Experimental observation of the slowdown of optical beams by a volume-index grating in a photorefractive LiNbO$_3$ crystal

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We investigate the group velocity of light in a one-dimensional volume-index grating inside a photorefractive LiNbO$_3$ crystal. The slowdown of the group electromagnetic propagation is observed experimentally by tuning of the wave number of the optical beam close to the outside edge of the forbidden bandgap. We obtain a large group index of up to 7.5 in a 3.5-cm crystal sample. The group index is compared with the result of a theoretical derivation. The results are presented and discussed. © 2000 Optical Society of America

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It is well known in solid-state physics that the energy-band structure has a zero slope at the edges of the Brillouin zone.[1] In other words, the group velocity of either electrons or photons at the band edges of the electronic or the photonic band structure of a periodic structure is zero. The detailed dispersion relationship of a one-dimensional periodic structure has been studied extensively.[2,3] This periodic structure exhibits a strong group-velocity dispersion. An expression of the group velocity of an infinite periodic layered medium has been obtained.[4] In addition, a group index of up to 13.5 and its dispersion of the propagation of optical pulses in a GaAs–AlAs periodic layered medium have been measured.[5] Bragg soliton propagation in periodic media has also been investigated.[6,7] A Bragg soliton in a fiber grating with a velocity as low as 50% of those in untreated fibers has been observed.

In this Letter we report the results of our experimental investigation of the propagation of optical pulses in a finite segment of a periodic medium. Specifically, we have measured the group velocity of light in a one-dimensional volume-index grating recorded inside a photorefractive LiNbO$_3$ crystal. It is known that this group velocity exhibits strong dispersion near the bandgap of the photonic band structure of the periodic structure. The dispersion of group velocity in a finite segment of a periodic medium was investigated previously.[8,9] Using coupled mode analysis, we obtain the following expression for the phase shift of the transmitted beam:

$$\phi = \frac{\pi}{\Lambda} L + \tan^{-1}\left(\frac{\Delta k}{2s} \tanh sL\right), \qquad (1)$$

where Λ is the period of the index grating, L is the length of the grating, Δk is the phase mismatch, given by

$$\Delta k = 2n \frac{\omega}{c} - \frac{2\pi}{\Lambda}, \qquad (2)$$

and s is given by

$$s = [\kappa^2 - (\Delta k/2)^2]^{1/2}, \qquad (3)$$

where n is the refractive index of the host medium, ω is the angular frequency of light, and κ is the coupling constant, given by

$$\kappa = \pi n_1/\lambda, \qquad (4)$$

where n_1 is the index modulation of the volume-index grating.

By differentiating the phase shift per unit length with respect to angular frequency ω, we obtain the following expression for the effective group velocity:

$$V_g = v_g \frac{(\Delta k/2)^2 - \kappa^2 \cosh^2 sL}{(\Delta k/2)^2 - \kappa^2 \dfrac{\sinh sL}{sL} \cosh sL}, \qquad (5)$$

where v_g is the group velocity of electromagnetic waves in the host medium in the absence of the volume-index grating. At the center of the forbidden gap (where $\Delta k = 0$), and the effective group velocity is

$$V_g = v_g \frac{\kappa L}{\tanh \kappa L}, \qquad (6)$$

which is an increasing function of κL and approaches $\kappa L v_g$ as κL becomes very large. The effective group velocity decreases to near v_g near the band edges. Figure 1 shows the normalized effective group velocity

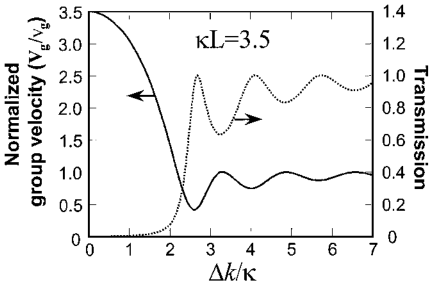

Fig. 1. Calculated transmission (dotted curve) and effective group velocity (solid curve) of a periodic medium.

and the intensity transmission as functions of normalized frequency detuning $\Delta k/\kappa$. We note that in the forbidden gap ($-2\kappa < \Delta k < 2\kappa$) the intensity transmission is indeed very low, reflecting the nature of the stop band. In the immediate vicinity of the band edges where $sL = i\pi$, the intensity transmission is unity, and the effective group velocity is, according to Eq. (5),

$$V_g = v_g \frac{\pi^2}{\kappa^2 L^2 + \pi^2}, \tag{7}$$

which can be very small as κL becomes very large. The oscillating behavior of the effective group velocity is a result of the interference between the reflected waves at the end of the periodic medium. It is important to note that the group velocity is very dispersive near the band edges.

In our experiment we have recorded a volume-index grating in a 1 cm × 1 cm × 3.5 cm photorefractive $LiNbO_3$ crystal, using a pair of argon-ion laser beams, which are symmetrically input into the crystal from the two opposite sides at an angle of 1.8° relative to the normal of crystal surface. The corresponding grating period of the volume-index grating is 0.257 μm. The c axis of the crystal is along the long dimension (3.5 cm) of the sample. To facilitate the experimental measurement we orient the grating wave vector of the recorded index grating along the c axis, which is the normal of the crystal surface. After recording of the index grating, a weak beam from the same argon-ion laser was used to probe the volume-index grating at various angles of incidence. Specifically, we measure the time of flight and the intensity transmission of the probe beam as functions of angle detuning. We have designed a novel scheme to measure the group velocity of light near the band edges of the photonic band structure of the volume index grating. It is known that the group velocity of light exhibits strong dispersion near the band edges.[8,9] In other words, group velocity is a fast-varying function of frequency. Thus, to ensure an accurate measurement of group velocity, we must use an electromagnetic wave with a narrow bandwidth. In other words, the electromagnetic wave cannot be an ultrashort pulse. We use an optical beam that consists of two frequencies. Temporal beating creates a sinusoidally modulated beam of light; this achieved by use of a Bragg cell. Figure 2 shows a schematic diagram of our experimental setup. An argon-ion laser beam at 514.5 nm is first split into two beams. One beam is utilized to record a volume-index grating. The other is directed toward a Bragg cell driven at a modulation frequency of ~70 MHz. The diffracted and the undiffracted beams are recombined by mirrors and a beam splitter. This recombination results in a sinusoidally modulated beam of light at a modulation frequency of ~70 MHz. The combined beam is then directed toward the sample, and the group velocity is measured. The transmitted probe beam and a reference beam are detected and then compared by use of an oscilloscope. Figure 3 shows the measured intensity of the transmitted probe beam at three different angle detunings relative to a reference beam. We note that an additional group delay of 590 ps was obtained when the angle detuning corresponded to a transmission maximum outside the bandgap. This 590 ps corresponds to a group index $n_g = 7.5$.

We have also measured the intensity transmission as a function of angle detuning. This measurement yields information about the index modulation, n_1. Figure 4 shows the measured reflectivity and the group delay as functions of angle detuning. From the measurement we obtain an index modulation $n_1 = 2.1 \times 10^{-5}$ by fitting the experimental data to the reflection spectrum of the volume grating. This measured index modulation of the volume-index grating is consistent with a group index $n_g = 7.8$, according to Eq. (7). This number is very close to the results measured with the group-delay method.

In addition to the measurement in the immediate vicinity of the band edges, where $sL = i\pi$, we have

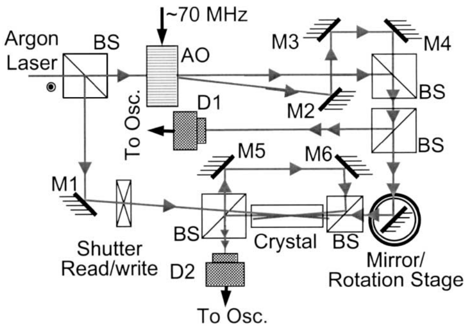

Fig. 2. Schematic of the experimental setup: BS's, beam splitters; AO, acousto-optic Bragg cell; M1–M6, mirrors; Osc., oscilloscope; D1, D2, detectors.

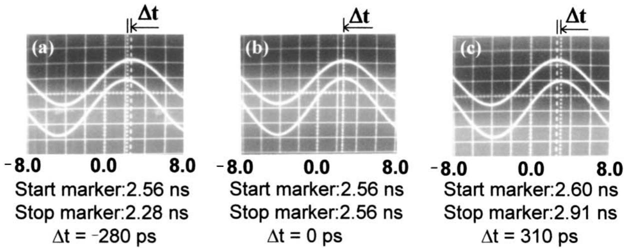

Fig. 3. Measured intensity of the transmitted probe beam for three cases: (a) without the grating and (b), (c) angle detuning corresponding to the first transmission maximum outside the bandgap (b) before and (c) after saturation of grating recording. In (a)–(c), the top signal is the reference beam detected by D1, and the bottom signal is the probe beam detected by D2.

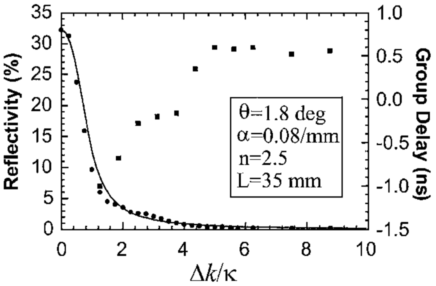

Fig. 4. Measured reflectivity (circles) and group-delay time (squares) as functions of angle detuning. The solid curve was obtained by fitting of the experimental data with the theoretical analysis. The fitting parameters are shown in the legend (α, absorption coefficient; n, refractive index; L, interaction length).

also measured the group delay inside the bandgap and beyond the band edges. The measured group velocity is greater than c. In other words, the group index is less than 1. This is consistent with the theoretical prediction according to Eq. (6). We note that group delay (Fig. 4) is an increasing function of angle detuning. The minimum group delay occurs near the center of the bandgap, which corresponds to a small group index or a high group velocity (even greater than c). This phenomenon is consistent with previous results. We also note that the sinclike sidelobes are absent from both curves in Fig. 4. This result is different from what was predicted from Fig. 1. The absence of the sidelobes is due to the linear absorption of our $LiNbO_3$ crystal sample. The effect of the linear absorption is like a tapering of the index grating. The tapering removes the sidelobes and the oscillatory behavior of the group-velocity dispersion. In the experiments the maximal group delay occurs as the reflectivity approaches zero when the angle is detuned outside the bandgap.

In summary, we have investigated the effective group velocity of light inside a photoinduced one-dimensional volume-index grating that was recorded in a photorefractive $LiNbO_3$ crystal. The effective group velocity can be very small relative to c, provided that the grating is long and the frequency of the beam of light is tuned to the band edges of the photonic band structure. In our sample of 3.5-cm $LiNbO_3$ crystal we obtained a group index $n_g = 7.5$. An even larger group index can be obtained if the length of interaction is longer or if the index modulation is higher. Fiber gratings are good candidates for achieving a long interaction region. Organic polymers are good candidates for achieving index gratings with a large index modulation.

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