Time-Bandwidth Problem in Room Temperature Slow Light

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For many applications of slow or stopped light, the delay-time-bandwidth product is a fundamental issue. So far, however, slow-light demonstrations do not show a large delay-time-bandwidth product, especially in room temperature solids. Here we demonstrate that the use of artificial inhomogeneous broadening has the potential to solve this problem. A proof-of-principle experiment is done using slow light produced by two-beam coupling in a photorefractive crystal Ce:$BaTiO_3$ where Bragg selection is used to provide the artificial inhomogeneity. Examples of how to generalize this concept for use with other room temperature slow-light solids are also given.

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Much of the current interest in slow light is due to potential applications such as optical communication (all optical buffers, ultrasensitive switches), radar beam steering (true time delay), and quantum information storage. However, the major challenge that current slow-light technologies are facing is that the delayed output pulses suffer from substantial distortion or short delay times. This problem is often characterized by the delay-time-bandwidth product, but this gives the illusion that stopped light can easily solve the problem. For example, in photorefractive crystals, stopped light has been demonstrated [7] and could theoretically have storage times up to months, but only one pulse at a time can be stored in each crystal. Therefore, a better metric is the number of pulses that can be slowed (or stopped) in the material at one time, which is equal to the delay-time-bandwidth product in the case of slow light. Key applications require a delay-time-bandwidth product of 100–1000 or more. However, the best performance achieved so far is about five in lead vapor [2] (i.e., the delay time is 5 times the pulse width). In principle, using electromagnetic induced transparency (EIT) [3], one can overcome this limit by using a highly absorptive material and applying enough pump laser power to saturate the EIT transition. This is possible in vapors because the optical resonances are very narrow, and the material can withstand a high laser power. However, in room temperature solids, which are strongly preferred for many applications, the optical resonances are significantly broadened, for example, by phonons. Therefore a much higher pump power would be needed to saturate these transitions, and this would easily exceed the damage threshold of the material well before even 100 pulses could be slowed. This analysis applies to most if not all slow-light and stopped-light techniques demonstrated so far.

The key to suppressing the distortion and enhancing the delay-time-bandwidth product is to simultaneously slow down all harmonic components of the input pulse using inhomogeneous broadening. This decouples the delay time and bandwidth in a way that otherwise cannot be realized with a homogeneously broadened material due to the Kramers-Kronig restriction. The independent slowing of each spectral component also gives the flexibility needed to insure that the output pulse has the same frequency spectrum as the input pulse, thereby suppressing distortions. Meanwhile, the delay time is determined by the inverse homogeneous bandwidth of the slow-light material so that the delay-time-bandwidth product is improved by the ratio of the inhomogeneous to homogeneous bandwidth width. Thus, even for a slow-light material with a delay-time-bandwidth product near one, the introduction of inhomogeneous broadening can give a large overall delay-time-bandwidth product.

In certain solids under cryogenic conditions, the necessary inhomogeneous broadening already exists, for example, in the EIT transition in Pr:YSO [4]. A theoretical analysis of inhomogeneous broadening in EIT systems has also been done recently [5] and shows good pulse fidelity. In this Letter, we propose a general approach to achieve a large delay-time-bandwidth product that is even applicable to room temperature solid-state slow-light materials. The key point is to artificially induce the necessary inhomogeneous broadening. An example of this approach considering the use of a dispersive inhomogeneity is shown in Fig. 1(a). Here, the basic idea is to first split an input pulse, or sequence of pulses, into independent spectral channels. This can be done using a dispersive element such as a prism or grating, as in femtosecond pulse shaping, chirp compensation, and high power optical pulse amplifiers. Each spectral channel sees a relatively long subpulse, whose length is determined by the inverse spectral resolution of the dispersive element, and whose center frequency is determined by the channel number. These long subpulses are then slowed by bandwidth-matched slow-light array elements, and later recombined using another dispersive element to produce the output pulse. If each of the subpulses has been independently delayed by an equal amount of time, then the short output pulse will see this same time delay, which can easily be much greater than its pulse width. For example, in the case of a slow-light array, wherein the individual array elements have a time-

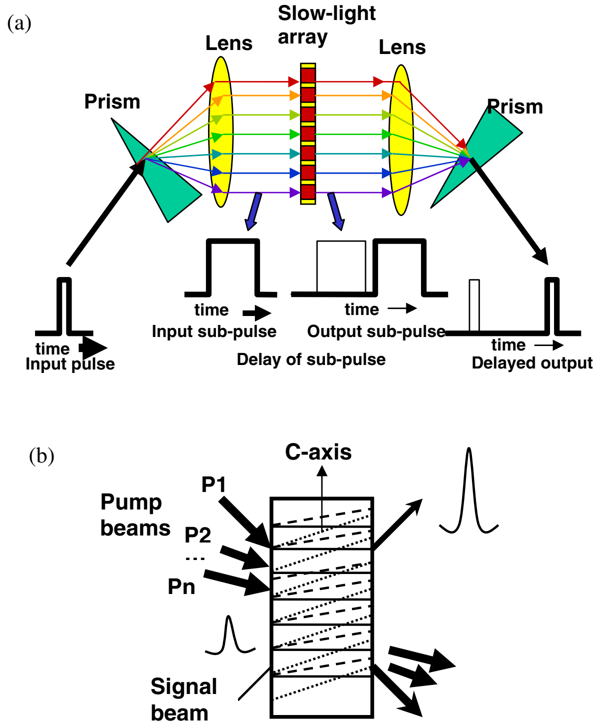


FIG. 1 (color online). (a) Proposed scheme for large delay-time bandwidth for slow light using a dispersive inhomogeneity. (b) Scheme for simultaneously slowing multiple spectral components of an input optical pulse using multiple pump frequencies and Bragg selection in a single photorefractive crystal.

bandwidth product of one, the time-bandwidth product of the reconstructed pulse will be given by the number of array elements. This can be on the order of 100–1000 for many room temperature materials. Here we assume that the phases of the individual subpulses will be adjusted as required by using an array of phase elements [not shown in Fig. 1(a)] similar to those used in existing femtosecond pulse shapers. In principle, this approach is suitable for any slow-light material that has a narrow-band frequency-adjustable gain or transmittance, such as EIT, optical resonators [6], optical spectral hole burning [8], resonance Raman [4], coherent population oscillation [7], photorefractive two-wave mixing [1,9,10], narrow-band fiber and semiconductor amplifiers, and others. In practice, spatially separating the pulse frequencies, as shown in Fig. 1(a), reduces the available pump intensity at each frequency. Thus, the preferred material for the slow-light array is one that can take advantage of the intensity increase due to focusing by the input lens in Fig. 1(a), for example, a material that is either thinner than the depth of focus or one that can be made into a waveguide array. A particularly interesting material for the slow-light arrays is vertical-cavity surface-emitting laser amplifiers [11].

In the remainder of this Letter, we will describe a proof-of-principle experiment that demonstrates the validity of the artificially induced inhomogeneity approach by simultaneously slowing more than one spectral component of an input optical pulse. For this demonstration, we choose a room temperature solid-state material, namely, a photorefractive crystal, wherein slow-light is produced by the narrow-band gain due to two-beam coupling. Here the necessary artificial inhomogeneity is produced by Bragg selectivity, which allows for multiple two-beam coupling gratings to be generated simultaneously inside the crystal in real time, without crosstalk, where each one is tuned to a particular spectral component of the input pulse.

For photorefractive crystals, the pulse-delay effect is well-known [12]. It has been applied to pulse shaping [13] and to optical delay lines [14]. The first experimental demonstration of slow light via two-wave mixing with photorefractive crystals was carried out by Podivilov *et al.* [1]. In their experiment no external voltage was applied to the crystal, and only intensity coupling exists. However, Zhang *et al* proposed [9] and demonstrated [10] that light could also be slowed by utilizing the phase coupling in two-wave mixing (with an external dc voltage applied to the crystal). Appealing advantages of photorefractive two-wave mixing are that the delay time can be controlled by varying the pump laser intensity, and the input pulses get amplified instead of attenuated while being slowed down. The drawbacks of photorefractives are their slow response time, narrow bandwidth, and erasure in the case of multiple pump beams. Nevertheless, this material is adequate for a proof-of-principle experiment involving two to three pump frequencies [see Fig. 1(b)], which is enough to demonstrate the validity of our approach.

To determine the amplitude of the output signal in photorefractive two-beam coupling, we let the electric field of the two beams be noted by $E_j(t, r) = A_j e^{i(\omega_j t - k_j \cdot r)}$, where $j = s, p$, standing for signal and pump beam respectively; A, ω, and k stand for complex amplitudes, angular frequencies, and wave vectors, respectively. Under the condition that the power of the pump beam is much larger than signal beam, and that the pump beam is undepleted, the emerging output signal can be expressed by [1,15]

$$A_s(\omega_s, d) = A_s(\omega_s, 0) \exp\left[\frac{\Gamma(\omega_s)d}{2}\right] \exp\left[i\left(\frac{2\pi n}{\lambda} + K\right)d\right], \quad (1)$$

where $\Gamma(\omega_s) = \Gamma_0/[1 + (\omega_s - \omega_p)^2\tau^2]$, is the gain coefficient of intensity, d is the path length of the signal traveled in the crystal, τ is the space-charge field rising time, and n is the refractive index of the crystal, respectively. K is additional phase change per unit length caused by the photorefractive effect and is given by

$$K = \frac{\Gamma_0}{2}\left[\frac{(\omega_s - \omega_p)\tau}{1 + (\omega_s - \omega_p)^2\tau^2}\right]. \quad (2)$$

Following the same procedure as in Ref. [9], the group velocity can be expressed by

$$v_g = \frac{c}{n + c dK/d\omega_s} \approx \frac{d\omega_s}{dK} = \frac{2[1 + (\omega_s - \omega_p)^2\tau^2]^2}{\Gamma_0\tau[1 - (\omega_s - \omega_p)^2\tau^2]}. \quad (3)$$

In Fig. 2, the normalized gain, the phase change, and the group velocity as functions of $\omega_s - \omega_p$ are shown. The minimum group velocity is $v_g = 2(\Gamma_0 \tau)^{-1}$ when $\omega_s = \omega_p$. As expected, these plots show that the harmonic components of the input pulse with a frequency deviating from ω_p by more than the two-beam coupling bandwidth will have a larger group velocity. This can be interpreted in terms of the electro-optic effect by noting that the interference fringe pattern between a component of the signal beam with frequency $\omega_p + \Delta\omega$ and the pump beam (ω_p) is not stationary but moving at a velocity of $c\Delta\omega/\omega$. Because of the movement, the space-charge field is continuously erased and rewritten, and the resultant refractive index modulation is consequently weakened compared with a stationary fringe pattern [16]. In other words, the frequency components of the input pulse different from ω_p do not produce good gratings, and hence have larger group velocities, resulting in distortion of the output pulse.

As mentioned earlier, this distortion problem can be solved with multiple pump beams and crystals, as shown in Fig. 1(a). However, to simplify the experimental setup for our demonstration, a single crystal and three or fewer pump frequencies were used. This is possible because Bragg angle selection allows multiple sets of gratings to work independently in the same crystal. Thus, the photorefractive crystal simultaneously works as both a dispersive and a slow-light element. Of course, one has to bear in mind that there are limitations to the number gratings that can be written in a single photorefractive crystal due to grating competition. Thus for practical uses requiring hundreds of frequency channels, multiple crystals are necessary.

To perform a two-frequency proof-of-principle experiment, a collimated 532 nm YAG laser (Compass 315M-100, Coherent Co.) was split into a signal beam (S) and two pump beams (P1 and P2). Each of these beams was independently switched on or off using acoustic-optics-modulators (1206C, Isomet Co.), which also shifted their

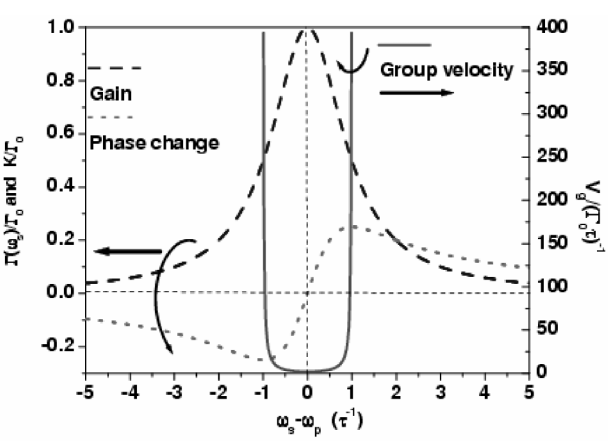


FIG. 2. Normalized group velocity, phase change per unit length, and gain coefficient as functions of the frequency difference between ω_s and ω_p.

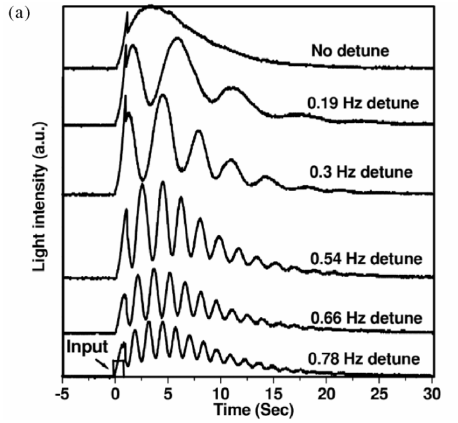
center frequencies as desired. The beams were intersected in a Ce:$BaTiO_3$ crystal ($7.73 \times 7.04 \times 4.8$ mm, Photox Opt. Sys.) with an angle about 40° between S and P2, 15° between P2 and P1, 30° between P1 and the c axis of the crystal. A photodiode (PDA400, Thorlab Inc.) was used to detect the output signal, and the waveforms in the time domain were recorded by a digital oscilloscope (TDS640A, Tektronix). All the incident waves were p polarized. The typical beam intensity used in the experiment was about 6.5 mW/cm^2 for the S beam, 637 mW/cm^2 for the P2 beam, and 716 mW/cm^2 for the P1 beam. Both S and P1 beams were shifted by a frequency of 110 MHz, and the S beam was further subject to a time gate to generate a rectangular pulse with a duration of 1 s and a repetition time of 40 s. The P2 beam was shifted by $110M + \Delta f$ Hz, where Δf was varied from 0 to 1 Hz.

The top trace of Fig. 3(a) shows the slowing of a single spectral component of the input pulse when Δf for P2 is 0 Hz. From this data, the group velocity is estimated to be around 1 mm/s, which is in good agreement with the theoretical prediction, $v_g = 2(\Gamma_0 \tau)^{-1}$ ($\tau = 3.5$ s and $\Gamma_0 = 6.2$ cm^{-1} in our case). As expected, this value is close to the speed of movement of the envelope of the refractive index grating in the crystal [17]. Because the response time of the crystal is 3.5 times longer than the input pulse (1 s), the output pulses suffered serious broadening and distortion.

The remaining traces in Fig. 3(a) shows the successful simultaneous slowing of two spectral components of the input pulse. From top to bottom, P2 is detuned away from P1 by 0.19, 0.3, 0.54, 0.66, and 0.78 Hz, as shown. The oscillating behavior of the output waveforms verifies that the two Fourier components of the input pulse were simultaneously slowed without loss of phase information. The high contrast of the oscillation indicates that the fidelity is high.

We also performed a three-frequency slowing experiment and this is shown in Fig. 3(b). Here, the top three traces show the output signals when any two of the three pump beams were on, and are similar to what is shown in Fig. 3(a), except that the signal to noise is degraded because our laser source, after being divided into three pump beams, did not have enough power to adequately pump the gratings. The frequency shifts Δf for P2 and P3 are 0.4, and 0.54 Hz, respectively, and the intersection angles of P1, P2, and P3 with the c axis are 54, 49, and 42 degrees, respectively. The next trace shows the output signal when all three pumps were on. As seen, the output signal has almost same delay time and begins to show the presence of a sharper peak. For reference, the bottom trace with circles shows the theoretically predicated output pulse based on both the one- and two-frequency measurements, and is in approximate agreement with the experimental results.

We simulated the shape of the output pulse that would be seen if more pump frequencies were available. This was done by summing up the delayed output pulses for six Fourier components of the input, corresponding to each



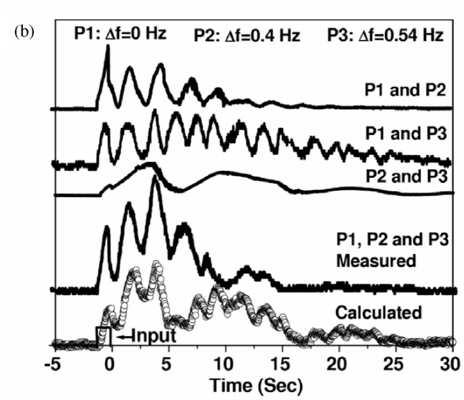


FIG. 3. Demonstration of the simultaneous slowing of up to three Fourier components of signal beam S, which is a rectangle pulse with a duration of 1 s and a repetition time of 40 s. (a) Output pulses when two pump frequencies are used. From top to bottom, P2 is detuned away from P1 by 0, 0.19, 0.3, 0.54, 0.66, and 0.78 Hz. (b) Detailed analysis of the case when three pump beams are used. P2 and P3 are detuned away from P1 by 0.4 Hz and 0.54 Hz, respectively. The top three curves are the output pulses when two of the three pump beams are applied. The next trace is the output when all the three pump beams are turned on. The bottom trace, with circles, is a theoretical prediction corresponding to the three-frequency data.

of the frequencies in Fig. 3(a), in the same way as was done to generate the theoretical curve in Fig. 3(b). The result appears in Fig. 4, which shows an output pulse with a time width of about 1 s and a delay time of about 4 s. This clearly shows that the bandwidth of output pulse can be significantly improved by multiple frequencies pumping, and, consequently, enlarge the delay-time-bandwidth product.

In conclusion, we have proposed a general technique to solve the delay-time-bandwidth limitation in solid-state room temperature slow light. To demonstrate proof of principle, we have performed an experiment in a Ce:$BaTiO_3$ crystal, wherein two to three spectral components of an input optical pulse were simultaneously slowed. A theoretical projection for multiple pump beams shows that the effective delay-time-bandwidth product can be significantly extended with this approach.

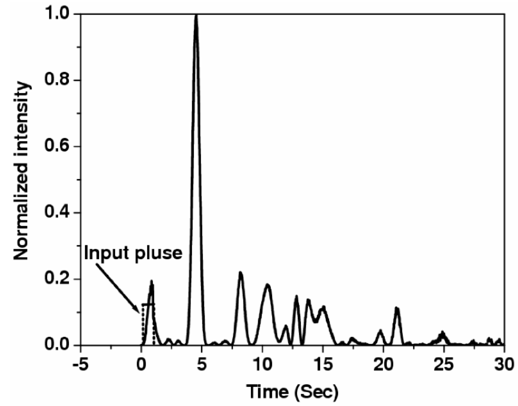


FIG. 4. Simulated output pulse with six pump beams. The simulation is based on the measured two-frequency waveforms corresponding to each of the pump beam detunings. The frequencies of six pump beams are ω_p, $\omega_p + 0.19$ Hz, $\omega_p + 0.3$ Hz, $\omega_p + 0.54$ Hz, $\omega_p + 0.66$ Hz, and $\omega_p + 0.78$ Hz.

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