Group Velocity Modulation Based on Electrooptic Photonic Crystal With Waveguide Structure

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***Abstract*—We propose an electrooptic photonic crystal with a periodically poled lithium niobate (PPLN) waveguide structure based on electrooptic effect, where the group velocity of input optical beam can be continuously modulated from subluminal to superluminal by adjusting the applied external electric field in the z-direction of the crystal. The slow light propagation at the band edges was investigated and analyzed, in which a large group index in a PPLN waveguide was obtained, and the group refractive index or the transmission as a function of the applied electric field, operation temperature, and different input wavelength were also presented and discussed in detail.**

***Index Terms*—Electrooptic effects, group velocity modulation, optical waveguides, photonic crystal (PC).**

I. Introduction

THE group velocity modulation of light has been intensively studied [1]–[5] for its potential applications, such as optical information processing and storage [3], low-intensity nonlinear optics, optical buffering, and variable true time delay [2]. The first demonstration, electromagnetically induced transparency (EIT), performed in a gaseous resonant media with an extremely low operating temperature [1], is not suitable for practical applications. Further progress on coherent population oscillations (CPOs) demonstrated both slow and superluminal light in a room temperature solid [2], but the operating wavelength is inherently determined by the energy level of the medium. Recently, a study on slowing down the group velocity of light by a volume-index grating, recorded in photorefractive $LiNbO_3$ crystal by the interference of a pair of symmetrically input argon–ion laser beams, has been reported [6]. The grating period can be designed for the desired wavelength. However, the reduction in the group velocity by this method is limited by the refractive-index modulation induced by the photorefractive effect.

In this letter, we introduce the external electric field applied on periodically poled lithium niobate (PPLN) crystal to form the volume-index grating. By this means, the refractive index of the crystal can be periodically modulated just like the traditional photonic crystal (PC). So this crystal can be named as an electrooptic photonic crystal (EOPC). The group velocity of the input light can be continuously modulated from subluminal to superluminal by changing the applied voltages on the crystal within only several volts.

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II. Operation Principles

Now we consider a periodic domain inverted electrooptic crystal with electric field applied along the z direction. A light beam of frequency ω incidents along the normal of the crystal surface. Similar to the previous analysis presented in [6], the expression for the effective group velocity can be obtained as follows:

$$V_g = v_g \frac{\left(\frac{\Delta k}{2}\right)^2 - \kappa^2 \cosh^2 sL}{\left(\frac{\Delta k}{2}\right)^2 - \kappa^2 \frac{\sinh sL}{sL} \cosh sL} \quad (1)$$

where v_g is the group velocity of electromagnetic waves in the host medium in the absence of the volume index grating. According to (1), the corresponding transmission is

$$T(L) = \frac{s}{s \cosh sL + i \frac{\Delta k}{2} \sinh sL} \quad (2)$$

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

$$\Delta k = 2n\frac{\omega}{c} - \frac{2\pi}{\Lambda}. \quad (3)$$

And s is given by

$$s = \left[\kappa^2 - \left(\frac{\Delta k}{2}\right)^2\right]^{1/2} \quad (4)$$

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

$$\kappa = \frac{\pi n_1}{\lambda} \quad (5)$$

where n_1 is the index modulation of the volume-index grating, and λ is the wavelength of the input light.

If taking the electrooptic effect of the host medium into account, we gain the ability to externally control the group velocity of the light beam propagating inside it. It is noted that when an external electric field is applied along the z-axis of a domain inverted electrooptic crystal, the refractive index will change due to the linear electrooptic or Pochels effect [7]. The positive and the negative domain in a periodically poled domain

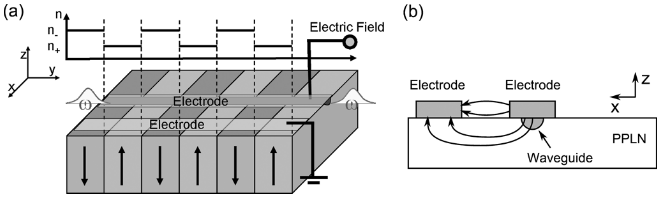

Fig. 1. (a) Schematic diagram of periodic domain inverted electrooptic crystal with an applied voltage along the z-axis. (b) Cut-off of such a configuration along the y-axis.

inversion crystal have the opposite response to the magnitude of the applied electric field because the electrooptic coefficient in the negative domain region changes its sign after domain inversion. By this means, electrooptic Šolc-type wavelength filters in periodically and quasi-periodically poled lithium niobate have been demonstrated [9], [10]. As shown in Fig. 1, when a voltage is applied along the z-axis, the indexes of the positive and negative domain are given as follows, respectively:

$$\begin{cases} n_+ = n_e - \frac{1}{2}n_e^3 \cdot r_{33} \cdot \frac{U}{d}, & \text{for positive domain} \\ n_- = n_e + \frac{1}{2}n_e^3 \cdot r_{33} \cdot \frac{U}{d}, & \text{for negative domain} \end{cases} \quad (6)$$

where n_e is the refractive index of domain inverted electrooptic crystal for z polarization input light, r_{33} is its electrooptic coefficient, U is the applied voltage in the z-axis, and d is the thickness of the crystal.

III. Theoretical Analysis and Numerical Simulation

In our simulations, we take a PPLN crystal as an example of this kind of periodic domain inverted electrooptic crystal. Considering a 5 cm $(X)\times$ 2 cm $(Y)\times$ 0.5 cm (Z) PPLN crystal, the operation temperature is set to be 25 °C. The poling period is set to satisfied the Bragg reflection condition, $n\Lambda = \lambda/2$ for $\lambda = 1550$ nm, where n is the refractive index of the crystal without applied electric field. In our simulation, a Ti-indiffusion PPLN waveguide with 6-μm depth and 10-μm width is used. One electrode is placed on the top of the waveguide and the other is placed beside it with a gap as shown in Fig. 1(a). And the gap between the electrodes is set to be 30 μm. So in this configuration, the applied electric field in the waveguide of the crystal is aligned along the z direction as shown in Fig. 1(b). Therefore, several volts is enough to control the group velocity for such a waveguide structure. Fig. 2 shows the effective group velocity and the intensity transmission as functions of normalized frequency detuning $\Delta k/\kappa$ with an applied voltage of 2 V. We note that in the $-2\kappa < \Delta k < 2\kappa$ region, the transmission is near zero which reflects its nature of forbidden gap. In the immediate vicinity of the band edges (see point A in Fig. 2), the intensity transmission is near unity and the normalized group velocity is as low as 0.42 (i.e., $V_g = 0.42v_g$).

Here we notice the group velocity of light exhibits strong dispersion near the band edges (as shown in Fig. 3). Here we apply 2-V voltages along the z-direction of the crystal; both the magnitudes of the group velocity dispersion at points A and B are equal to 9.66×10^{17} ps^2/km. According to the approximation made in [8], we can estimate that the duration of the input light wave should be of nanosecond order. A light beam such as sinusoidally modulated light used in [6] or analogy can be used to ensure an accurate measurement of group velocity.

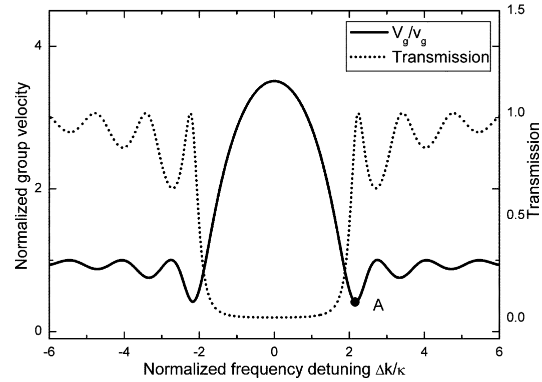

Fig. 2. Calculated transmission (dotted line) and effective group velocity (solid line) in a periodic domain inverted EOPC.

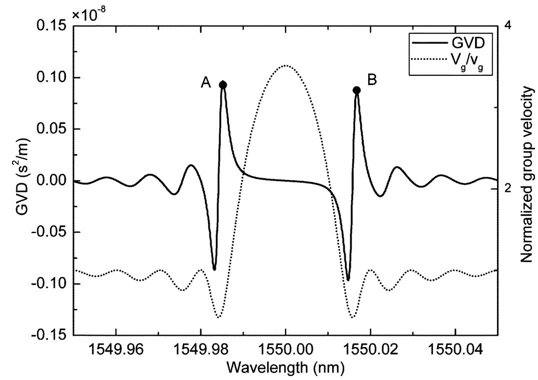

Fig. 3. Group velocity dispersion in the vicinity of the photonic band edges. Solid line shows the group velocity dispersion and dashed line shows the effective group velocity.

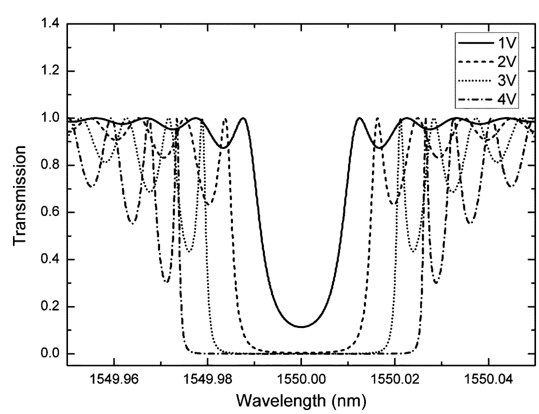

Fig. 4. Transmission of the light beam propagation in PPLN crystal with different voltages (from upper to bottom, 1, 2, 3, 4 V, respectively) applied along the z direction.

We also investigate the dependence of voltage on achievable maximum group index (i.e., minimum group velocity). We should note that the minimum group velocity cannot be realized at finite wavelength because the increasing voltage gives rise to progressive widening of the forbidden gap (as shown in Fig. 4).

It can be seen in Fig. 5 that, when we enhance the voltage of the z direction electric field from 0 to 8 V, the achievable maximum group index will be increased from 1.0 to over 46.5. The external electric field is thus demonstrated to be an efficient means to control the group index of this type of domain inverted electrooptic crystal.

Noticing the statement mentioned above, we try to fix a certain wavelength to investigate the voltage dependence of

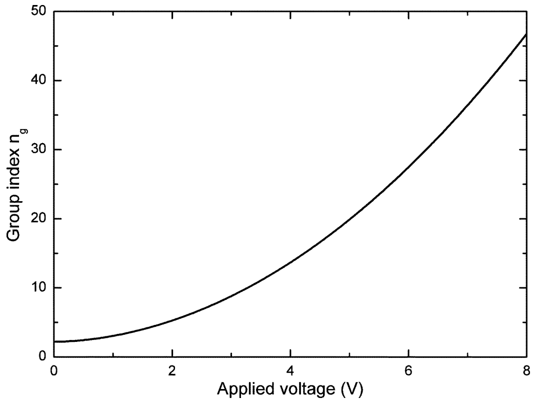

Fig. 5. Achievable maximum group index as a function of the applied voltage.

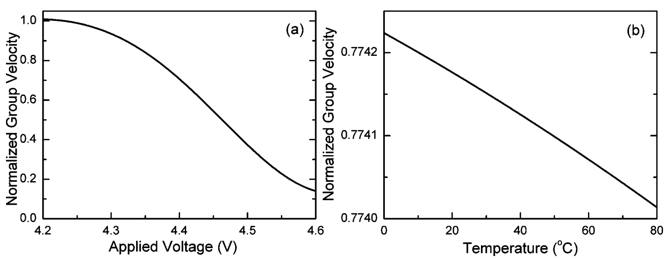

Fig. 6. (a) Applied voltage and (b) operation temperature dependence of transmission for input wavelength of 1550.03 nm.

group velocity. We just choose the input light wavelength of 1550.03 nm to find out the voltage range that can continuously tune the group velocity of light. As shown in Fig. 6, when the voltage is about 4.2 V, the group velocity is 1 (i.e., $V_g = v_g$, which means the input light propagates inside an unmodulated lithium niobate crystal). If we tune the voltage from 4.2 to 4.6 V, the effective group velocity decreases to 15% as low as the beam freely propagating velocity inside lithium niobate crystal. In addition, we compare this method with the way of adjusting the operation temperature (another way to vary the index of each domain) to control the group velocity. Contrasting with the efficient scheme based on the electrooptic effect, the temperature modulation on crystal can just change the group velocity in a small range as shown in Fig. 6. So changing the temperature scheme is not sensitive enough to modulate the group velocity of light propagating inside the crystal.

To further understand the situation as mentioned above, we have plotted the group velocity versus input wavelength under different applied voltages, as shown in Fig. 7, to exhibit how the group velocity is controlled by the external electric field. Fig. 7 clearly shows that the bandwidth of the forbidden band will be broadened in accord with the enhanced applied electric field. For a finite wavelength such as $\lambda = 1550.013$ nm (dashed line), when the voltage is 1.5 V, a normalized group velocity as low as 0.55 will be obtained (point A). Then if we increase the voltages to 2 and 3 V, 1 (point B) and 2.3 (point C) of normalized group velocity can be obtained, respectively. So in the region from 1.5 to 3 V, optical wave propagation of both subluminal and superluminal can be realized continuously.

IV. Conclusion

In summary, we have demonstrated a scheme to efficiently control the group velocity of light beam propagating inside

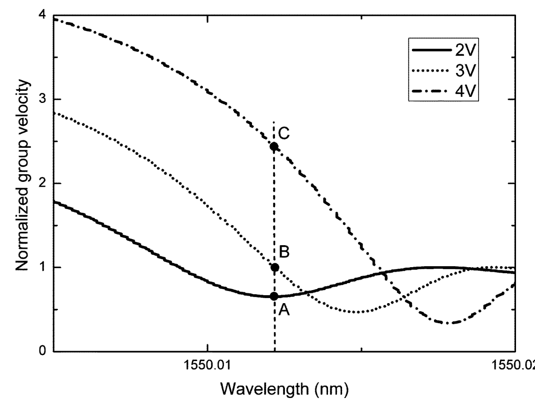

Fig. 7. Effective group velocity at different applied z-direction voltages (solid line for 1.5 V, dotted line for 2 V, and dashed–dotted line for 3 V), where points A, B, and C denote normalized group velocity of 0.55, 1, and 2.3 at input wavelength of 1550.03 nm.

a one-dimensional electrooptic grating in periodic domain inverted EOPC. We note that the poling period used in our simulation is as small as the order of subwavelength ($\Lambda = 305$ nm), which will result in the difficulty in micro-fabrication of device. To solve this problem, the poling period with the order of micrometer fulfilling the high order Bragg reflection conditions, can be employed in practical application. For example, in the case of Fig. 2, we can use the 11th-order grating, whose period is 3.8 μm, as a substitute without changing other conditions, the normalized group velocity will be 0.99 ($V_g = 0.99v_g$). To obtain group velocity with the same magnitude as is modulated by first-order grating ($V_g = 0.42v_g$), a 20-V voltage should be employed.

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