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Coherently refreshing hypersonic phonons for light storage

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Acoustic waves can serve as memory for optical information; however, propagating acoustic phonons in the gigahertz (GHz) regime decay on the nanosecond time scale. Usually this is dominated by intrinsic acoustic loss due to inelastic scattering of the acoustic waves and thermal phonons. Here we show a way to counteract the intrinsic acoustic decay of the phonons in a waveguide by resonantly reinforcing the acoustic wave via synchronized optical pulses. We experimentally demonstrate coherent on-chip storage in amplitude and phase up to 40 ns, 4 times the intrinsic acoustic lifetime in the waveguide. Through theoretical considerations, we anticipate that this concept allows for storage times up to microseconds within realistic experimental limitations while maintaining a GHz bandwidth of the optical signal.

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1. INTRODUCTION

Coupling optical and mechanical waves in cavities, waveguides, and nanostructures offer great potential for optical signal processing [1–8], especially for delay lines and light storage [9–19]. Also, other very promising schemes based on electromagnetically induced transparency (EIT) [20–22] have been demonstrated for optical storage. One particular optomechanic interaction with gigahertz (GHz) acoustic phonons is Brillouin scattering, which describes the interaction between optical and traveling acoustic waves [23,24]. While spontaneous scattering is initiated by noise [25,26] and hence is not coherent, stimulated Brillouin scattering (SBS) involves a coherent excitation of acoustic phonons with GHz frequency solely by optically forces. It was shown recently that one can use these acoustic phonons to store and delay optical signals [9,17,19]. The optical information is resonantly transferred to a coherent acoustic phonon and is then transferred back to the optical domain by a delayed optical retrieval pulse completely preserving the phase and amplitude [17] and the wavelength of the signal [19]. However, propagating high-frequency acoustic phonons decay exponentially with a lifetime of a few nanoseconds determined by the material properties at room temperature. This inherent decay is due to the damping of the acoustic waves while propagating through the material. Therefore, the optical information stored in the acoustic waves is lost, and a way of preserving the coherent acoustic vibration is needed.

Here, we introduce and demonstrate a concept to counteract the intrinsic acoustic decay of the phonon in a waveguide by resonantly reinforcing the coherent acoustic phonons via synchronized optical pulses. Instead of converting the acoustic waves back to the optical domain, refresh pulses at the wavelength of the original data pulses transfer energy to the acoustic wave and counteract the decay. We experimentally demonstrate that information can be stored and retrieved for 40 ns—a time much longer than the intrinsic acoustic lifetime of 10 ns—and we confirm that the coherence is preserved in this process by measuring the optical phase after 40 ns via homodyne detection. We also experimentally demonstrate an increase in readout efficiency for storage times shorter than the acoustic lifetime. We theoretically explore the limits of the scheme and demonstrate that, within practical limits, even storage times up to microseconds are within reach while maintaining a broad GHz bandwidth of the stored optical pulses. This scheme allows the extension of the time during which the coherent acoustic phonons can be detected, removing previous constraints of phonon-based optical signal processing schemes. It also increases the efficiency of the optoacoustic memory, and, most importantly, it decouples the possible delay time from the bandwidth of the stored pulses, which limits nonrefreshed schemes such as slow light concepts based on nonlinear effects, atomic vapors, and cold atoms.

2. PRINCIPLE AND SETUP

The storage concept is based on the coupling of two optical waves with a traveling acoustic wave via the effect of SBS. The acousto-optic coupling depends on the overlap of the optical and acoustic waves and the intrinsic photo-elastic material response. The addressed acoustic wave is at $\Omega = 7.8$ GHz, and the nonlinear gain is in the order of $G_b = 500\ \mathrm{W^{-1}\ m^{-1}}$ for the used photonic waveguide made out of As_2S_3 with a cross section of 2.2 µm by 800 nm and a length of 4 cm.

Figure 1 shows schematically the principle of storing, coherently refreshing the acoustic phonons and retrieving the delayed optical information. The information of the optical data pulse is initially transferred to the acoustic phonons by a counterpropagating optical write pulse, offset in frequency by the acoustic resonance frequency of the waveguide $\omega_{\text{acoustic}} = \omega_{\text{data}} - \omega_{\text{write}} = 7.8$ GHz [Figs. 1(a) and 1(b)]. The acoustic resonance frequency relates to the acoustic velocity V_A, the effective refractive index n_{eff}, and the pump wavelength λ_{Pump} as $\Omega = \frac{2n_{\text{eff}}V_A}{\lambda_{\text{Pump}}}$. The acousto-optic coupling not only requires energy conservation but also phase-matching as $k_{\text{acoustic}} = k_{\text{data}} - k_{\text{write}}$. An efficiency of up to 30% can be reached depending on the bandwidth of the optical pulse [17]. This initial storage process is a Stokes process because the data wave loses energy to the acoustic wave. Without further action, the acoustic phonons decay after several nanoseconds [Fig. 1(b)] due to the intrinsic dissipation of the material. A read pulse at $\omega_{\text{read}} = \omega_{\text{write}}$ cannot efficiently couple to the acoustic grating, and the information is lost [Fig. 1(c)]. To reinforce the acoustic vibration, we use optical refresh pulses [Fig. 1(d)] with the same frequency and propagation direction as the data pulse, $\omega_{\text{refresh}} = \omega_{\text{data}}$. Herewith, the refresh pulses are scattered by the existing acoustic phonons—with two consequences: a portion of energy is transferred to the acoustic phonons, which refreshes the memory, and pulses with less energy at frequency $\omega_{\text{write}} = \omega_{\text{refresh}} - \omega_{\text{acoustic}}$ are backscattered. This can be related to a Stokes process originating from the refresh pulses and the coherent acoustic wave. In order to retrieve the original data, a counterpropagating optical read pulse at $\omega_{\text{read}} = \omega_{\text{write}}$ finally converts the information stored in the acoustic phonons back to the optical domain [Fig. 1(e)].

The refresh process can also be understood in the context of coherent heating [27] as the existing acoustic phonons are coherently amplified by the refresh pulses that satisfy the energy and momentum requirements for a Stokes process. It can also be seen as a classical SBS backscattering process, however, not initiated by thermal phonons but initiated by a deterministic localized seed created through the previous storage process. The refresh pulses do not contain any additional information but are coherent and synchronized with the data pulse as they are generated from the same laser. The number of refresh pulses depends on how long the storage is needed and in principle can extend the memory by several orders of magnitudes, fully countervailing the intrinsic exponential decay of the acoustic wave. However, in practice, the signal-to-noise ratio (SNR) of the optical pulses, the dissipation of the material at room temperature, and the broadening of the acoustic dynamic grating due to the convolution with finite control pulses limit the time after which the delayed optical signal can still be detected.

The refreshed optoacoustic memory is implemented in a highly nonlinear As_2S_3 chip with 2.2-µm-large rib waveguides. A simplified experimental setup is shown in Fig. 2. A continuous wave diode laser at 1550 nm is separated into two branches: one for the write and read pulses and the other one for the data stream and refresh pulses. The write and read pulses with 420 ps duration are carved in by an electro-optic modulator driven by an arbitrary waveform generator. The time distance between them can be adjusted arbitrarily and defines the storage time in the memory. They are amplified to about 20 W peak power and coupled into the chip from one side by lensed fibers. The other optical branch is first upshifted in frequency by the corresponding Brillouin frequency shift, here 7.8 GHz. The frequency shift is implemented by a single-sideband modulator. Then a data stream in amplitude and phase is encoded by a second electro-optic modulator and a second channel of the arbitrary waveform generator. The data pulses are 270 ps long and are amplified to a peak power of about 100 mW and inserted from the opposite side as the write and read pulses into the photonic chip. In order to reinforce the acoustic wave, coherent refresh pulses are sent into the photonic waveguide, following the data stream. Here, we experimentally implement the refresh pulses by the same electro-optic modulator as the data stream with help of an arbitrary waveform generator. The pulses are 280 ps long and the peak power is varied to match the appropriate pulse area [9,28], here about 200 mW. The length, peak power, and number of the refresh pulses have to be adjusted carefully in order to minimize distortion due to spontaneous Brillouin scattering and interaction with the optical background of the write and read pulses. After passing through the photonic chip, the data stream is filtered by a 3 GHz broad filter to prevent from detecting backreflections of the write and read pulses at another wavelength. Then, an optical

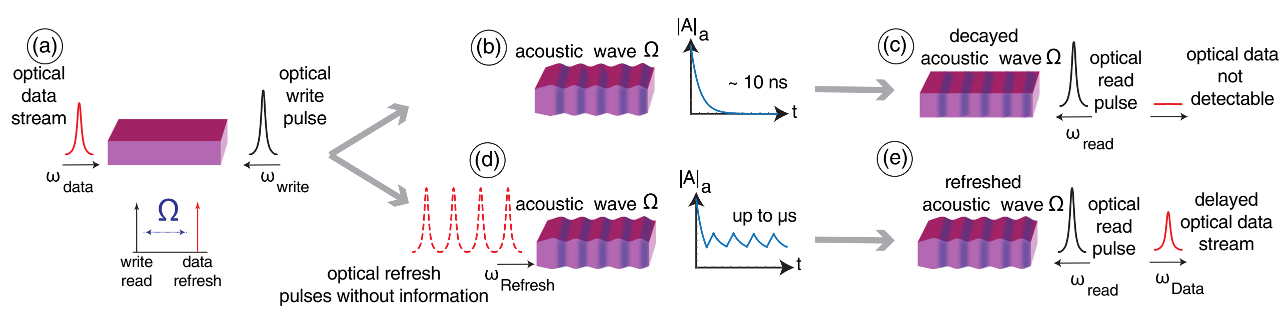

Fig. 1. Concept of the refreshed optoacoustic memory. (a) An optical write pulse converts the information of an optical data stream to an acoustic wave. (b) The acoustic wave propagates at a 5 orders of magnitude lower speed in the waveguide and decays with the acoustic lifetime. (c) In normal operation, the acoustic wave dissipates, and the read pulse cannot sufficiently interact with the acoustic wave; therefore, the information of the optical data is lost. (d) To counteract the acoustic decay, optical refresh pulses at $\omega_{\text{refresh}} = \omega_{\text{data}}$ transfer energy to the acoustic phonons. (e) An optical read pulse converts the information back to the optical domain, and the delayed optical information exits the waveguide.

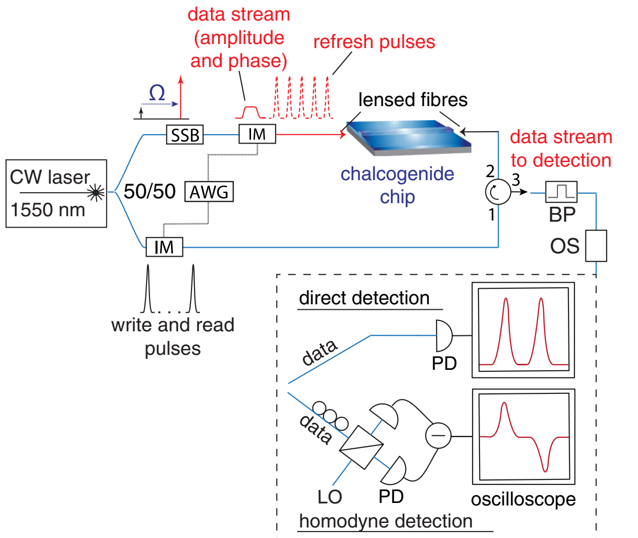

Fig. 2. Experimental setup for the refreshed optoacoustic memory. SSB, single-sideband modulator; IM, intensity modulator; AWG, arbitrary waveform generator; BP, bandpass filter; OS, optical switch; LO, local oscillator; PD, photodiode.

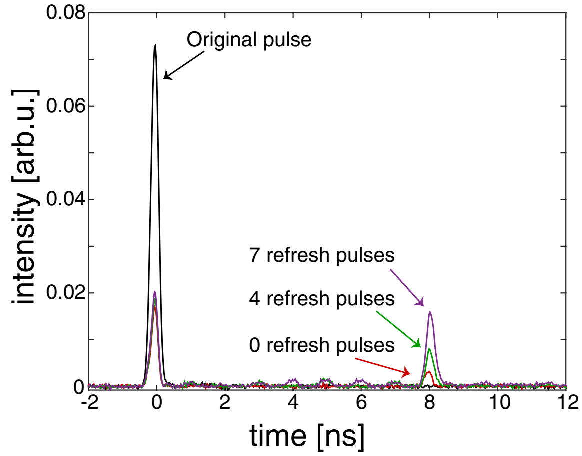

Fig. 3. Experimental results for increasing the efficiency with help of the refreshed Brillouin-based memory with a readout after 8 ns (within the acoustic lifetime): comparison of the efficiency while using 0, 4, and 7 refresh pulses showing a 3 and 5 times enhancement, respectively. The four refresh pulses were sent after 1, 3, 5, and 7 nanoseconds compared to the data pulse. The seven refresh pulses were sent in with a 1 ns time difference after the data pulse.

switch filters out residual refresh pulses. This optical switch can be made superfluous when using the opposite polarization for refreshing the memory. The detection is done either directly by a photodiode (amplitude) or using homodyne detection (phase). In the latter case, the data are interfered with a local oscillator at the same wavelength, and the different phases are seen as positive or negative signal on the oscilloscope.

3. EXPERIMENTAL RESULTS

As a first experimental proof, we show that the efficiency of the Brillouin-based storage increases when the acoustic wave is refreshed (Fig. 3). Therefore, we compare the amplitude of the retrieved data at a given storage time of 8 ns. Without refresh pulses, the retrieval efficiency is about 4%. With four or seven refresh pulses, the efficiency can be increased to 10% and 20%, respectively. The seven refresh pulses were sent in with a time delay of 1 ns after the data pulse with 1 ns time spacing, and the four refresh pulses at times 1, 3, 5, and 7 ns after the data pulse. We use an optical switch to remove residual refresh pulses. However, as an alternative, the refresh pulses could also be inserted at orthogonal polarization, such that an optical switch is not necessary.

The increase of the efficiency allows for a far more important feature, which is extending the storage time beyond the intrinsic acoustic lifetime, which so far limited the storage time of the memory to a few nanoseconds. As a proof of principle, we show in Fig. 4 that refreshing the acoustic phonons enables a storage time far beyond the acoustic lifetime of about 10 ns in As_2S_3, in this case 40 ns. In Fig. 4(a), an original data pulse (black solid line) is transferred to an acoustic phonon. The latter is refreshed by 39 consecutive refresh pulses that are subsequentially filtered out by an optical switch before detection. 40 ns after the initial data pulse, a read pulse converts the information back to the optical domain, and we retrieve our delayed optical pulse (red dashed line). To be certain that this was not an artefact stemming from reflection, spontaneous Brillouin scattering, or an unwanted acoustic grating, we took several precautions. The pulses were synchronized such that the acoustic waves in the waveguide contain only the information of the data stream. This means that the write pulse encounters the data pulse in the waveguide and encounters all other refresh pulses outside of the waveguide. Furthermore, we tested different combinations of data, refresh, write, and read pulses in switched-on or switched-off modus. For instance, when the data are switched off, but all other pulses are switched on (write, read, refresh), no retrieved data are found because no acoustic grating was established and therefore also not refreshed. Another scenario is when the data, write, and refresh pulses are switched on but the read pulse is off. In this case, the grating is written and refreshed, but no readout is observed. Hence, we can exclude that the readout we measure comes from a refresh pulse interacting (in any form) with the written grating and causing an artefact readout. An even more important proof though is to retrieve the phase information of the data.

Therefore, in a second measurement, we use homodyne detection to show that this process is coherent by storing and retrieving the optical phase. In this experiment, two optical pulses with opposite optical phase "0" and "π" are sent into the chip and stored via a counterpropagating write pulse. The phase is detected via homodyne detection. After refreshing the memory with 39 pulses, we can detect the phase information after 40 ns [Fig. 4(b)].

In order to illustrate the transfer of energy of the refresh pulses to the acoustic wave, we show the transmitted refresh pulses without the optical switch (Fig. 5). In Fig. 5(a), the original data pulse and the refresh pulses are depicted (black solid trace). When switching on the write and read process (red dashed trace), one can see that the original data are depleted and that the refresh pulses lose energy that is transferred to the coherent acoustic phonons and backscattered pulses at frequency $\omega_{\text{write}} = \omega_{\text{refresh}} - \omega_{\text{acoustic}}$. The energy transfer from the refresh pulses to the acoustic grating depends on the optical pulse area as it is the case for the original storage process [28]. This has implications when using a pulse train for the data because the refresh power will decay while propagating through the acoustic gratings. This is caused by the energy transfer to the acoustic gratings themselves but also due to linear optical

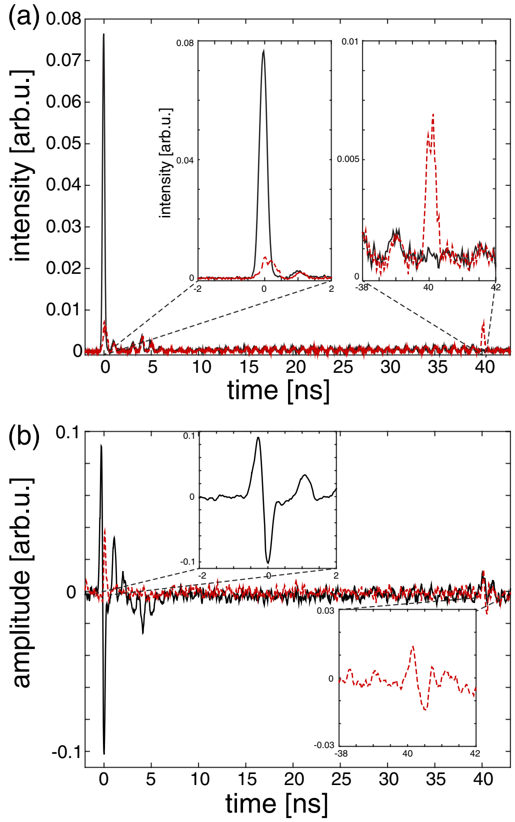

Fig. 4. Experimental results of the refreshed memory with 40 ns storage time. (a) Direct detection of the original data pulse (black solid line) and its retrieval after 40 ns storage (red dashed line); (b) homodyne detection of the coherent phase of two original data pulses, encoded with phase 0 and π (black solid line), and their retrieval after 40 ns storage (red dashed line).

loss. Therefore, it is beneficial to be able to use as short data pulses as possible, as has, for instance, been demonstrated in Ref. [29]. Despite the coherent refresh pulses not carrying any additional information, note that the backscattered pulses contain the information of the stored acoustic phonons. Countermeasures such as an isolator can prevent us from giving the stored information into the opposite direction of the transmission line. In Fig. 5(b), the refresh pulses have been suppressed by an optical switch. As mentioned, this method can be improved by using the orthogonal polarization, which was not possible in our case, due to high polarization-dependent loss of the photonic chips.

Our experimental setup appeared to be limited by the following predominant factors: First, the extinction ratio of the optical modulators leads to a nonzero background between the optical pulses, which acts as a seed for acoustic phonons that do not hold information. This ultimately limits the detection of the relevant stored information. Second, spontaneous Brillouin scattering can build up, initiated by room temperature phonons and amplified by the refresh pulses. A third limitation is the SNR of the retrieved optical pulse in the photodetection process, limited by the electronic noise of the detector and the oscilloscope. At last, the acoustic dynamic grating broadens with each refresh process due to the convolution with refresh pulse with a finite width, which limits the detectable signal at the photodiode.

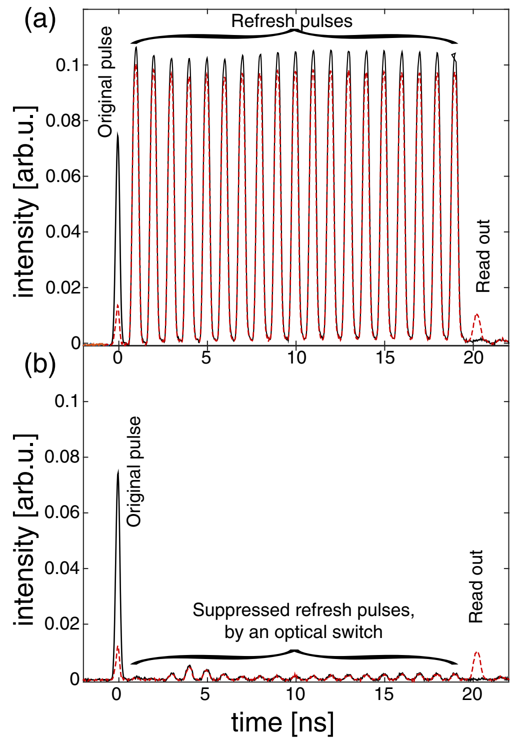

Fig. 5. Refreshed memory for storage time of 20 ns. (a) Original data pulse with 19 refresh pulses (black solid line); retrieved data after 20 ns (red dashed line) with refresh pulses transferring energy to the acoustic phonon; (b) original data (black solid line) and retrieved data (red dashed line) with suppressed refresh pulses by an optical switch.

4. DISCUSSION

While the experimental results demonstrate that the limits of an unrefreshed Brillouin-based memory can be beaten, the question arises how long the storage time can be extended. In other words, how does the SNR evolve over time such that we can still recover the information. To answer this, we performed a simple analysis of the noise accumulation assuming a train of Dirac-shaped refresh pulses (spaced by some time τ) chosen such that the acoustic amplitude is kept constant on average. We decompose the acoustic field into the nonfluctuating excitation (the stored pulse including accumulated noise) and a fluctuating field caused by thermal excitations. Both seek to exponentially approach thermal equilibrium with the acoustic decay constant α. A refresh pulse amplifies both fields, adding a snapshot of the fluctuating field to the stored pulse. This effectively "resets" the fluctuation field, which is exponentially repopulated $\sim[1-\exp(-\alpha t)]$. As a result, the SNR ratio after n loss-compensating refresh pulses is

$$\mathrm{SNR}_{\mathrm{refreshed}}(n\tau) \approx \frac{\mathrm{SNR}_{\mathrm{initial}}}{n[1-\exp(-\alpha\tau)]}. \quad (1)$$

This means that the exponential decay $\mathrm{SNR} \simeq \exp(-\alpha t)$ of the unrefreshed signal is transformed into a first-order algebraic decay $\mathrm{SNR} \simeq t^{-1}$. Therefore, refreshing dramatically extends the visibility of stored information. For example, doubling the initial SNR doubles the practical readout time with refreshing, while it only leads to a constant extension $\ln(2)/\alpha$ without refresh. In reality, the refresh pulses have a finite width, and each refresh operation applies a convolution to the stored data [30]. In our case, this effectively leads to a dispersion-like broadening of the dynamic grating without imparing the coherence or bandwidth of the signal. Assuming that this convolution effect can be reverted (e.g., using chirped pulses [31]) and assuming loss-compensating ideal refresh pulses, we estimate that it should be possible to maintain data in our system for at least 350 ns. This is based on the apparent SNR of the experiment, which includes significant detector noise in addition to the thermal acoustic noise and a constant background due to the finite extinction ratio of the modulator. Therefore, storage times into the microsecond range are within reach.

Another parameter to be considered when refreshing traveling acoustic phonons is the waveguide length. As the GHz acoustic phonons propagate at the speed of sound in As_2S_3 (approximately 2600 m/s), we can calculate a maximal propagation length of 2.6 mm for storage times of a microsecond. This is currently a minor constraint in the several-centimeter-long integrated waveguides.

It should be emphasized that the refreshing concept not only works for different amplitude and phase states [17] but could also be executed at different parallel frequency channels [19]. In the latter, it has been demonstrated that the Brillouin interaction can be used for simultaneous storage at different frequencies. This greatly enhances the capacity of the Brillouin-based memory as information can be stored in amplitude, phase, and frequency for each data pulse of an information stream.

5. CONCLUSION

We demonstrated a way to compensate for the intrinsic acoustic decay of a coherent acoustic phonon in a chip-integrated waveguide. This leads to an increase in efficiency of the Brillouin-based memory and importantly allows us to overcome the limitation in storage time set by the acoustic lifetime. The acoustic phonons are coherently refreshed allowing the storage and retrieval of the optical phase, paving the way for long phonon-based light storage. This demonstration overcomes the usual constraint of the bandwidth-delay product because it offers the possibility to extend the delay time by several orders of magnitude while keeping the bandwidth of the stored data pulses constant. Conservative estimation promises storage times into the microsecond regime while conserving the large GHz bandwidth of the optical pulses. The resulting bandwidth-delay product can therefore reach the regime of EIT systems [20,21] while having the technological advantage of being fully integrated on a photonic chip. It is continuously tunable in storage time, operates at room temperature, and is optically controlled, which means that the waveguide can also be used as a normal transmission medium when the control pulses are not operated. There are techniques that can offer a longer storage time [21], however, at the expense of a reduced bandwidth, and they require operation in a cryogenic environment. The efficiency of the refreshed optoacoustic memory increases greatly compared to other optoacoustic and optomechanical storage approaches [9,12,17]. When increasing the available refresh pulse power and number of refresh pulses, one can imagine storage efficiencies that exceed 90% as, for example, those achieved using warm rubidium vapor [22]. Refreshing the acoustic waves and, therefore, increasing the efficiency and extending the storage time are relevant for a number of applications such as telecommunication networks and optical interconnects, and ultimately may be interesting for quantum communication systems.

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