV waveguides fabricated with various conditions, we obtain the following parameters: 1030 nm laser wavelength with 300 fs pulse duration, 20 kHz repetition rate and 1.7 µJ per-pulse energy, the polarization of the laser is along the b axis. Since the defects on the crystal also affect the effect of FLM [26], we fabricate several type IV waveguides in the Eu³⁺:Y₂SiO₅ crystal, in order to find a high-quality waveguide to conduct the experiments. The coupling efficiency of our type IV waveguide into the single-mode fiber is 10.4%.

III. EXPERIMENT SETUP

The laser source is a frequency-doubled semiconductor laser at 580 nm (TA-SHG, Toptica). To meet the requirements of narrow line-width in the optical memory experiments, the laser is locked to a Fabry-Perot cavity to achieve a linewidth of approximately 0.1 kHz. We use the acousto-optic modulators (AOMs) and an arbitrary waveform generator (AWG) to modulate and control the laser beam. As shown in Fig. the AOM1 and AOM2 are used to modulate input mode and preparation & control mode, respectively. The sample is assembled on a cryostat (Montana Instruments) that can provide an environment of low vibration and a base temperature of approximately 3.2 K. Besides, an electronically controlled three-axis stage is installed on the cryostat and its accuracy is on the order of 10 nm, which makes it convenient to couple the laser beam into waveguides.

IV. RESULT

A. Characterization of the type IV waveguide

To check whether the optical properties of the type IV waveguide are modified as compared to that of the bulk area, we first measure the optical inhomogeneous broadening of the optical transition (7F₀ → 5D₉) of Eu³⁺ ions in different sections of the crystal firstly. We choose three representative positions of the crystal, including the type IV waveguide region, the bulk section at the same depth (13 µm) beneath the upper surface of the crystal as the waveguide region (marked as bulk 1) and the bulk section at the center region, which is 1.6 mm beneath the top surface of the crystal (marked as bulk 2). We scan the frequency of incident light to obtain the absorption spectrum of the sample. The measured peak absorption frequency of bulk 1 is 516.84762 THz and its
full width at half maximum (FWHM) length is 2.0 GHz; the peak absorption frequency of bulk 2 is $516.84762\,\mathrm{THz}$ and its FWHM length is 2.0 GHz; the peak absorption frequency of the waveguide region is $516.84722\,\mathrm{THz}$ and its FWHM length is 2.5 GHz. The results show that the surface of the crystal has the same optical inhomogeneous broadening as the center of the crystal. The maximum absorption frequency of the waveguide has a red-shift of 400 MHz compared to that of the two bulk sections and the linewidth is slightly broadened by 500 MHz.

The optical coherence time ($T_2$) is another important parameter to characterize the coherent properties of the type IV waveguide. Two-pulse photon echo [34] is implemented in the three representative regions (the type IV waveguide area, bulk1 area and bulk2 area) of the sample. Fig. 2 shows the two-pulse photon echo amplitude as a function of the two-pulse spacing, the optical coherence time ($T_2$) is extracted from the inverse of the slope of the fitted curve. In the type IV waveguide area, we get $T_2$ of $124 \pm 4\,\mu\mathrm{s}$ when the peak power of the input pulse is 1.8 mW. The $T_2$ is $113 \pm 3\,\mu\mathrm{s}$ in the bulk 1 area and $119 \pm 4\,\mu\mathrm{s}$ in the bulk 2 area, with the peak power of the input pulse is 4.7 mW and 4.6 mW, respectively. The obtained $T_2$ for waveguide region is essentially the same as that measured in the bulk regions. Therefore, we conclude that the fabrication process of the type IV waveguide has negligible effects the optical coherent property of the sample, and this on-chip waveguide is ready for use as optical quantum memories.

### B. optical storage based on the type IV waveguide

The atomic-frequency-comb (AFC) scheme is a widely-employed quantum memory schemes in solid-state systems [8] with the main advantages are broadband [11, 12], high multimode capacity [13–16], and high storage fidelity [19, 20]. Taking advantage of the large inhomogeneous broadening of the optical transition ($^7F_0 \rightarrow ^5D_0$) of Eu$^{3+}$ ions, a comb structure can be shaped on the spectrum by utilizing spectral hole burning technique [33]. The frequency periodicity of the comb can be denoted as $\Delta$. When an optical pulse is absorbed by Eu$^{3+}$ ions in comb structure at the initial moment, those ions with a detuning of $m \cdot \Delta$ will be collectively excited where $m$ is an integer. During the dephasing of the excited atoms, a coherent AFC photon echo will emit at time $1/\Delta$ [30]. Long storage time and on-demand retrieval can be...
achieved by further utilizing the spin-wave AFC scheme \cite{55}. The core of this method is utilizing a control pulse to transfer the atoms from the excited state into the extra empty ground state which freezes the AFC evolution and suppress the two-level AFC echo. Then, another control pulse is applied to bring back the excitation. The dephasing process of AFC scheme will continue and emit a photon echo (called spin-wave AFC echo). The total storage time of the spin-wave AFC memory is \( t_{\text{tot}} = \tau_s + 1/\Delta \), with \( \tau_s \) of the time between the two control pulses.

The \(^{1}F_0 \rightarrow ^{5}D_0 \) level structure of the \(^{153}\)Eu\(^{2+}\) ions in the \( \text{Y}_2\text{SiO}_5 \) crystal is shown in the Fig. 3. We utilize the spectral hole-burning process \cite{26,37,38} to prepare a AFC comb structures, including class cleaning, population polarization, and creating the AFC comb structures at \( |\pm 1/2\rangle \)\_) while keeping \( |\pm 3/2\rangle \)\_) empty. The details of the preparation process can be found in our recent work \cite{26}. The prepared AFC has a bandwidth of 2 MHz and a storage efficiency of 2.4\% at a storage time of 8 \( \mu \)s. The storage efficiency is primarily limited by the low absorption (\( \alpha = 0.9 \text{ cm}^{-1} \)) of the sample since the dopant has two natural isotopes (\(^{151}\)Eu and \(^{153}\)Eu) and only \(^{151}\)Eu\(^{2+}\) is employed here. At the time of \( t = 0 \), an input pulse with the frequency of \( f_0 \) and the FWHM length of 750 ns is injected into the type IV waveguide and its AFC echo appears after 8 \( \mu \)s. Next, two control pulses with a center frequency of \( f_1 \) and a chirp bandwidth of 2 MHz are applied to implement spin-wave AFC scheme. The peak power of the control pulses are 58 m\( \mu \)W before the cryostat and they each have a duration (\( \tau_s \)) of 2.5 \( \mu \)s. The estimated transfer efficiency of a single control pulse is 58.3\%. The spin-wave echo appears at \( t_{\text{tot}} = \tau_s + 8 \mu \)s.

Due to the spin dephasing, the spin-wave AFC echo decays when \( \tau_s \) increases. As shown in Fig. 3 the spin-wave AFC echo amplitude can be linear fitted with storge time in spin state (\( \tau_s \)) in log scale, which indicates a Lorentzian profile of the spin inhomogeneous broadening for \( |\pm 1/2\rangle \)\_) \( \rightarrow \) \( |\pm 3/2\rangle \)\_). According to Ref. \cite{39}, the echo amplitude (\( A \)) can be represented by,

\[
A = A(0)e^{-\pi \gamma_s \tau_s}
\]

where \( \gamma_s \) is the inhomogeneous linewidth of the spin transition, \( A(0) \) is the spin-wave AFC echo amplitude with \( \tau_s = 0 \). The \( \gamma_s \) is fitted as 33 \( \pm \) 1 kHz in our type IV waveguide. This value is approximately the same as that measured in the bulk material \cite{14}, shown that the spin transition is also well protected in the waveguide fabrication process.

To characterize the fidelity of the entire storage process, we implement an interference test between the spin-wave AFC echo and a coherent reference pulse. The reference pulse is tuned precisely to overlap with the readout echo in the time domain \cite{26,42}. Meanwhile, the relative phase \( \varphi \) between the signal pulse and the reference pulse is modulated to obtain the interference curve. The interference between them is detected using a calibrated photomultiplier tube (PMT) \cite{26}. We used the same AFC preparation sequence, input pulse and control pulse as the previous experiment. We set \( \tau_s = 2.5 \mu \)s and record the signal when increasing the relative phase \( \varphi \) with a step of 30 degrees. The results are shown in Fig. 5 with a fitted interference visibility \( V \) of 0.95 \( \pm \) 0.01. This high visibility demonstrates the reliability of the on-chip optical memory in coherent phase storage. The remaining imperfection is mainly attributed to the imperfection of mode matching between the readout echo and the reference pulse and the detection noise.

\[\text{FIG. 4. Exponential decay of the spin-wave AFC echo amplitude with storage time in the spin state (} \tau_s \text{). The red solid line is the result of linear fitting, and the inhomogeneous linewidth of the spin transition (} |\pm 1/2\rangle \text{ } \rightarrow \text{ } |\pm 3/2\rangle \text{) is 33 \pm 1 kHz.}\]

\[\text{FIG. 5. Interference between the readout echo and a reference pulse. Here } \varphi \text{ corresponds to the relative phase between the input pulse and the reference pulse. The data points are fitted by } I(\varphi) = (I_{\text{max}}/2)[1 + V \sin(\varphi + \varphi')] \text{, where } I_{\text{max}} \text{ is the maximum intensity, } V \text{ is interference visibility, } \varphi' \text{ is initial phase. The fitting curve is represented by the red line with } V = 0.95 \pm 0.01.\]
V. CONCLUSION

A laser-written on-chip type IV waveguide is fabricated on an Eu$^{3+}$:Y$_2$SiO$_5$ crystal. Coherent optical storage based on spin-wave AFC scheme is implemented with high fidelity. We find the fabrication of the type IV waveguide will shift the absorption center and expand the optical inhomogeneous broadening slightly, while the optical coherence time is shown to be unchanged during the fabrication. The spin inhomogeneous broadening of Eu$^{3+}$ ions inside the type IV waveguide is essentially unchanged as compared to that of the bulk region. This is in contrast to that of the type II waveguide fabricated in Eu$^{3+}$:Y$_2$SiO$_5$ where a significant expansion of both the optical broadening and spin broadening is observed. This can be caused by the fact that the fabrication process of the type IV waveguide here has less damage to the crystal as compared to that of the type II waveguide.

Because of its on-chip structure, the type IV waveguide has its unique benefits in future practical applications. Nevertheless, several extensions of the current work can be considered. First, the coupling efficiency is currently limited by the rough edges of the ridges which can be improved by using higher magnification objective to increase the accuracy of FLM and constructing the new

VI. ACKNOWLEDGMENTS

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