Multifunctional on-chip storage at telecommunication wavelength for quantum networks

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Quantum networks will enable a variety of applications, from secure communication and precision measurements to distributed quantum computing. Storing photonic qubits and controlling their frequency, bandwidth, and retrieval time are important functionalities in future optical quantum networks. Here we demonstrate these functions using an ensemble of erbium ions in yttrium orthosilicate coupled to a silicon photonic resonator and controlled via on-chip electrodes. Light in the telecommunication C-band is stored, manipulated, and retrieved using a dynamic atomic frequency comb protocol controlled by linear DC Stark shifts of the ion ensemble’s transition frequencies. We demonstrate memory time control in a digital fashion in increments of 50 ns, frequency shifting by more than a pulse width (±39 MHz), and a bandwidth increase by a factor of 3, from 6 to 18 MHz. Using on-chip electrodes, electric fields as high as 3 kV/cm were achieved with a low applied bias of 5 V, making this an appealing platform for rare-earth ions, which experience Stark shifts of the order of 10 kHz/(V/cm).

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1. INTRODUCTION

Optical quantum memories will enable long-distance quantum communication using quantum repeater protocols [1–3]. A quantum memory device that can control the bandwidth and frequency of stored light is additionally useful, as it can interface between optical elements that have different optimal operating points. Erbium-doped materials are a promising solid-state platform for ensemble-based optical quantum memories because of their long-lived optical transition in the telecommunication C-band that is highly coherent at cryogenic temperatures [4,5]. This allows for integration of memory systems with low-loss optical fibers, opening up opportunities for repeaters over continental distances, as well as integration with silicon photonics [6,7], one of the most advanced platforms for integrated photonics. Spin transitions in $^{167}$Er$^{3+}$-doped yttrium orthosilicate ($^{167}$Er$^{3+}$:Y$_2$SiO$_5$) have also been shown to have long relaxation and coherence lifetimes at cryogenic temperatures and high magnetic fields [8], which opens the possibility for long-term spin-wave memories.

There have been several demonstrations of optical storage in erbium-doped materials [9–14], including storage at the quantum level [9,10,14] and on-chip storage [10,14]. These results are part of a larger body of optical quantum memory research [3,15] using rare-earth-ion-doped crystals [16–19], atomic gases [20,21], and single atoms or defects [22,23]. In parallel with efforts to increase the efficiency [20] and storage time [18,19] of quantum memories, several works have focused on new types of multifunctional devices [24–27] in which control fields are used to modify the state of the light during storage.

In many quantum repeater protocols [28], quantum memories act as interfaces between emitters such as quantum dots [29] or individual atoms [7]. Dynamic control of the optical pulses stored in these memories can correct for differences between individual emitters, leading to higher indistinguishably for Bell state measurements at the entanglement swapping stage of quantum repeater protocols [1]. In addition, with control over the frequency of stored light, one can map an input mode to a different output mode in a frequency multiplexed quantum memory, which enables quantum networks with fixed-time quantum memories [30].
In this work, we use a silicon resonator evanescently coupled to $^{167}\text{Er}^{3+}$:$\text{Y}_2\text{SiO}_5$ ions and gold electrodes to realize a multifunctional on-chip device that can not only store light but also dynamically modify its frequency and bandwidth. Electrodes create a DC electric field that can be rapidly switched, which enables control of the $^{167}\text{Er}^{3+}$ ions’ optical transition frequency via the DC Stark shift [31]. Using a resonator increases the interaction between light and the ion ensemble, allowing on-chip implementation of the atomic frequency comb (AFC) memory protocol [32]. This protocol allows multiplexing in frequency, which offers a significant advantage in quantum repeater networks [33]. Additionally, the on-chip electrodes are patterned close together to achieve the high electric fields required for Stark shift control with CMOS-compatible applied voltages. We demonstrate dynamic control of memory time in a digital fashion as well as modification of the frequency and bandwidth of stored light.

2. HYBRID $\alpha\text{Si}^{167}\text{Er}^{3+}$: $\text{Y}_2\text{SiO}_5$ RESONATOR WITH ELECTRODES

The multifunctional device consists of an optical resonator coupled to $^{167}\text{Er}^{3+}$:$\text{Y}_2\text{SiO}_5$ ions between gold electrodes. Using the AFC quantum storage protocol [35] and the ions’ Stark shift, light can be stored and manipulated in this device. Figure 1(a) shows a schematic of the device and the three functionalities demonstrated in this work: memory time control, frequency control, and bandwidth control. Different electric field configurations are created by applying a positive (blue) or negative (red) bias to each electrode. For the true device dimensions, see the micrograph in Fig. 1(h).

The optical resonator used in this work is a Fabry–Perot resonator comprised of a 100 µm amorphous silicon ($\alpha\text{Si}$) waveguide on $^{167}\text{Er}^{3+}$:$\text{Y}_2\text{SiO}_5$ with photonic crystal mirrors on either end. Figures 1(b)–1(d) show simulations and micrographs of this resonator. The waveguide is $h = 310$ nm tall and $w = 605$ nm wide. Ten percent of the energy of the transverse-magnetic (TM) optical waveguide mode penetrates into the $^{167}\text{Er}^{3+}$:$\text{Y}_2\text{SiO}_5$ and evanescently couples to the $^{167}\text{Er}^{3+}$ ions. Photonic crystal mirrors on either side are formed by a repeating pattern of elliptical air holes in the $\alpha\text{Si}$ waveguide with period $a_z = 370$ nm. A grating coupler is used to couple light from a free-space mode into and out of the resonator. The amorphous silicon resonator is fabricated on top of an $^{167}\text{Er}^{3+}$:$\text{Y}_2\text{SiO}_5$ chip using a deposition and etching process similar to Ref. [6]. The $^{167}\text{Er}^{3+}$:$\text{Y}_2\text{SiO}_5$ substrate is doped with isotopically purified $^{167}\text{Er}^{3+}$ ions at 135 ppm, measured by}

![Fig. 1](image-url)
secondary ion mass spectrometry, and cut perpendicular to the $D_1$ crystal axis, such that the electric field of the TM optical mode is polarized along this axis. The $x$, $y$, and $z$ axes in Fig. 1 correspond to the $D_2$, $b$, and $D_1$ $Y_2SiO_5$ crystal axes, respectively.

Quality factors of up to 10^5 were measured for weakly coupled resonators, where the photonic crystal mirrors on both sides were designed to be highly reflective. The device used in this work is made one-sided for more efficient quantum storage [14,35] by using fewer photonic crystal periods in one mirror to make it less reflective. Light is sent into and measured from the side with the lower-reflectivity mirror. The intrinsic quality factor for this device is also lower than the weakly coupled resonators, leading to a quality factor of $3 \times 10^5$ and a coupling ratio of $\kappa_{in}/k = 0.2$, where $\kappa_{in}$ is the coupling rate through the lower-reflectivity mirror and $k$ is the total decay rate [36]. The lower- (higher-)reflectivity mirror consists of 6 (30) regularly spaced holes, with an additional 15 holes in the tapers on either side. Several one-sided devices with different numbers of regularly spaced holes on the lower-reflectivity side were fabricated on the same chip, and the device with the best combination of quality factor and $\kappa_{in}/k$ was chosen.

Electrodes are used to apply electric fields to those ions coupled to the optical resonator. There are four independently biased gold electrodes, each comprised of a 70 $\mu$m diameter circle connected to a 20 $\mu$m x 60 $\mu$m rectangle. They are patterned onto a 5 V to the electrodes.}

In an ensemble of $^{167}$Er$^{3+}$:$Y_2SiO_5$ ions, four different Stark shifts will be observed for an arbitrary electric field due to the four orientations of each crystallographic site [39]. For electric fields parallel or perpendicular to the $b$ axis, the Stark shifts of the four subclasses are pairwise degenerate, resulting in two Stark shifts $\delta f_{\pm} = \pm \epsilon E$. In this work, all electric fields are applied parallel to the $b$ axis, so we will simply refer to two $^{167}$Er$^{3+}$ subclasses.

4. ATOMIC FREQUENCY COMB STORAGE WITH DYNAMIC MEMORY TIME CONTROL

After a photon is absorbed by an ensemble of ions, the ensemble of ions is described by a Dicke state [35]

$$|\Psi\rangle = \sum_{j=1}^{N_{\text{num}}} c_j e^{i2\pi(f_j t + f_j(\tau))} e^{-ik\tau t} |0\ldots j\ldots 0_N\rangle. \quad (1)$$

Each ion has a different transition frequency $f_j$ and position $r_j$. For AFC storage, the transition frequencies $\{f_j\}$ form a frequency comb with period $\Delta$. When a photon is absorbed at $t = 0$, the ensemble of ions first dephase then rephase every $t = \frac{m\pi}{\Delta}$, $m \in \mathbb{N}$, leading to a coherent reemission of the light [35]. A Stark shift $\delta f_j(t)$ enables dynamic control of light stored in the AFC by changing the optical transition frequencies of the ions. $\delta f_j(t)$ can be varied over time by changing the amplitude of the applied electric field (slowly relative to optical frequencies). This enables two types of control: electric field pulses applied between the absorption and emission of light modify the phase of the output, while electric field pulses applied during emission of light modify the frequency profile of the output light.

To achieve dynamic control of storage time, the electrodes are biased in a parallel configuration as shown in the top panel of Fig. 1(a). When an electric pulse is applied, the two $^{167}$Er$^{3+}$:$Y_2SiO_5$ subclasses experience opposite frequency shifts $\pm \delta f(t) = \pm \epsilon E$. By appropriately choosing the length in time $\tau$ and amplitude $E$ of the electric pulse, a $\pi$ phase difference between subclasses can be introduced: $\pi = 2\pi \times (\pm \epsilon E - (\mp \epsilon E)) \times t$, which will prevent any coherent emission from the ensemble. An
equal-area electric pulse with opposite sign can then rephase the two subclasses, and it allows coherent reemissions from the AFC. This procedure of dephasing and rephasing the ensemble works even if the electric field distribution is not perfectly homogeneous, as shown in the context of Stark echo modulation memory in Reference [41]. Recently, dynamic control of memory time in AFC was demonstrated using this same procedure in Pr$^{3+}$: Y$_2$SiO$_5$ [42]. Reference [12] proposed a similar protocol but using an electric field gradient.

The pulse sequence used to achieve dynamic control of AFC storage is shown in Fig. 2(a). Not shown is the initialization to move most of the population into one hyperfine state, which is performed before every experiment (see Supplement 1 Section 2 and Refs. [8,14]). First, an AFC with period $\Delta$ is created by repeatedly burning away the population between the teeth of the comb, $n_{comb} = 20$ times. Then an input pulse indicated by the red laser pulse is sent into the resonator at $t = 0$ and is absorbed by the AFC. Shown in light red are possible emissions corresponding to rephasing events of the AFC at times $t = \frac{m}{\Delta}$. Without electric field control, the output of the memory (the first and largest emission) would be centered at $t = \frac{1}{\Delta}$ ($m = 1$). The schematic shows instead an emission in red at $t = \frac{3}{\Delta}$ ($m = 3$), obtained when a first electric pulse is applied before the first emission and a compensating pulse is applied immediately before the third emission.

Figure 2(b) shows the AFC used in this experiment. The period of the comb, extracted from the fit, is $19.7 \pm 0.1$ MHz, which corresponds to a minimum storage time of $t = \frac{1}{\Delta} = 50$ ns. Figure 2(c) shows dynamically controlled storage for various values of $m$. The input pulse is a weak coherent pulse corresponding to an average photon number in the resonator of $\langle n_{cav} \rangle = 1.9$. Two electric pulses were used to control memory time. The first was a 10 ns long pulse with amplitude 2 kV/cm centered at $t_{\text{pulse}1} = 25$ ns. The second was 10 ns long with an opposite amplitude of -2 kV/cm, and its center position was varied as $t_{\text{pulse}2} = 25 \times 10^\mathrm{-}n + (m - 1) \times 50 \times 10^\mathrm{ns}$ to allow the emission at $t_{\text{memory}} = \frac{m}{\Delta}$. The electric pulses were calibrated to ensure optimal suppression of the emission (see Supplement 1 Section 3). Between the two electric pulses, emission was suppressed down to the dark counts level, a factor of 100 lower than peak emission counts. For the $m = 1$ case, no electric pulses were applied. The presence of multiple smaller pulses following the output pulse is a feature of the high finesse and low efficiency of the memory (see Supplement 1 Section 4). For higher-efficiency, high-finesse AFCs, subsequent emissions are significantly suppressed [42].

Figure 2(d) shows the energy emitted in the $m$th time bin for $t_{\text{memory}} = \frac{m}{\Delta}$. The data is fit to the dephasing term in the theoretical storage efficiency for a comb with Gaussian teeth: $\exp(-\frac{\pi^2}{2\Delta^2}m^2)\gamma{\Delta}$) [12,35], where $F = \Delta/\gamma$ is the comb finesse and $\gamma$ is the full width at half-maximum (FWHM) of each tooth. The $m = 1$ data point is excluded from the fit because the approximately 100 ns dead time of the single photon detector after the input pulse is thought to lead to undercounting in that time bin. A comb finesse of $F = 12.2 \pm 0.2$ ($\gamma = 1.6$ MHz) is extracted from this fit. This corresponds to a 1/e point of 240 ns ($m = 4$ for digital storage time). To improve on this scaling requires a smaller tooth width $\gamma$.

The gray data in Fig. 2(d) show the total counts in the $m$th time bin when the previous output pulses are not suppressed. The frequency of light stored in an AFC can be dynamically modified during emission. The atomic frequency comb is shifted in frequency during the emission of stored light by biasing the electrodes in the parallel configuration shown in the middle panel of Fig. 1(a). The pulse sequence used to achieve AFC storage with
frequency control is shown in Fig. 3(a). The first step is to eliminate one of the two $^{16}E^3{\text{S}}$ subclasses from the spectral window, leaving only ions that experience a positive Stark shift $\delta f_s = +sE$ (the choice of subclass is arbitrary). This is accomplished using a two-part comb burning procedure. With the first burning step, a normal AFC containing both subclasses is created using a sequence of laser pulses. For the second burning step, the two subclasses are split by $\Delta/2$ using a parallel electric field, and a similar sequence of laser pulses is used, but with a frequency shift of $\Delta/4$. This burns away ions with a negative shift $\delta f_s = -sE$.

Repeating the comb burning procedure $n_{\text{comb}} = 5$ times, an AFC with width 145 MHz and a period $\Delta = 5$ MHz is created. An input pulse is sent in, and the rephasing of the AFC causes an emission at $t = \frac{\Delta}{2} = 200$ ns. During this emission, an electric field pulse with amplitude $E_{\text{pulse}}$ applied in the parallel configuration will cause the ions to emit with a frequency shift of $f = +sE_{\text{pulse}}$. Figures 3(b) and 3(c) show the light emitted from the memory, with and without a frequency shift. A heterodyne measurement is used to measure the frequency of the output pulse directly. To detect the output pulse with this lower-sensitivity detection method, bright input pulses were used ($n_{\text{comb}} = 46 \times 10^3$).

The decrease in output amplitude with frequency shift evident in Figs. 3(b) and 3(c) is mainly due to the broadening of the teeth width, which is caused by inhomogeneity of Stark shifts experienced by the ions (see Supplement 1 Section 1). This broadening results in a decrease in efficiency via the dephasing term introduced in the previous section.

6. DYNAMIC BANDWIDTH CONTROL

The bandwidth of stored light can be dynamically controlled by biasing the electrodes in a quadrupole configuration as shown in the bottom panel of Fig. 1(a). In the quadrupole configuration, electric pulses create a gradient electric field across the ions so that each ion experiences a different Stark shift. Figure 4 shows the

![Figure 3](image)

**Fig. 3.** AFC storage with frequency control. (a) Pulse sequence (not to scale; details in main text). (b)–(c) Examples of AFC output pulses with (green, lighter) and without (blue, darker) a frequency shift. The filled-in area is a Gaussian fit to the data (circles). Detuning is measured from 194.822 GHz. Frequency shifts of (b) 9 MHz and (c) 30 MHz are shown. (d) The output detuning as a function of electric field applied during emission. Circles are the centers of Gaussian fits as shown in (b)–(c). The error bars, which are smaller than the markers, are 95% confidence intervals for those fits. The solid line is a linear fit to the data, yielding a slope of 13.0 MHz/cm, similar to the Stark shift value measured by hole-burning spectroscopy (see Supplement 1 Section 1).

![Figure 4](image)

**Fig. 4.** AFC storage with bandwidth control. (a) Pulse sequence (not to scale; details in main text). (b) AFC storage with (bottom) and without (top) bandwidth broadening. Colored areas are Gaussian fits to photon counts data (circles) from which widths are extracted. The partially reflected input pulse with FWHM 77.4 ns (5.7 MHz FWHM in the frequency domain) is shown in gray (lighter color) in both traces at $t = 0$, demagnified by a factor of $10^3$. The top trace shows the case without bandwidth broadening $E_{\text{max}}(t = 630 \text{ ns}) = E_{\text{max}}(t = 0) = 0.67 \text{ kV/cm}$, where the width of the output (blue, darker) is $77.1 \pm 2.0$ ns ($5.7 \pm 0.1$ MHz). The bottom trace shows the maximum bandwidth broadening $E_{\text{max}}(t = 630 \text{ ns}) = 4 \times E_{\text{max}}(t = 0) = 2.8 \text{ kV/cm}$, where the width of the output (blue, darker) is $24.3 \pm 0.5$ ns ($18.1 \pm 0.4$ MHz). Insets show schematics of electrode pulse sequences. (c) Bandwidth of pulses as a function of the $E_{\text{max}}$. In all cases, $E_{\text{input}} = 0.67 \text{ kV/cm}$. Filled black circles are FWHM data. The error bars, which are smaller than the markers, represent 95% confidence intervals from fits. The unfilled gray circles are simulation data (see main text and Supplement 1 Section 5).
pulse sequence used to achieve AFC storage with bandwidth control. First, an AFC with $\Delta = 1.6$ MHz and bandwidth 144 MHz is created by repeatedly burning away population $n_{\text{comb}} = 20$ times. Next, an input pulse ($\langle n_{\text{comb}} \rangle = 1.9$) is sent into the device, leading to an output pulse at $t = \frac{1}{2} = 630$ ns. A gradient field applied during the AFC emission causes the bandwidth of the absorbing ion ensemble to broaden, such that the emitted pulse is also broader in frequency relative to the input pulse. However, the gradient field also alters the phase evolution of each ion by changing its resonant frequency. If not compensated, the different phases accumulated across ions in the ensemble could prevent emission altogether. For this reason, three electric pulses are applied during the input and output optical pulses and also during the wait time. These three pulses have the same area but can have different amplitudes. The first and second pulses are used to add phase compensation such that the net electric-field-induced phase shift is zero for each ion, accounting for the fact that AFC storage is first-in-first-out [24,43].

Figure 4(b) shows AFC storage with no broadening (top) and with the maximum achieved bandwidth broadening (bottom). A broadening in frequency space is seen as a narrowing of the output pulse in time. By fitting the output pulses to Gaussians, the temporal FWHMs ($\Delta t$) of input and output pulses are extracted and converted to bandwidth or frequency FWHMs ($\Delta f$) using $\Delta f = \frac{4\Delta t^2}{\pi^2} (\Delta t)^{-1}$. Figure 4(c) shows the trend of output bandwidth as a function of the maximum electric field applied during the third pulse $E_{\text{max}}$ (the electric field across the resonator ranges from $-E_{\text{max}}$ to $E_{\text{max}}$). To confirm that the trend observed in the data is expected given the atomic frequency comb profile, the input pulse, and the electric field distribution $E_f(x)$, a simulation of the experiment was performed by numerically integrating the time-evolution equations of the atoms and cavity (see Supplement 1 Section 5). The simulation data reproduces the trend in FWHM as a function of field. The only previously unknown parameter used in this simulation was the distance that the optical mode penetrates into the photonic crystal mirrors, which modifies the effective resonator length and changes the value of $E_{\text{max}}$. This parameter was found to be $x_{\text{eff}} = 6$ $\mu$m for each mirror by coarsely sweeping $x_{\text{eff}}$ in $1 \mu$m increments in the simulation to find the best fit to the data.

**7. DISCUSSION**

In this work, we have demonstrated the capabilities of an on-chip optical storage device with DC Stark shift control. Taking this technology on chip has two main advantages. First, it allows miniaturization and future integration with other optical components on chip. Second, it enables simple generation of large electric fields. Because the distance between electrodes across the resonator is small (a minimum of 20 $\mu$m), electric fields of 3 kV/cm are generated with just $\pm$ 5 V of applied bias in the parallel configuration. Such biases were easily supplied by a function generator with no additional amplification. In the quadrupole configuration, electric field gradients of up to 50 V/cm/$\mu$m were generated, corresponding to gradient of 0.58 MHz/$\mu$m in $^{167}$Er$^{3+}$:Y$_2$SiO$_5$ transition frequencies.

For the dynamically controlled memory times in Fig. 2(d), an excellent match was found between the amplitude of stored light as a function of time and the theoretical limit due to the dephasing of a comb with finesse $F = 12.2$, indicating that the two electric field control pulses did not introduce any irreversible dephasing. This was also confirmed using a two-pulse photon echo measurement, where inserting two electric field pulses with equal area and opposite sign between the first and second optical pulses was found not to decrease the optical coherence time $T_2$, which was measured in this device to be $108 \pm 13$ $\mu$s.

Frequency control was demonstrated for up to $\pm$ 39 MHz. In this work, the maximum shift was set by the maximum applied electric field of 3 kV/cm. One technical difficulty is that ions from the other subclass that are outside of the comb will act as an absorbing background when the comb is shifted in frequency and the other subclass experiences an opposite frequency shift. Assuming that the comb can be sufficiently separated in frequency from the other subclass using high electric fields, a more fundamental limit is set by the inhomogeneity of the Stark shifts, which leads to a decrease in storage efficiency with increasing frequency shift. In this device, the Stark shift inhomogeneity was dominated by an electric field distribution that was not perfectly homogeneous [see Fig. 1(g)]. Even in a perfectly homogeneous field, however, some inhomogeneity in Stark shifts will exist due to crystal field variations throughout the crystal [31].

The bandwidth of stored light was changed by a factor of 3 from 6 to 18 MHz. The maximum broadening demonstrated was limited by the maximum electric field gradient of 50 V/cm/$\mu$m. With higher gradients, stored pulses could be broadened up to half the bandwidth of the comb, and the bandwidth of combs in this material is limited to $\sim$ 150 MHz [14]. Decreasing the bandwidth of a stored pulse is not possible with this procedure because the AFC cannot be made narrower with a gradient electric field, only wider. Narrowing the AFC could be accomplished with a frequency-selective shift such as the AC Stark shift. The storage efficiency was observed to decrease when changing the bandwidth of the stored pulse. This decrease in efficiency, which was also seen in simulation, was stronger when the bandwidth change was larger, and it was not present when the three electric pulses had equal amplitude (corresponding to no change in pulse bandwidth).

An on-chip resonator allows for storage efficiencies approaching unity if the impedance matching condition is met [32]. In this device, the storage efficiency was up to 0.4%, depending on the finesse of the comb created, and it was limited by the low coupling between the ensemble of ions and the optical mode of the resonator, characterized by an ensemble cooperativity $C < 1$, and the small coupling ratio of the lower-reflectivity mirror $\kappa_{\text{in}}/\kappa = 0.2$ (see efficiency discussion in Appendix D of Reference [14]). The storage time on an optical transition is ultimately limited by the optical coherence time $T_2$. However, in $^{167}$Er$^{3+}$:Y$_2$SiO$_5$, superhyperfine coupling to yttrium nuclear spins in the crystal prevents the creation of narrow spectral features, which means a low storage efficiency for storage times longer than $\sim$ 500 ns [14]. Superhyperfine coupling is a major limitation to high-efficiency long-lived storage in $^{167}$Er$^{3+}$:Y$_2$SiO$_5$ when using memory protocols based on spectral tailoring such as AFC.

For quantum repeater applications, the efficiency and duration of on-chip storage must be improved. The storage efficiency in hybrid aSi-$^{167}$Er$^{3+}$:Y$_2$SiO$_5$ devices can be increased by using thinner silicon to increase the fraction of the optical mode energy in the $^{167}$Er$^{3+}$:Y$_2$SiO$_5$, which would increase the ensemble cooperativity, and by optimizing the resonator nanofabrication procedure to decrease scattering and absorption loss in order to achieve higher intrinsic quality factors. For example, using crystalline silicon
could mitigate absorption loss. Higher intrinsic quality factors would increase both the ensemble cooperativity and the coupling ratio $\kappa_{in}/k$, both of which affect storage efficiency. To overcome the superhyperfine limit to storage time, creative solutions such as using clock transitions in $^{167}\text{Er}^{3+}$:Y$_2$SiO$_5$ [38,44,45], which are less sensitive to superhyperfine coupling, or finding new crystal hosts for erbium ions can be used. Longer storage times can also be realized by combining AFC storage with spin-wave storage, where the optical excitation is reversibly transferred to a hyperfine level [35]. Spin-wave storage could be combined with the bandwidth and frequency control demonstrated here, and it would eliminate the need for memory time control with electric fields. Another requirement of quantum memories is to store quantum states of light with high fidelity. This has already been demonstrated with the AFC protocol [9]. Storage of weak coherent states of light with high fidelity. This has already been demonstrated with the AFC protocol [9].

The functionality of the device is not limited to the demonstrations in this work. For example, a gradient field could be used instead of a homogeneous field to dynamically control the storage time. The bandwidth or frequency of emissions at any time $t=\frac{t}{T}$ could be modified, frequency and bandwidth control could be combined, and the order of two pulses could be reversed. A device that enables Stark shift control of an ion’s transition frequency is useful for other technologies as well. For example, a gradient electric field could be used to tune two $^{167}\text{Er}^{3+}$ ions coupled to the same resonator into resonance with one another. This would enable entangling gates between the two ions, a key step in quantum repeater protocols using single ions [46].

8. CONCLUSION

In this work we demonstrated a multifunctional on-chip device that can store light while dynamically modifying its storage time, frequency, and bandwidth. Dynamic control of the memory time and the frequency profile of the output light was achieved via the linear DC stark shift of $^{167}\text{Er}^{3+}$ ions in Y$_2$SiO$_5$. We demonstrated dynamic control of memory time in a digital fashion with storage times that were multiples of 50 ns, for up to 400 ns. The frequency of stored light was changed by up to $\pm 39$ MHz, and the bandwidth of stored light was increased by up to a factor of 3, from 6 to 18 MHz. This on-chip platform, comprising a resonator evanescently coupled to an ensemble of atoms that experience a DC Stark shift and on-chip electrodes, can be adapted to other materials and other quantum memory protocols.

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See Supplement 1 for supporting content.

**These two authors contributed equally to this work.**

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