

Using electric fields for pulse compression and group-velocity control

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In this article, we experimentally demonstrate a way of controlling the group velocity of an optical pulse by using a combination of spectral hole burning, the slow-light effect, and the linear Stark effect in a rare-earth-ion-doped crystal. The group velocity can be changed continuously by a factor of 20 without significant pulse distortion or absorption of the pulse energy. With a similar technique, an optical pulse can also be compressed in time. Theoretical simulations were developed to simulate the group-velocity control and the pulse compression processes. The group velocity as well as the pulse reshaping are solely controlled by external voltages which makes it promising in quantum information and quantum communication processes. It is also proposed that the group velocity can be changed even more in an Er-doped crystal while at the same time having a transmission band matching the telecommunication wavelength.

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I. INTRODUCTION

Controlling the group velocity of light has attracted more and more attention due to its potential application in data synchronization, tunable optical buffer in optical communication [1], optical information processing, and optical switching [2]. To date, various techniques of controlling the group velocity of a pulse have been studied, such as electromagnetic-induced transparency (EIT) [3,4], coherent population oscillation (CPO) [5], stimulated Raman scattering (SRS) [6], and stimulated Brillouin scattering (SBS) [7]. More recently, group-velocity control was demonstrated in silicon-based resonators [8,9], with the target for on-chip application. However, the delay there is only typically in the range of hundreds of picoseconds. One major drawback of the above-mentioned methods for group-velocity control is their needs of a simultaneous optical pump beam which might introduce some background noise to the system, which could be especially detrimental in background-sensitive single-photon applications. It was experimentally demonstrated that the optical pulse delay can be controlled by using transient spectral hole burning at different magnetic fields [10]. However, the requirement of recreating the transient spectral hole for each specific group velocity makes it less feasible in practice. In this article, we present a technique where one spectral hole was prepared and the group velocity of an optical pulse can be solely controlled by an electric field. This is a desired feature when working with weak-light situations; for example, in quantum information and quantum communication processes.

Our technique of controlling the group velocity of an optical pulse uses the combination of spectral hole burning induced slow-light effect and Stark effect and can be described as follows: A 16 MHz spectral hole was prepared in the center of the inhomogeneous broadening of a rare-earth-ion-doped crystal, with the goal of making the edges of the hole as sharp as possible. A principle sketch of the final hole structure together with the real part of the refractive index is shown in Fig. 1(a). The blue and red colors represent ions with positive and

negative Stark coefficients, respectively. If a voltage is applied across the crystal, the resonance frequencies of the “blue” and “red” ions will shift in different directions, which leads to a narrower hole. The change of the hole width is proportional to the applied external voltage since the frequency shift of the ions is proportional to the applied voltage according to the linear Stark shift. For an applied voltage of 40 V, a sketch of the new structure, as well as the real part of the refractive index, are shown in Fig. 1(b), where in the vicinity of the left side of the hole there are only “blue ions,” while in the vicinity of the right side of the hole there are only “red ions.” The dispersion across the transmission window is much steeper than that in Fig. 1(a). This causes the group velocity of an optical pulse to be much slower when propagating in the transmission window shown in Fig. 1(b) than when propagating in a transmission window as shown in Fig. 1(a) [see Eqs. (1) and (3) in Sec. II for further information).

When a 10- μ s-long pulse with a Gaussian frequency profile is sent into the crystal, the group velocity of the pulse could be changed continuously by a factor of 20 by changing the external voltages applied across the crystal, and the group velocity decreases monotonically as the external field is increased. Furthermore, an optical pulse can be reshaped by changing the hole width while the pulse is still inside the crystal. A 1- μ s-long pulse was sent into the crystal at the presence of an external voltage of 40 V, which corresponds to a hole width of about 1 MHz. The group velocity of the pulse was small enough that almost the entire pulse was accommodated in the crystal. The electric field was then decreased rapidly, increasing the group velocity. In this way the first part of the pulse propagated a longer distance inside the crystal with a slower speed than the later part of the pulse, which caused the pulse transmitted from the crystal to be compressed in time. Another way of pulse shortening by sudden increase of the amplitude of the coupling field in an EIT scheme was proposed by Shakhmuratov *et al.* [11]. The drawback of the scheme is the necessity of the strong optical coupling field, which brings extra optical noise to the process.

Although the present experimental demonstration was carried out in Pr:Y₂SiO₅, it can be used in other rare-earth-ion-doped materials where spectral hole burning is

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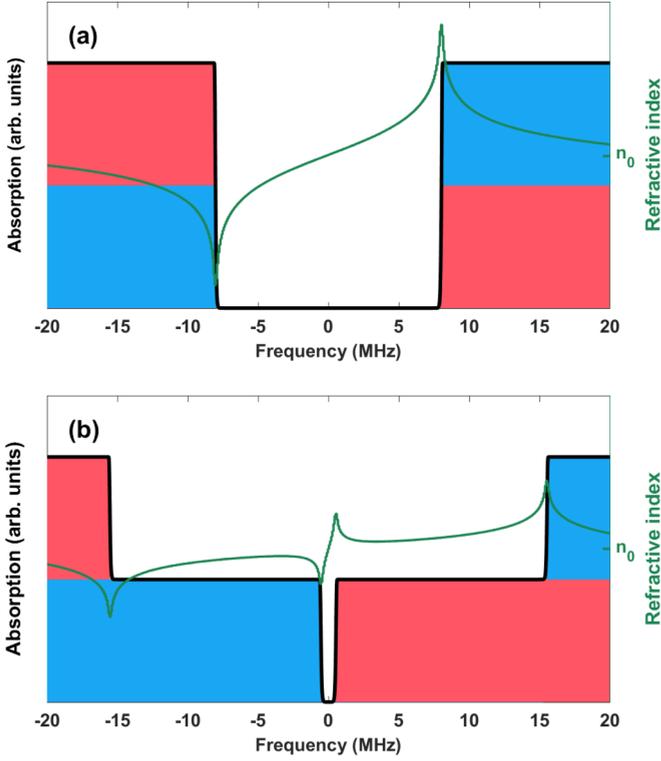


FIG. 1. A simplified sketch of the absorption structure, as well as the dispersion of the refractive index, where the red and blue color represents ions with opposite sign of their Stark coefficients while the black line shows the overall absorption. The green trace shows the real part of the refractive index over the frequency range, where n_0 stands for the refractive index of the host material and in this case $n_0 = 1.8$. (a) The original 16 MHz hole, no external voltages applied. (b) The 1 MHz spectral hole structure when an external voltage of 40 V is applied. The width of the hole as well as the slope of the dispersion changes as the external voltage is changed, which in return changes the group velocity.

possible and Stark or Zeeman effects can be applied to change the hole width. For example, in Er-doped crystals (e.g., Er:Y₂SiO₅). Er ions have an optical transition around 1.5 μm , at the telecommunication wavelength, where the fiber loss is minimum. The Stark coefficient is about 20 kHz/(V/cm) in Er:YAlO₃ [12], and 25 kHz/(V/cm) in Er:LiNbO₃ [13]. The ground-state hyperfine splitting for Er ions is much wider than that of Pr ions [14,15], a spectral hole of 575 MHz can be prepared in Er:Y₂SiO₅ according to the hyperfine splittings provided in Ref. [16]. Since the tuning range of the group velocity is only limited by the widest hole width that can be created and the external voltages applied, the tuning range of the group velocity can be much larger in Er than that in Pr.

II. GROUP VELOCITY

The group velocity \mathbf{v}_g of an optical pulse can be calculated via the following equation:

$$\mathbf{v}_g = \frac{c}{n + v \frac{dn}{dv}}, \quad (1)$$

where c is the speed of light in vacuum, n is the real part of the refractive index (for the phase velocity), and v is the frequency of the light pulse. When an optical pulse propagates inside a dispersive medium, in our case inside a narrow transmission window, the real part of the refractive index can change dramatically; therefore, $v \frac{dn}{dv}$ can be much higher than n itself, which in the present experiments can decrease the group velocity by four or five orders of magnitude [17,18].

Another way of interpreting the group-velocity reduction is from the light-matter interaction perspective. As shown in Refs. [19–21] (note that in Refs. [20,21], the assumption is made that the material has a refractive index of $n = 1$), the group velocity can be expressed as a temporal energy storage process of the optical pulse energy in the absorbing ions via off-resonance interaction,

$$\mathbf{v}_g = \frac{c/n}{1 + \frac{U_c}{U_{em}}}, \quad (2a)$$

where U_c is the energy density accumulated in the excitation of the off-resonant centers and U_{em} is the energy density of the electromagnetic field propagating with phase velocity c/n in the medium in the absence of dispersion. The equation shows that, the more energy is temporarily stored in the resonance centers, the lower the group velocity of the light.

In fact, the refractive index n also originates from the off-resonant interaction but between light and the host material. Therefore, when light propagates inside a nondispersive medium, the energy density U_{em} also contains two parts: one is the energy density of the pure electromagnetic wave, U_{vac} , and another one is the energy density accumulated in the host atom, U_{host} . Similar as in Ref. [19], the energy flow across a unit cross section inside the crystal per unit time is $\mathbf{v}_g(U_{vac} + U_{host} + U_c)$, which should be the same as the energy flow through a unit cross section per unit time outside the crystal, cU_{vac} . Then the group velocity can be expressed as

$$\mathbf{v}_g = \frac{c}{1 + \frac{U_{host}}{U_{vac}} + \frac{U_c}{U_{vac}}}, \quad (2b)$$

hence,

$$\mathbf{v}_g = \frac{c}{1 + \frac{U_{med}}{U_{vac}}}, \quad (2c)$$

where $U_{med} = U_{host} + U_c$ is the energy density accumulated in the medium which contains the effect from the host atoms and the resonant centers. In the case of no dispersion, the group velocity equals the phase velocity and we get $n = 1 + \frac{U_{med}}{U_{vac}}$. Thus the higher the refractive index is, the stronger is the interaction between the light and the material, hence the more energy is stored inside the material. To verify this, we can take a nondispersive material with refractive index of n , assume that we have a light beam with a certain amplitude and normal incidence that enters a material with refractive index of n from vacuum. By comparing the energy density inside and outside the material (denoted U_{inside} and U_{vac} , respectively) from the boundary condition, we get $U_{inside} = nU_{vac}$. If we make the same analogy as Courtens did in Ref. [19] that the energy density inside a material can be written as $U_{inside} = U_{med} + U_{vac}$, we get that $n = 1 + \frac{U_{med}}{U_{vac}}$. We note that Eq. (2a) is based

on the assumption that the dispersion is due only to resonance centers other than the host material, while Eq. (2c) is suitable for any general case. That is with and without dispersion and where the dispersion can come from the host atoms or other resonance centers in the material or from both. Therefore, when an optical pulse enters a medium, a certain portion of the pulse energy is stored in the off-resonant ions (atoms) of the medium, and the Bloch vectors of these ions (atoms) are lifted up slightly from their ground-state position. These ions will rephase at a later time, their Bloch vectors will point straight down again and the energy is returned back to the optical field. Intuitively, one can imagine that this process causes the light to propagate slower inside the medium.

In the case where the group-velocity reduction is mainly caused by the spectral hole burning in an absorption profile such as our case here, the group velocity v_g can be approximately calculated by [17,22,23],

$$v_g \approx \frac{2\pi\Gamma}{\alpha}, \quad (3)$$

where Γ is the width of the transmission window and α is the absorption coefficient outside the transmission window.

Equations (1)–(3) can all be used to describe the group velocity but they emphasize different aspects. Equation (1) is the formula to calculate the group velocity when one knows the dispersion, while Eqs. (2b) and (2c) are ways to interpret the physical process of group velocity for the so-called material slow-light case [18,19,24]. Equation (3) provides an approximate but convenient estimate of the group velocity inside a spectral hole and is especially useful in our case here for making the first estimate of the tunability of the group velocity since it is proportional to the width of the transmission window and inversely proportional to the absorption coefficient. It is then straightforward to see that the tunability of the group velocity is proportional to the tuning range of the transmission window.

III. EXPERIMENT

The experiment was performed on a $6 \times 10 \times 10 \text{ mm}^3$ (crystal axes $b \times D1 \times D2$), 0.05%-doped Pr:Y₂SiO₅ crystal at $\sim 2 \text{ K}$. The top and bottom surfaces of the crystal were coated with two sets of gold electrodes indicated as the red and black lines on the crystal in Fig. 2(a) (a photo of the crystal can be found in the appendix of Ref. [18]). The energy levels involved in this experiment belong to the 3H_4 - 1D_2 transition centered around 605.978 nm with an inhomogeneous broadening of about 5 GHz and a homogeneous broadening of about 3 kHz. The hyperfine lifetime of the Pr³⁺ ion ground-state levels is about 100 s and can be extended to about 30 min at the presence of a weak (0.01 T) magnetic field [25].

A simplified setup is shown in Fig. 2(a), where a laser beam from a frequency-stabilized Coherent 699-21 ring dye laser tuned to the center of the inhomogeneous broadening was split into two parts by a 90/10 beam splitter, where the stronger beam was focused onto the center of the crystal and used for the spectral structure preparation and characterization and then measured by a photodetector (PD2) [26], while the weaker one was directly measured by another photodetector (PD1) and used as a reference beam to calibrate intensity variations.

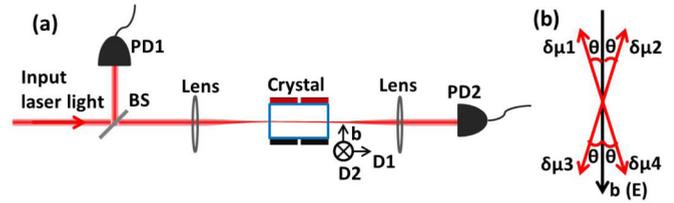


FIG. 2. Experimental setup. Laser light polarized along the $D2$ axis of the crystal is divided into two beams by a 90/10 beam splitter (BS), where the stronger beam is focused and directed along the center line of the crystal and recorded by a photodetector (PD2) while the weaker one is recorded by another photodetector (PD1) and used as a reference beam to calibrate any intensity fluctuations of the laser. (b) The permanent electric-dipole-moment difference between excited state and ground state of the Pr³⁺ ($\delta\mu_1, \delta\mu_2, \delta\mu_3, \delta\mu_4$) relative to the electric field applied (\mathbf{E}). The electric field is along the b axis of the crystal and the magnitude of the projection of the dipole moment difference onto the electric field direction is the same for all the four possible $\delta\mu$ ($\theta = 12.4^\circ$).

The permanent electric-dipole moment of the ground state is different from that of the excited state for Pr³⁺ ions and there are four possible orientations for the dipole-moment difference [18,27]. When an external voltage is applied across the crystal, the resonance frequency of the ions will be Stark shifted by Δ_s , where

$$\Delta_s = \frac{\delta\mu \cdot \mathbf{E}}{\hbar} = \pm \frac{|\delta\mu| \cos(\theta)}{\hbar} \times \frac{\Delta V}{d}, \quad (4)$$

where \hbar is the reduced Planck constant, $\delta\mu$ is the difference between the excited- and ground-state dipole moments for Pr³⁺ ions, \mathbf{E} is the electric field across the crystal (along the b axis), θ is the angle between the electric field and $\delta\mu$, ΔV is the difference in the electric potential between the top and bottom electrodes, and d is the distance between these two electrodes which in our experiment is 6 mm. The four possible $\delta\mu$ of Pr³⁺ are oriented at an angle of $\theta = 12.4^\circ$ relative to the b axis of the crystal, as shown in Fig. 2(b). The magnitude of $\delta\mu/\hbar$ is about 111.6 kHz/(V/cm) [27]. Since the \mathbf{E} field is applied along the b axis and because of the symmetry of $\delta\mu$, there will be two effective Stark coefficients for Pr³⁺ with the same magnitude but opposite signs. At the presence of a certain electric field, the resonance frequency of half of the ions, those with positive Stark coefficient (referred as blue ions), will shift to higher frequencies while the rest of the ions, those with negative Stark coefficient (referred to as red ions), will shift to lower frequencies.

Originally, a 16 MHz square transmission window was created by using optical pumping. However, due to the inhomogeneity of the \mathbf{E} field inside the crystal (see the appendix in Ref. [18]) and the possible small mismatch of the electric field with the b axis of the crystal, when an electric field is applied to change the hole width, different ions see a slightly different electric field and shift slightly different amount in frequency, which smears out the sharpness of the hole edge and induces some absorption close to the edge of the hole. To compensate for this effect, the actual hole burning sequence was optimized in the following way, 16 MHz, 8 MHz, 1 MHz, and 500 kHz hole burning sequences were employed

consecutively in the presence of 0, 20, 40, and 41.5 V external voltages, followed by the same 16 MHz hole burning at 0 V in the end. This process is repeated 50 times until a hole with high transmittance and sharp edges was achieved. The sharpness of the hole was optimized by sending a frequency-chirped readout pulse after the hole creation and examine the coherent beating signal at the first hole edge. The higher the beating amplitude, the sharper the hole edge. The Rabi frequency of the hole burning sequence was kept low to avoid any power broadening and instantaneous spectral diffusion [28,29] in order to make the hole edge as sharp as possible. The whole process took about half a minute, so a 0.01 T magnetic field was applied to decrease the hyperfine relaxation rate such that the hole did not degrade much during the preparation process. A simplified sketch of the final hole structure as well as the structure at the presence of an external voltage of 40 V together with the real part of the refractive index can be found in Fig. 1.

IV. RESULT AND DISCUSSION

A. Group-velocity control

After the structure preparation, 16 Gaussian pulses, each with a full width at half maximum (FWHM) of 10 μ s and a cutoff duration of 100 μ s, were sent into the crystal successively while the external voltage applied across the crystal was increased monotonically for each probe pulse from 0 to 42.5 V. A part of the incoming pulse (reference beam) and the transmitted pulse were measured by PD1 and PD2 shown in Fig. 2(a). By comparing the time delay of the transmitted signal and the reference beam, the group velocity of the optical pulses can be calculated for each electric field. The relative efficiency was calculated by comparing the area of the transmitted pulse at different electric fields with the area of the transmitted pulse with no external voltage (widest hole) after correction using the reference beam signal. The measurement was repeated 150 times and the result is shown in Fig. 3, where the dot represents the average value for

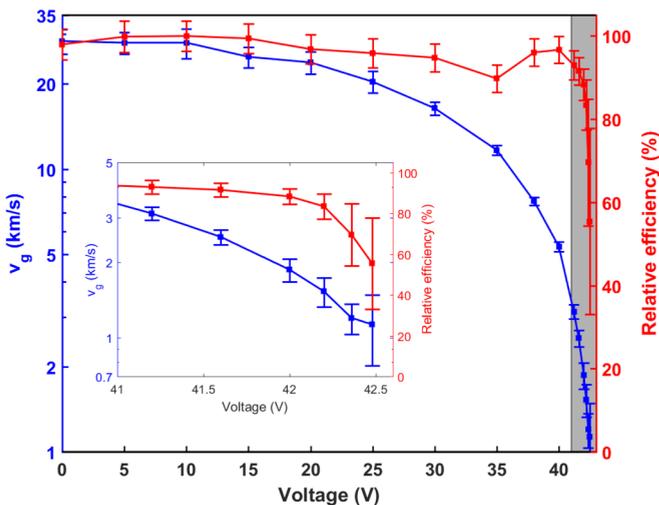


FIG. 3. The group velocity (blue) and the relative transmission efficiency (red) at different external voltages. The group velocity can be changed by a factor of 20 while keeping the relative efficiency more than 80%.

each voltage and the bars associated with the dots are one standard deviation away from the average. The gray area was zoomed in as an inset. The group velocity of the probe pulse changed from 30 to 1.5 km/s (when external voltages were changed from 0 to 42.2 V) while still having more than 80% relative transmittance. Beyond this, the absorption increases dramatically as the hole width becomes comparable to the frequency width of the pulse. 1 km/s was achieved with about 50% transmittance.

We can interpret the reduction of the group velocity from the three aspects that were discussed in Sec. II. From Eq. (1), it is clear that the steeper the dispersion, the slower the group velocity. When an external voltage is applied across the crystal the hole becomes narrower, and the slope of the dispersion becomes steeper as shown in Fig. 1. Hence $v \frac{dn}{dv}$ becomes much bigger, which decreases v_g greatly.

As revealed from Eq. (2c), the more energy stored in the medium, the slower the group velocity of the light. When the hole becomes narrower, the resonant frequency of the absorbing ions are much closer to the probe frequency; therefore, the off-resonance interaction between the light and the ions becomes much stronger, which leads to more energy stored in the off-resonant ions and the group velocity decreases. For the 16 MHz hole, with group velocity of $v_g = 30$ km/s, according to Eq. (2c), the fraction of energy temporarily stored in the crystal is 99.98%, while for a group velocity of $v_g = 1.5$ km/s, the fraction of energy stored in the crystal is 99.9991%.

We can easily estimate the tunability of the group velocity of the structure from Eq. (3), when the width of the hole changes from 16 MHz (0 V) to 0.25 MHz (estimated experimental hole width at the bottom of the hole at 42.2 V), a reduction of a factor of $\frac{16}{0.25} \times \frac{1}{2} = 32$ should be achieved (the $\frac{1}{2}$ comes from the fact that the absorption coefficient just outside the hole changes by a factor of two for these two structures; see Fig. 1). However, experimentally we only get a factor of 20 in group-velocity reduction, which is probably due to the decrease in the sharpness of the hole edge, so even though the window of full transmission is only 0.25 MHz, the full width at half maximum of the hole is actually much wider than that.

Concerning the absolute efficiency, it has been shown previously that the remaining absorption inside a 18 MHz spectral hole of a Pr:Y₂SiO₅ crystal with the same doping concentration as in the present experiment can be less than 0.1 dB/cm [17]. In our case this will correspond to an absolute transmission efficiency of higher than 97% for the 16 MHz spectral hole. We can then renormalize the relative efficiency according to this number to estimate the absolute efficiency for each group velocity.

In principle, as shown in Eq. (3), the tunability of the group velocity is only limited by the tunable range of the spectral hole width. Therefore, it could be greatly expanded if a much wider hole can be prepared from the beginning. For example, in Er:Y₂SiO₅, a spectral hole that is 575 MHz can be prepared given the hyperfine structures of the ground and excited states [16]. Therefore instead of a factor of 20 demonstrated here, a factor of 600 could be achieved ideally. Besides this, the absolute group velocity can be changed by changing the absorption coefficient at the hole edges and this

can be easily changed by changing the laser frequency to the side of the inhomogeneous absorption profile for the structure preparation process (or changing to another crystal with higher or lower absorption coefficient). The closer to the center of the absorption, the lower group velocity one can get while keeping the same tunability.

The bandwidth-delay product **BD** for such a slow-light structure can be approximately calculated by [21]

$$\mathbf{BD} = \frac{L}{v_g} \Gamma \approx \frac{\alpha L}{2\pi}, \quad (5)$$

where L is the length of the crystal. Since the absorption coefficient can easily be changed by going to another wavelength and the length of the crystal can be altered according to the purpose of the application, the bandwidth-delay product can therefore be easily changed. A more detailed discussion can be found in Refs. [17,30].

B. Pulse compression

Group-velocity control can also be used to reshape an optical pulse in time. After the creation of the 16 MHz hole [structure shown in Fig. 1(a)], a 1- μ s-long pulse was sent into the crystal at time $t = 0$, shown as the black dashed trace in Fig. 4. When no voltage is applied, the pulse comes out of the crystal at time $\tau_1 = 350$ ns, shown as the blue trace, and the group velocity of the pulse is $v_{g1} = L/\tau_1 \approx 29$ km/s, while when the pulse enters the crystal in the presence of an external voltage of 40 V [structure shown as in Fig. 1(b)], it propagates with a much lower group velocity, $v_{g2} \approx 6.5$ km/s, and comes out of the crystal at $\tau_2 = 1.54$ μ s, shown as the green trace in Fig. 4.

Because of the low group velocity when 40 V was applied across the crystal, the 1- μ s-long light pulse was strongly compressed, from a length of 300 m long in air to about 6 mm

inside the crystal. Therefore, almost the entire pulse can be accommodated inside the crystal. If the external voltage is switched off when the pulse is just about to exit, then the first part of the pulse will go through the entire crystal with a group velocity of $v_{g2} = L/\tau_2$, while the last part of the pulse will initially propagate with group velocity v_{g2} and change to a group velocity of v_{g1} after the **E** field is switched off. Therefore, the last part of the pulse spends much shorter time inside the crystal and the pulse will be compressed in time; shown as the red trace in Fig. 4.

A possible way to estimate how much a pulse can be compressed in time might be to assume that the pulse propagates with a group velocity of v_{g2} at first, the pulse length is $l = v_{g2}\tau$, and the crystal is long enough to accommodate the whole pulse length. If the group velocity is changed to v_{g1} instantaneously just when the first part of the pulse is about to exit, it takes $\tau' = l/v_{g1}$ for the last part of the pulse to exit the crystal. Therefore, a pulse initially with a duration of τ will be changed to $\tau' = \frac{v_{g2}}{v_{g1}}\tau$. Therefore, the compression factor, defined to be the ratio of the duration of the original pulse to the duration of the compressed pulse in time, would be $\frac{\tau}{\tau'} = \frac{v_{g1}}{v_{g2}}$. Hence, the bigger the ratio of the two group velocities, the more the pulse can be compressed. In reality, the electric field cannot be changed instantaneously, so the compression factor will be smaller. However, the compression factor will always be $\frac{v_{g2}}{v_{g1}}$, if the whole pulse is inside the crystal during the time while the **E** field is changed.

If we look at the pulse compression process from the energy density point of view, the pulse first propagate in a structure as in Fig. 1(b), where the group velocity is low, the energy of the optical pulse is mainly stored in the nearby off-resonant ions. When the electric field is decreased, those ions will shift outwards relative to the hole center, constitute a wider hole, and emit light at another frequency, so the pulse coming out would have a wider frequency distribution compared with the pulse sent in. The wider frequency span may be viewed as enabling a pulse compression in time.

A relevant quantity about the pulse compression is the efficiency of the compression process, which can be calculated by comparing the pulse area of the compressed pulse with that of the uncompressed pulse from Fig. 4. If the transmitted energy for a 16 MHz hole (blue trace) is set to 100%, then the transmitted energy for the 1 MHz hole is about 96.6% while the energy transmitted for the compressed pulse is about 66%. To evaluate the energy loss during the pulse compression process, a Maxwell–Bloch simulation was performed, and the detailed information about the simulation can be found in the simulation section of Ref. [18]. Two different simulations were carried out for comparison. Case I corresponds to the actual experiment when a 1 μ s pulse is sent into the 1 MHz transmission window as shown in Fig. 1(b). Before the pulse exits, the **E** field is switched off and the transmission window changes to 16 MHz, just as shown in Fig. 1(a). In this case, if we look at the right-hand side of the hole structure there only exists red ions before the field changes so the energy will mainly be stored in the red ions, while the red and blue ions overlap after switching off the **E** field. Therefore, when light was re-emitted by the red ions, it might be resonantly absorbed by the blue ions. We expect this will cause some energy loss.

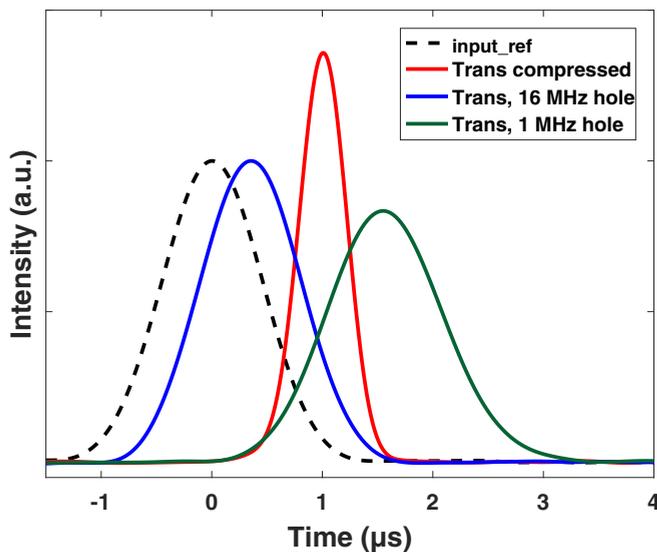


FIG. 4. Pulse compression. Dashed black trace is the reference incoming pulse, the blue trace is for 0 V, the dark green trace is for 40 V, and the red trace is for 40 V changed to 0 V just before the pulse is about to exit the crystal.

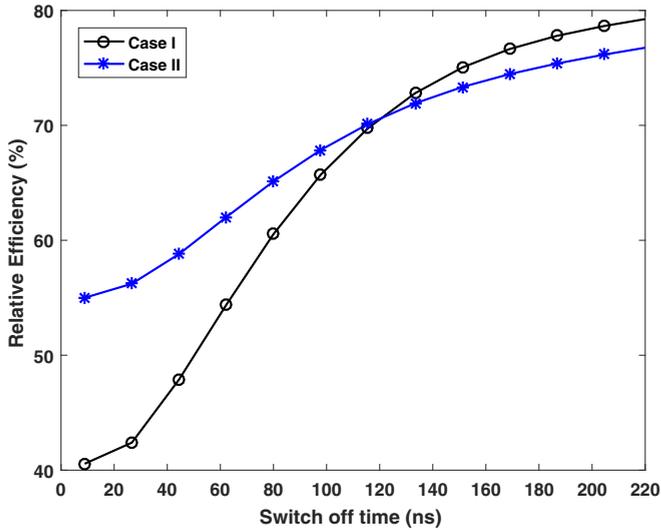


FIG. 5. Pulse compression efficiency as a function of \mathbf{E} field switch off time. The black circles are from simulation case I while the blue stars are from simulation case II. See main text for the description of the two cases.

Therefore, case II is simulating a similar situation but on the right side of the hole all the ions are red ions while on the left side of the hole all the ions are blue ions as the structure shown in Fig. 1(b) if the top half part is neglected. For this simulation, there will consequently never be any overlap of the resonance frequency of the two groups of ions. Hence by comparing these two cases, the energy loss due to the overlap in resonance frequency of the two groups of ions can be mapped out.

The simulated efficiency of the pulse compression process as a function of the switch-off time of the \mathbf{E} field can be found in Fig. 5. It shows that, the slower the \mathbf{E} field is switched off, the higher is the efficiency and when the \mathbf{E} field is switched off almost instantaneously, the energy loss is 40.5% for case I and 55% for case II, respectively. The 15% lower efficiency in case I can be attributed to the overlap of the two groups of ions (red and blue) as discussed above. However, even for case II where the ions never overlap with each other, the efficiency is still only 55% when the \mathbf{E} field is switched off rapidly and this is probably due to the fact that the energy distribution of the $1 \mu\text{s}$ pulse propagating inside a 1 MHz hole and a $1/16\text{-}\mu\text{s}$ -long pulse (theoretical estimation of the FWHM of the compressed pulse according to the discussion above) propagating inside a 16 MHz hole are quite different as shown in Fig. 6. When the \mathbf{E} field is switched off almost instantaneously, the ions will Stark shift to another resonance frequency accordingly and the hole changes from 1 to 16 MHz. However, the resulting energy distribution does not match the 16 MHz structure; therefore, the rephasing process will not be complete and it is reasonable to assume that some energy would be lost due to this. As can be seen from Fig. 5, when the \mathbf{E} field is switched more slowly the energy loss due to this effect decrease for both simulation cases.

In case I, if the \mathbf{E} field is switched off in 200 ns, the relative efficiency one can reach is around 79% while in our experiment, only 66% was achieved. This could be due to

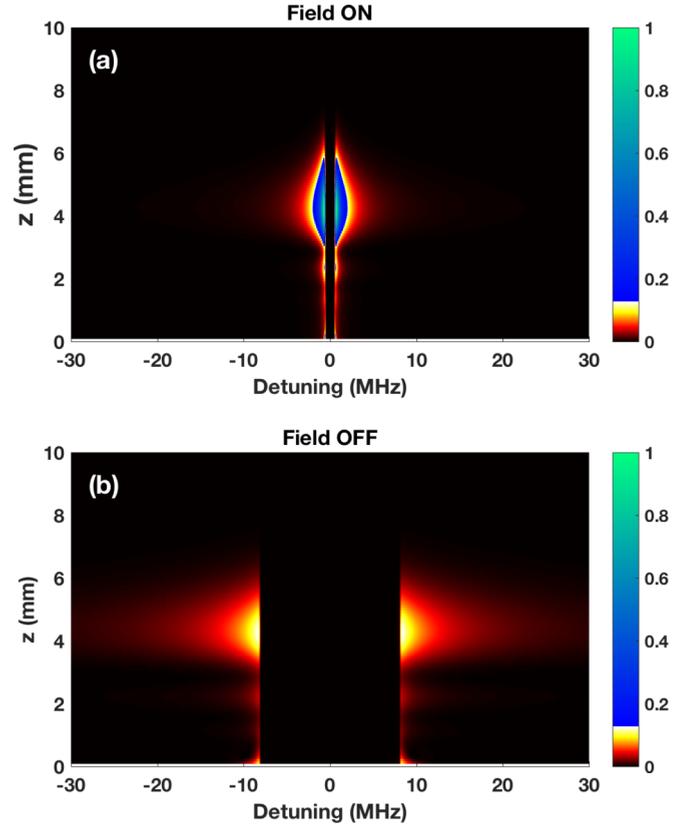


FIG. 6. The energy distribution of optical pulses propagate inside different hole structures. (a) A $1 \mu\text{s}$ pulse in a 1 MHz hole and (b) a $1/16 \mu\text{s}$ pulse in a 16 MHz hole. The color represents the relative energy stored in the ions calculated from the normalized angle of the ions' Bloch vector when optical pulses are propagating in the material. The maximum scale of 1 represents the maximum angle of the ions' Bloch vector relative to the w axis (in this simulation, for an input pulse area of $\pi/20$ this maximum angle is 2.56°), while 0 indicates that the ions' Bloch vector is pointing straight down, which means no energy is stored. The bigger the angle, the more the energy is stored in the ion. As can be seen, the energy is much more confined in frequency for a $1 \mu\text{s}$ pulse propagating in the 1 MHz hole.

absorption by ions remaining in the hole. As can be seen from Fig. 3, there is a specific absorption for each voltage when the pulse propagates inside the hole. For an applied voltage of 35 V, the transmission loss is about 10%. This could be minimized by further optimizing the structure preparation process.

In principle this technique can be used to stretch the pulse in time as well by having a higher group velocity at the beginning and then change to a lower one. However, this would require a crystal that is long enough to fit the entire pulse when it propagates at a higher group velocity, therefore it is practically more difficult to implement. Nevertheless, one might be able to do this with a multipass beam arrangement in a crystal or in a slow-light cavity [17].

V. CONCLUSION

In conclusion, we demonstrate a device in which the group velocity of an optical pulse can be changed continuously by a factor of 20 solely by applying an external electric field. The

energy loss of the transmitted pulse is kept below 20% over the whole group-velocity-tuning range. The device can also be used to reshape and compress the pulse. The maximum compression of a pulse depends on the ratio of the maximum and minimum group velocity with which the pulse propagates inside the crystal. The device is based on creating a semipermanent transmission window in the absorption line of a rare-earth-doped crystal using optical pumping. By Stark shifting the resonance frequency of the ions, the structure of the transmission window as well as the dispersion of the refractive index across the transmission window will be changed, hence the group velocity of the pulse propagating inside the transmission window will be changed accordingly. It is proposed that the tunable range of the group velocity can be further extended in other rare-earth-doped crystals, such as Er^{3+} -doped crystals. Because the group velocity is controlled purely by an external electric field and does not require any additional optical pulses, it can be especially useful in weak-light situations. For example, in quantum information and quantum communication processes. Moreover, since it is a solid-state device it can be integrated with other devices and could open up the way for on-chip applications.

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APPENDIX

As can be seen from the inset of Fig. 3, the error bars for the relative efficiency become much bigger when the applied voltages are higher than 42 V (which corresponds to a hole width of less than 300 kHz). This is attributed to the 50 Hz noise in the high-voltage amplifier used for this experiment. As discussed before, the Stark shift of the ions is linearly proportional to the applied external field. The variation in the voltages applied to the crystal will cause variation in the Stark shift of the ions, which will affect the preparation process of

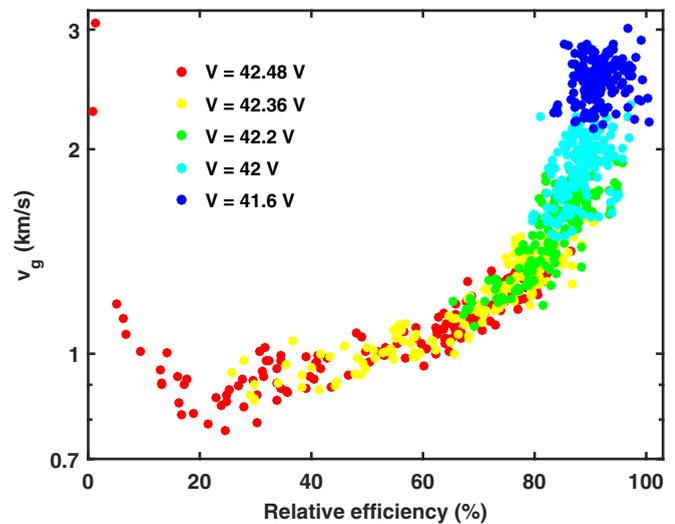


FIG. 7. The correlation of the group velocity and the relative efficiency at different external voltages.

the hole structure as well as the hole width when probing. When the width of the hole is comparable to the frequency spread of the optical pulse, a small fluctuation in the hole width can cause a dramatic change in the transmission as it changes exponentially with the number of ions inside the frequency width of the pulse. Therefore, the relative error for the transmission is much higher when the hole width is really narrow.

Since the fluctuation in the efficiency is caused by the fluctuation in the hole width, i.e., a lower efficiency is due to a narrower hole width. According to Eq. (3), a narrower hole width gives a lower group velocity as well. Therefore, the group velocity and the relative efficiency should be correlated to each other. This can be verified from Fig. 7 which shows the group velocity and relative efficiency of all 150 measurements when the applied voltages are higher than 41.6 V (i.e., hole width narrower than 500 kHz). It shows that, when the relative efficiency is higher than 20%, the group velocity is positively correlated with the relative efficiency, so that the lower the relative efficiency, the lower the group velocity. However, when the relative efficiency drops below 20%, the group velocity and the relative efficiency shows an anticorrelation.

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