Propagation of smooth and discontinuous pulses through materials with very large or very small group velocities

INSTITUTE OF PHYSICS PUBLISHING JOURNAL OF PHYSICS: CONDENSED MATTER

J. Phys.: Condens. Matter **18** (2006) 3117–3126 doi:10.1088/0953-8984/18/11/017

Propagation of smooth and discontinuous pulses through materials with very large or very small group velocities

Matthew S Bigelow[1,3], **Nick N Lepeshkin**[1,4], **Heedeuk Shin**[1] **and Robert W Boyd**[1,2]

[1] The Institute of Optics, University of Rochester, Rochester, NY 14627, USA
[2] Department of Physics and Astronomy, University of Rochester, Rochester, NY 14627, USA

Received 9 October 2005, in final form 20 January 2006
Published 2 March 2006
Online at stacks.iop.org/JPhysCM/18/3117

Abstract

We investigate the propagation of optical pulses through two different solid-state optical materials, ruby and alexandrite, for which the group velocity can be very small ($v_g \ll c$) or superluminal ($v_g \gg c$ or negative). We find that for smooth pulses the fractional delay or advancement is maximized through the use of pulses with durations comparable to the response time of the physical process—coherent population oscillations—that leads to these extreme group velocities. However, we find that the transmitted pulse shape becomes distorted unless the pulse is much longer or much shorter than this response time. We also investigate the transmission of pulses that possess an abrupt change in pulse amplitude. We find that, to within experimental accuracy, this nearly discontinuous jump propagates at the usual phase velocity of light c/n, even though the smoothly varying portions of the pulse propagate at the group velocity.

1. Introduction

Ultra-slow and superluminal group velocities can be observed in materials that possess large normal or anomalous dispersion, respectively. While this fact has been known for more than a century [1], recent experiments have shown that the dispersion can be very large without dramatically deforming a pulse [2–6]. As a result, the nature of pulse propagation through highly dispersive media and the description of this propagation in terms of pulse velocities is currently being re-examined.

[3] Present address: Laser and Optics Research Center, Department of Physics, United States Air Force Academy, Colorado Springs, CO 80840, USA.
[4] Present address: Department of Physics and Astronomy, San Francisco State University, 1600 Holloway Avenue, San Francisco, CA 94132, USA.

0953-8984/06/113117+10$30.00

In this paper, we describe our studies of pulse propagation through the solid-state materials ruby and alexandrite. As we reported earlier, group velocities as slow as 57 m s^{-1} can be observed in ruby [7], and velocities as 'fast' as -800 m s^{-1} can be observed in alexandrite [8]. In each case the extreme values of the group velocity result from the strong dispersion in the refractive index of the material induced by the process of coherent population oscillations. One aspect of the present work entails an investigation of how the width of a smooth incident pulse influences the delay and shape of the transmitted pulse. We find that as we decrease the pulse width, higher-order dispersion becomes significant because the bandwidth of the pulse becomes comparable to the spectral width of the region of induced dispersion of the material. These higher-order effects cause pulse distortion [9, 10]. When the pulse bandwidth becomes much larger than the spectral width of the interaction region, the measurable pulse delay or advancement disappears. In addition, we study the propagation of pulses containing nearly discontinuous jumps. As the spectral bandwidth associated with a rapid change of field amplitude is quite large and can have components lying outside the region of strong induced dispersion, we find that the advancement or delay of the discontinuity also disappears. We conclude that this discontinuity propagates at a speed c/n rather than at the group velocity.

Certain models [11, 12] of the transfer of information through a material system ascribe the information content of an optical field to its points of true mathematical discontinuity. Thus, studies of the propagation of pulses containing nearly discontinuous jumps may shed insight into the propagation of information through optical systems.

One can define the information velocity as follows. One first defines the information arrival time as the earliest possible moment at which, using an ideal detector, one can observe a 'change' in the electromagnetic field that propagates through a system. If T is the time required for information defined in this manner to propagate through a material system of length L, the information velocity is taken to be L/T. In principle, the information arrival time is the exact moment at which the transmitted electric field strength of a pulse first becomes non-zero. In practice, one can never detect this moment exactly. For propagation through a material with $n_g > 1$, the transmitted pulse is often preceded by a 'precursor,' which propagates more rapidly than the main pulse and consists of frequency components that are not strongly influenced by the dielectric response of the material medium. Such precursors have been observed experimentally with microwave pulses in dispersive waveguides [13] and in optical pulses in semiconductors [14]. Thus, in practice, the information arrival time is often the time of arrival of the earliest precursor to the main pulse.

While some have argued that the information velocity is equal to the group velocity even when the group velocity is superluminal [15], Stenner *et al* have presented compelling evidence that even in a material with a negative group velocity the information velocity is less than or equal to c [12]. These workers sent two different types of pulses into a system with large anomalous dispersion—a '1'-pulse that would suddenly jump to a higher value at the peak, and '0'-pulse that would rapidly drop to zero at the peak. They found that it was not possible to distinguish between '1'-pulses and '0'-pulses any earlier than for transmission through vacuum. In a similar experiment, they found that information was not delayed in a slow light material [16]. Brunner *et al* have obtained similar results in an optical fibre [17].

2. Impulse response function

In this section, we develop a model of pulse propagation through dispersive media. While it is possible to solve explicitly the density matrix equations for ruby and alexandrite [18], and thereby find how the pulse shape is changed upon propagation through these materials, we instead consider a simpler model that sheds good insight into the nature of propagation through

materials with extreme group indices. As noted by earlier workers [19–22], it is possible to model a fast (or slow) light system with an impulse response function. We write the electric field $\mathcal{E}(z, t)$ as

$$\mathcal{E}(z, t) = \mathrm{Re}\left[E(z, t)\mathrm{e}^{-\mathrm{i}\omega_0 t}\right], \tag{1}$$

where $E(z, t)$ is the complex pulse envelope, ω_0 is the mean pulse frequency and $k_0 = n_0\omega_0/c$ with n_0 denoting the refractive index of the host material. The transmitted pulse envelope after travelling a distance Δz through a material is related to the initial pulse shape through an impulse response function $h(t)$ as

$$E(z + \Delta z, t) = h_{\Delta z}(t) \otimes E(z, t), \tag{2}$$

where '$\otimes$' indicates a convolution operation. Correspondingly, we can relate the initial and final pulse spectra by means of a transfer function $H(\Omega)$ so that

$$\begin{aligned}\widehat{E}(z + \Delta z, \Omega) &= H(\Omega)\widehat{E}(z, \Omega)\\ &= \mathrm{e}^{\Gamma(\Omega)}\widehat{E}(z, \Omega)\\ &= \mathrm{e}^{F(\Omega)}\mathrm{e}^{\mathrm{i}\varphi(\Omega)}\widehat{E}(z, \Omega),\end{aligned} \tag{3}$$

where $\Gamma(\Omega)$ is the complex gain factor, $F(\Omega)$ is the real amplitude absorption factor and $\varphi(\Omega)$ is the induced phase advancement. The pulse envelope spectrum $\widehat{E}(z, \Omega)$ is the Fourier transform of the pulse envelope, and likewise, the transfer function $H(\Omega)$ is the Fourier transform of the impulse response function. As an example, for a material consisting of a collection of atoms with a single resonance frequency ω_r embedded in a non-absorbing host material of constant refractive index n, the complex gain factor becomes

$$\Gamma(\Omega) = \frac{\mathrm{i}(\omega_0 + \Omega)n}{c}\Delta z - \frac{\alpha\Delta z/2}{1 - \mathrm{i}(\omega_0 + \Omega - \omega_\mathrm{r})/\gamma}, \tag{4}$$

where α is the intensity absorption coefficient and γ is the dipole relaxation rate of the absorbing species. The first term in this equation describes the phase acquired by the frequency component at $(\omega_0+\Omega)$ in propagating through distance Δz of a material with host index n. The second term describes the complex phase acquired by interaction with the embedded resonant atoms. With a slight change in notation, it is equivalent to equation (6) of [22].

The system we want to model is only slightly more complicated. We do not have a single resonance line, but rather a Lorentzian-shaped spectral hole (or anti-hole) resulting from coherent population oscillations impressed on a broad background. As a result, the functional form of the transfer function is quite similar to that of equation (4). For our system, the complex gain factor is given by

$$\Gamma(\Omega, I_0) = \frac{\mathrm{i}(\omega_0 + \Omega)n}{c}\,\Delta z - \frac{\alpha_0\Delta z}{2(1 + I_0)}\left[1 \pm \frac{I_0}{(1 + I_0) - \mathrm{i}T_1\Omega}\right], \tag{5}$$

where α_0 is the unsaturated intensity absorption coefficient, I_0 is the pump intensity (normalized to the saturation intensity) and T_1 is the population relaxation time, and the minus (plus) sign pertains to the case of a saturable (reverse-saturable) absorber. This result follows from equations (6) and (7) of [7]. Note that, unlike for the case of a resonance line (equation (4)), here the complex gain factor depends on the pump intensity. As a result, the modified pulse shape must be calculated step-wise throughout the length of the material. From equation (5), we see that the phase is given by

$$\varphi(\Omega, I_0) = \frac{(\omega_0 + \Omega)n}{c}\Delta z \mp \frac{\alpha_0\Delta z}{2}\frac{I_0}{1 + I_0}\frac{T_1\Omega}{(1 + I_0)^2 + (T_1\Omega)^2}. \tag{6}$$

From this result we find that the (spatially averaged) refractive index that a pulse will experience in propagating over a distance Δz is given by

$$\Delta n(\Omega) = \mp \frac{\alpha_0 c}{\omega_0 \Delta z} \int_0^{\Delta z} \frac{I_0}{1 + I_0} \frac{T_1 \Omega}{(1 + I_0)^2 + (T_1 \Omega)^2} \, \mathrm{d}z. \tag{7}$$

The amplitude absorption factor is likewise seen to be given by

$$F(\Omega, I_0) = -\frac{\alpha_0 \Delta z}{2} \left[\frac{1}{(1 + I_0)} \pm \frac{I_0}{(1 + I_0)^2 + (T_1 \Omega)^2} \right]. \tag{8}$$

Correspondingly, we can express the intensity attenuation seen by the pulse (neglecting background absorption) as

$$A_{\text{pulse}}(\Omega) = \mp \alpha_0 \int_0^{\Delta z} \frac{I_0}{(1 + I_0)^2 + (T_1 \Omega)^2} \, \mathrm{d}z. \tag{9}$$

It can be shown that this expression is equivalent to the relative modulation attenuation (as defined in [7]).

3. Pulse distortion

For a pulse with a bandwidth much smaller than the width of the spectral region of large dispersion, the output pulse envelope will have the form

$$E'(z + \Delta z, t) = E(z, t - \theta), \tag{10}$$

where θ is the delay of the pulse travelling through the material and $E'(z, t)$ is the output field envelope that has been normalized to ignore background absorption. The value for θ can be defined as the delay of the 'centre-of-mass' of the envelope of the output pulse [22], but due to the nature of the distortion found in our experiments, we found it most useful to set the value of θ equal to the delay of the peak of the pulse. If the bandwidth of the pulse starts to become significant relative to the range of large dispersion, we should expect that the pulse will become distorted. The degree of pulse distortion can be characterized through use of the quantity

$$D = \left(\frac{\int_{-\infty}^{+\infty} ||E'(z + \Delta z, t)|^2 - |E(z, t - \theta)|^2| \, \mathrm{d}t}{\int_{-\infty}^{+\infty} |E(z, t)|^2 \, \mathrm{d}t} \right)^{\frac{1}{2}}. \tag{11}$$

The quantity D is a slightly modified form of equation (22) of [22], which was shown to be a good measure of the distortion of the pulse shape. Our expression differs from that of [22] in that we take the difference of the squared moduli of the field amplitudes, whereas [22] takes the squared modulus of the difference of field amplitudes. Our definition is much more convenient for use in a laboratory setting in which we do not have access to the phases of the optical fields. Note that D is equal to zero when the pulse is undistorted. This equation, when applied to our data, produces a small offset from zero even for an undistorted pulse because of noise. Nevertheless, we have found that equation (11) is a useful characterization of the pulse distortion for both pulse delays or advances (i.e. θ either positive or negative).

4. Pulse propagation through a 'fast-light' material

We have investigated the propagation of Gaussian pulses through alexandrite under conditions of a superluminal group velocity. Our experimental set-up is very similar to that described in [8]. The output of an argon-ion laser first passes through an electro-optic modulator which places a long (∼ms) pulse on the beam. We operated the modulator so that the pulses were

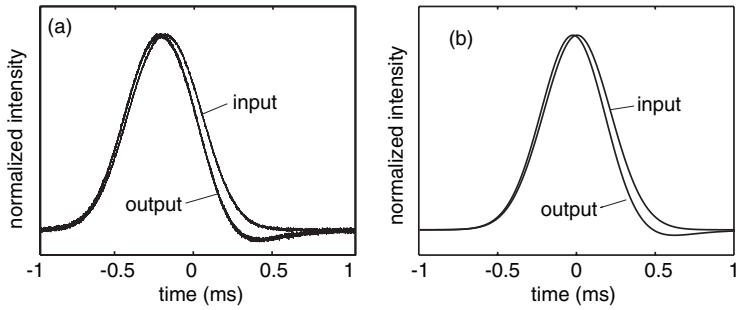

Figure 1. Experimental (a) and theoretical (b) input and output pulse shapes for a Gaussian input pulse of 0.5 ms width (FWHM) for propagation through 4 cm of alexandrite. The output pulse is seen to be advanced and to suffer some distortion.

superposed on a large background (580 mW) which acts as the pump. We used a wavelength of 476 nm because our previous work showed that this wavelength produces the largest fractional advancement [8]. The polarization of the light was chosen to maximize the pulse advance as described in [8]. The beam was focused with a lens of focal length 20 cm into a 4.0 cm long alexandrite crystal. The transmitted beam was passed through an interference filter to remove any signal caused by the fluorescence from the alexandrite crystal. The detected waveform was stored along with that of the reference beam on a digital oscilloscope, and the resulting traces were compared on a computer to calculate the relative delay and relative amplitude of the two signals.

Typical results are shown in figure 1. The plot on the left shows the measured input and output waveforms, and the plot on the right shows the predictions of our model for this situation. The values $\alpha_0 = 1.19\ \mathrm{cm}^{-1}$, $I_0 = I_{\mathrm{pump}}/I_{\mathrm{sat}} = 0.6$, and $T_1 = 290\ \mu\mathrm{s}$ were used in the calculation; these values agree acceptably well with our best laboratory estimates of these quantities. It can be seen that the output pulse is advanced in time and suffers some pulse distortion. It can also be seen that the laboratory results are well explained by the numerical model.

We have performed measurements of the sort shown in figure 1 for a range of input pulse lengths, and have extracted the peak advancement and distortion for each case. The fractional advancement is defined as the ratio of pulse advancement to pulse width (FWHM), and the distortion is defined by equation (11). These results are shown in figure 2. From part (a) of the figure, we see that the fractional advancement reaches a maximum for an input pulse width of approximately 0.5 ms, which is comparable to the value of the ground state recovery time T_1 of alexandrite. From part (b) of the figure we see that the distortion is appreciable for pulses with widths comparable to or shorter than approximately 0.5 ms.

These results can be understood in terms of the diagram shown in figure 3. Here for a variety of pulse widths we compare the initial pulse spectrum with the region of large anomalous dispersion. The change in the group index induced by the strong pump beam (calculated from equation (7)) is shown as the dashed line. We can see that when the pulse duration is large, most of the spectrum lies within the region of large anomalous dispersion (grey shaded region). From figure 2, we see that under this condition the fractional advancement is reasonably large and the pulse distortion is small. However, when the pulse duration becomes extremely short, the pulse bandwidth becomes too large to interact with the region of strong induced dispersion. As a result, this pulse travels with little distortion at velocity c/n through the material. The down-turn in distortion can be seen for the shortest pulse widths shown in part (b) of figure 2.

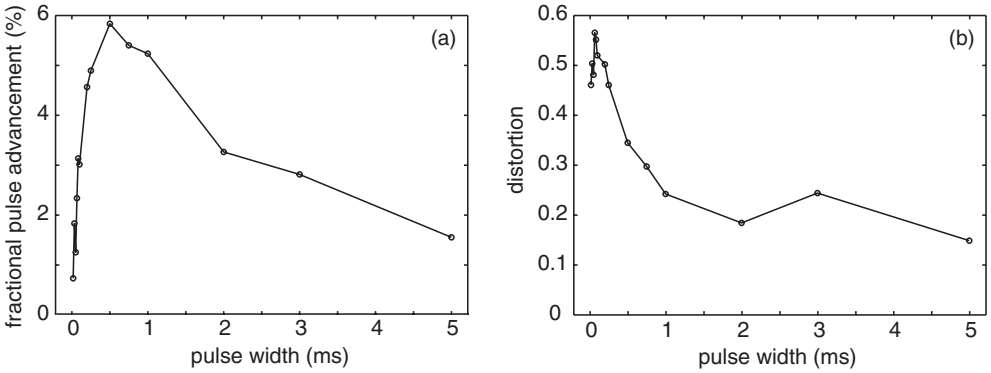

Figure 2. (a) Fractional advancement of the peak of a Gaussian pulse as a function of pulse width (FWHM) upon propagation through alexandrite. (b) The distortion (as defined in equation (11)) experienced by the pulse as a function of pulse width.

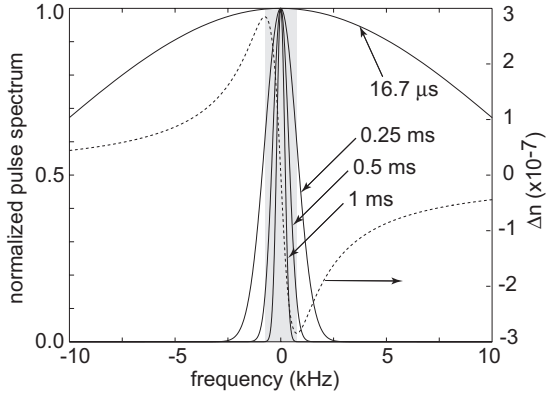

Figure 3. Spectra of the input pulses (solid lines) for some of the different pulse widths shown in figure 2, and the change in group index (Δn) induced by the strong pump beam (dashed line). The grey region shows the range of large anomalous dispersion.

To study the propagation of rapidly varying fields more systematically, we experimentally investigated the propagation of a pulse with an abrupt jump in intensity. The first half of the input pulse is Gaussian, but at the peak, the intensity rapidly drops to zero. An abrupt change in intensity models the non-analytic pulses of Chiao and Steinberg [11]. These authors argue that information is carried by these points of non-analyticity, and that in principle these points travel exactly at c in any material. Our pulse shape resembles the '0'-pulse that Stenner *et al* [12] used in their experiments. The results of our experiment are shown in figure 4. For this experiment, the group velocity is -760 m s^{-1}. As can be seen from the figure, the leading portion and peak of the pulse are advanced, but the sharp edge is not. The data are in good agreement with the numerical results of our model, for the choice of parameters $\alpha_0 = 1.19$ cm^{-1}, $I_0 = I_{\mathrm{pump}}/I_{\mathrm{sat}} = 0.65$ and $T_1 = 290$ μs. At the level of accuracy available in our experiment, we cannot determine whether the velocity of the sharp edge is c or c/n. However, based on the theoretical model introduced above, we conclude that this velocity should be c/n. The difference between our conclusion and the predictions of Chiao and Steinberg [11] presumably lies in the fact that they were considering the idealized situation

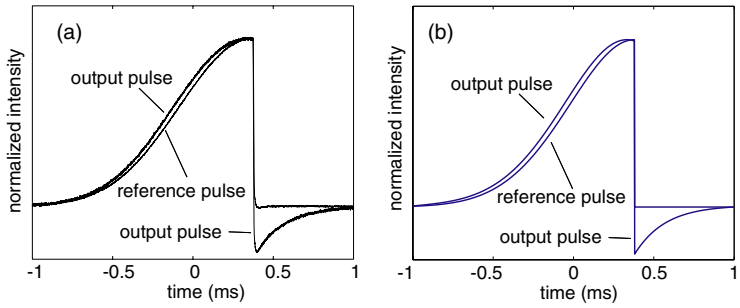

Figure 4. Measured (a) and calculated (b) input and normalized output intensities of a truncated Gaussian pulse after propagation through alexandrite. Without the sharp cutoff, the pulse would have had a width (FWHM) of 1 ms. Note that while the slowly varying leading edge of the pulse experiences a measurable pulse advancement, the abrupt trailing edge does not. Thus the velocity of the sharp edge is not equal to the group velocity.

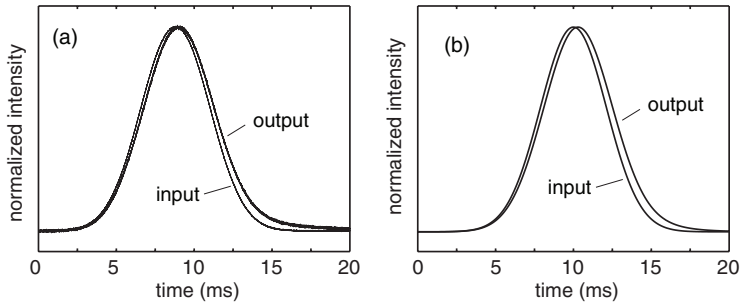

Figure 5. Experimental (a) and theoretical (b) input and output pulse shapes for a Gaussian input pulse of 5 ms width (FWHM) after propagation through 4.25 cm of ruby. The output pulse is seen to be delayed and to suffer some distortion.

of pulses containing a true mathematical discontinuity in intensity. Such a field would thus contain frequency components extending to infinite frequency, which would not be affected by the contribution to the refractive index of the material resulting from bound electrons. Thus, for these high-frequency components, the refractive index would equal unity and the velocity of the sharp edge c/n would reduce to c.

5. Pulse propagation through a 'slow-light' material

We also studied pulse propagation effects in ruby, under conditions of ultra-slow group velocities. Our experimental set-up is similar to that of reference [7], but we have modified the experimental set-up so that the pulses sit on a large background (230 mW). In addition, we used a shorter focal length lens (25 cm) to focus into a shorter ruby crystal (4.25 cm).

Typical results are shown in figure 5. The plot on the left shows the measured input and output waveforms, and the plot on the right shows the predictions of our model for this situation. The values $\alpha_0 = 1.17\ \mathrm{cm}^{-1}$, $I_0 = I_{\mathrm{pump}}/I_{\mathrm{sat}} = 0.23$, and $T_1 = 1.6$ ms were used in the simulation. It can be seen that the output pulse is delayed in time and suffers some pulse distortion. It can also be seen that the laboratory results are well explained by the numerical model.

From results such as those shown in figure 5, we have determined the dependence of the fractional delay and pulse distortion on the length of the input pulse. We show the delay in the

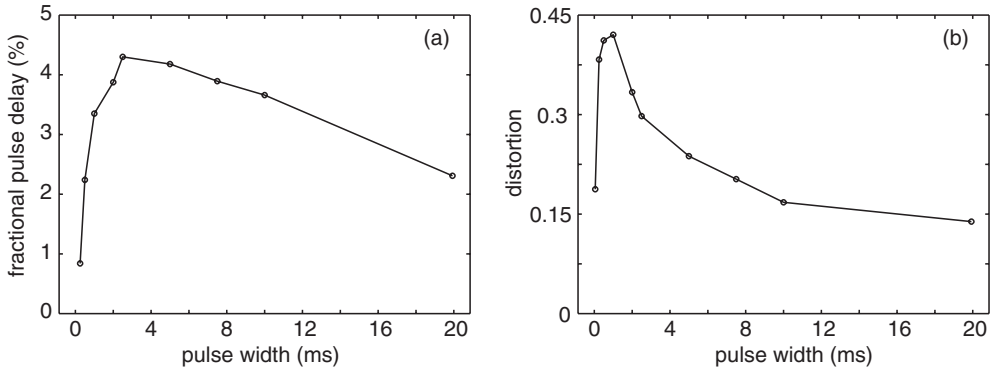

Figure 6. (a) Fractional delay of the peak of a Gaussian pulse as a function of pulse width (FWHM) upon propagation through ruby. (b) The distortion (as defined in equation (11)) experienced by the pulse as a function of pulse width.

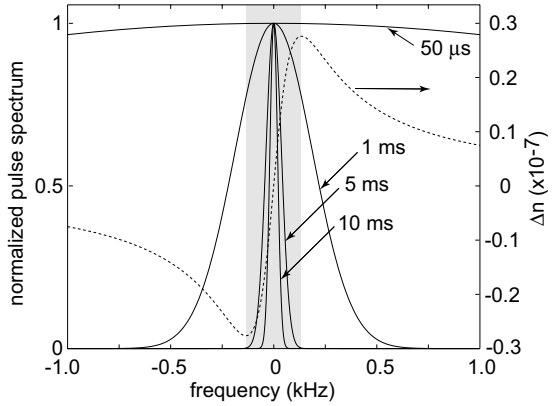

Figure 7. Spectra of the input pulses (solid lines) for some of the pulse widths shown in figure 6, and the change in group index (Δn) induced by the strong pump beam (dashed line). The grey region shows the region of large normal dispersion.

peak of the pulse for different pulse lengths in figure 6(a). Just as in the case of alexandrite, we see that the fractional delay is greatly reduced at small and large pulse widths. In figure 6(b), we show the pulse distortion D experienced by the pulse upon propagation through ruby. As in the case of the alexandrite experiment, we see that long pulses experience little distortion. Very long pulses have a very narrow spectrum that samples only those frequencies for which n increases essentially linearly with optical frequency, as illustrated in figure 7. Very short pulses have bandwidths that significantly exceed the region of induced dispersion.

We also investigated the propagation of truncated pulse shapes through ruby. The results of this experiment are shown in figure 8. Under our experimental conditions, the group velocity is 120 m s^{-1}. We see that even though the smoothly varying parts of the pulse propagate at the greatly reduced group velocity, the region of sudden decrease is not appreciably slowed and propagates at a velocity c/n. The data are well described by the results of our numerical model, with the parameters $\alpha_0 = 1.17$ cm^{-1}, $I_0 = I_{\mathrm{pump}}/I_{\mathrm{sat}} = 0.2$ and $T_1 = 2$ ms. The interpretation is the same as that given above for the analogous measurement for the case of alexandrite. These results demonstrate the important point that the velocity of a sharp edge is equal to c/n for both positive and negative values of the group velocity.

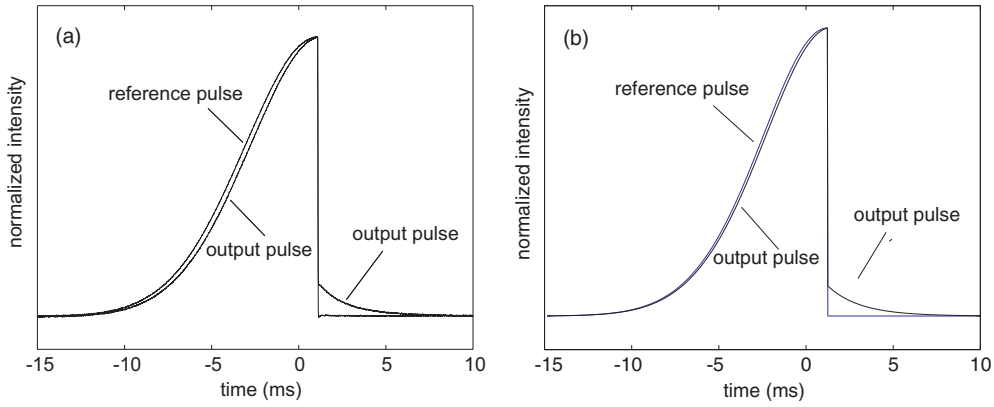

Figure 8. Measured (a) and calculated (b) input and normalized output intensities of a truncated Gaussian pulse after propagation through ruby. Without the sharp cutoff, the pulse would have had a width (FWHM) of 10 ms. Note that while the slowly varying leading edge of the pulse experiences a measurable pulse delay, the abrupt trailing edge does not. Thus the front velocity is not equal to the group velocity.

6. Analysis and conclusions

We have analysed pulse propagation in materials with both large normal dispersion and large anomalous dispersion. In one set of experiments we sent Gaussian pulses of various pulse widths through these materials. We found that the total delay or advancement was maximized through the use of relatively long pulses, and that the fractional delay or advancement became small for very short or very long pulses and was maximized through use of pulses of length comparable to the inverse of the spectral width of the region of induced dispersion. We also found that pulse distortion occurs unless the pulse is much longer or much shorter than the material response time.

In a second set of experiments, we sent pulses containing an abrupt change in intensity through these materials. We found that this edge propagates at velocity c/n, even though the smooth parts of the pulse propagate at the group velocity. There are good theoretical reasons [11, 12] to identify the propagation velocity of a true discontinuity with the information velocity. Since a true discontinuity would possess an infinitely broad frequency spectrum, it would propagate at velocity c, since no material could respond to arbitrarily large frequency components. One thus concludes that the information velocity is equal to c. Our laboratory results are consistent with this prediction. However, in our experiment the pulse edge was not truly discontinuous and thus travelled at velocity c/n rather than at c.

A vexing question is whether there are any practical uses of slow and fast light, if information always propagates at velocity c, independent of the value of the group velocity. As a first step towards addressing this question, we note that, for example, practical telecommunication systems do not make use of pulses with discontinuities of the sort used in the experiments of Stenner *et al* [12] or of the present work. In these real-world systems, the points of non-analyticity presumably lie near the far leading edge of each pulse. The presence of this point heralds the entire pulse that follows it. There is extremely little energy content in the regions surrounding this point of non-analyticity, and thus under practical circumstances the actual detection of the pulse relies on the intense portions of the pulse near the peak. Detection of the intense portion of the pulse leads to a much higher signal-to-noise ratio [23]. But the peak of the pulse propagates at approximately the group velocity. It is for this reason that

the group velocity plays a key role in determining the transmission properties of a slow-light system, despite the correct conceptual argument that the information velocity is always equal to c.

Acknowledgments

We thank D Gauthier for helpful discussions. We acknowledge financial support from DARPA and NSF grant ECS-0355206. In addition, this work was supported by the US Department of Energy Office of Inertial Confinement Fusion under Cooperative Agreement no DE-FC03-92SF19460 and the University of Rochester. The support of DOE does not constitute an endorsement by DOE of the views expressed in this paper.

References

[1] Brillouin L 1960 *Wave Propagation and Group Velocity* (New York: Academic)
[2] Garrett C G B and McCumber D E 1970 *Phys. Rev.* A **1** 305
[3] Chu S and Wong S 1982 *Phys. Rev. Lett.* **48** 738
[4] Hau L V *et al* 1999 *Nature* **397** 594
[5] Wang L J, Kuzmich A and Dogariu A 2000 *Nature* **406** 277
[6] Boyd R W and Gauthier D J 2002 *Progress in Optics* vol XLIII, ed E Wolf (Amsterdam: Elsevier) pp 497–530
[7] Bigelow M S, Lepeshkin N N and Boyd R W 2003 *Phys. Rev. Lett.* **90** 113903
[8] Bigelow M S, Lepeshkin N N and Boyd R W 2003 *Science* **301** 200
[9] Boyd R W, Gauthier D J, Gaeta A L and Willner A E 2005 *Phys. Rev.* A **71** 023801
[10] Peatross J, Glasgow S A and Ware M 2000 *Phys. Rev. Lett.* **84** 2370
[11] Chiao R Y and Steinberg A M 1997 *Progress in Optics* vol XXXVII, ed E Wolf (Amsterdam: Elsevier Science) pp 345–405
[12] Stenner M D, Gauthier D J and Neifeld M A 2003 *Nature* **425** 695
[13] Plesko P and Palécz I 1967 *Phys. Rev. Lett.* **22** 1201
[14] Aaviksoo J, Kuhl J and Ploog K 1991 *Phys. Rev.* A **44** R5353
[15] Nimtz G and Haibel A 2002 *Ann. Phys.* **11** 163
[16] Stenner M D, Gauthier D J and Neifeld M A 2005 *Phys. Rev. Lett.* **94** 053902
[17] Brunner N *et al* 2004 *Phys. Rev. Lett.* **93** 203902
[18] Agarwal G S and Dey T N 2004 *Phys. Rev. Lett.* **92** 203901
[19] Sherman G C and Oughstun K E 1981 *Phys. Rev. Lett.* **47** 1451
[20] Sherman G C and Oughstun K E 1995 *J. Opt. Soc. Am.* B **12** 229
[21] Solhaug J A, Oughstun K E, Stamnes J J and Smith P D 1998 *Pure Appl. Opt.* **7** 575
[22] Macke B and Ségard B 2003 *Eur. Phys. J.* D **23** 125
[23] Kuzmich A *et al* 2001 *Phys. Rev. Lett.* **86** 3925