Active control of group velocity by use of folded dielectric axes structures

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(Received 22 April 2010; accepted 26 July 2010; published online 16 August 2010)

A method was demonstrated for slowing light signals in electro-optical periodically poled lithium niobate. A forbidden band gap can be formed when the transverse electric field exceeds zero. The group velocity of a light near the band gap can be delayed via changes in electric field strength or wavelength, with a maximum delay of 20 ns in the experiment, which is attractive for electro-optical signal processing and all-optical signal processing. © *2010 American Institute of Physics*. [doi:10.1063/1.3480404]

The group velocity modulation of light[1–3] has attracted significant interest recently as a potential solution for optical delay lines and time-domain optical signal processing,[4,5] and the enhancement of nonlinear optical effects[6,7] due to the spatial compression of optical energy.[8,9] However, so far most of these methods bear inherent limitations that may hinder their practical deployment.[10–16] In this paper, a method was demonstrated to rapidly control the group velocity at the room temperature in electro-optical (EO) periodically poled lithium niobate (PPLN), where the group velocity of input optical beam can be modulated from subluminal to superluminal by simply adjusting the applied external electric fields. This EO PPLN with folded dielectric axes was usually considered to design devices such as Solc-type filters,[17–19] polarization controllers,[20,21] and laser-Q switches.[22,23] Significantly less research has focused on the potential of such structure for slowing light signals. It should be noted that this method simultaneously allows for high speed, low-light intensity, and room-temperature operation.

In PPLN, transverse dc external electric field can compel the optical axis of positive domains and negative domains to rotate by angles of $+\theta$ and $-\theta$ with respect to the plane of polarization of the input light.[24] The relative azimuth angle between the dielectric axes of two adjacent domains is assumed to be small so that the periodic alternation of the azimuth can be considered as a periodic, small perturbation. In this case, the coupled-wave equations of OW and EW with a periodic small perturbation are given by the following:[24,25]

$$dA_1/dz = -i\kappa A_2 \exp(i\Delta\beta z), \quad (1)$$

$$dA_2/dz = -i\kappa^* A_1 \exp(-i\Delta\beta z), \quad (2)$$

with $\Delta\beta=(\beta_1-\beta_2)-G_m$, $G_m=2\pi m/\Lambda$, and

$$\kappa = -\frac{\omega}{2c}\frac{n_o^2 n_e^2 \gamma_{51} E_y}{\sqrt{n_o n_e}}\frac{i(1-\cos m\pi)}{m\pi} \quad (m=1,3,5\ldots), \quad (3)$$

where A_1 and A_2 are the normalized amplitudes of OW and EW, respectively, β_1 and β_2 are the corresponding wave vectors, G_m is the m^{th} reciprocal-vector corresponding to the periodicity of poling, Λ is the period of PPLN, n_o and n_e are the refractive indices of OW and EW, respectively; γ_{51} is the EO coefficient and E_y is the electric field intensity. Assuming that the initial condition satisfies $A_1(0)=0$, $A_2(0)=1$, the exact solutions of the coupled-wave equations are given by

$$A_1(z) = \exp[i(\Delta\beta/2)z](-i\kappa/s)\sin(sz), \text{ and} \quad (4)$$

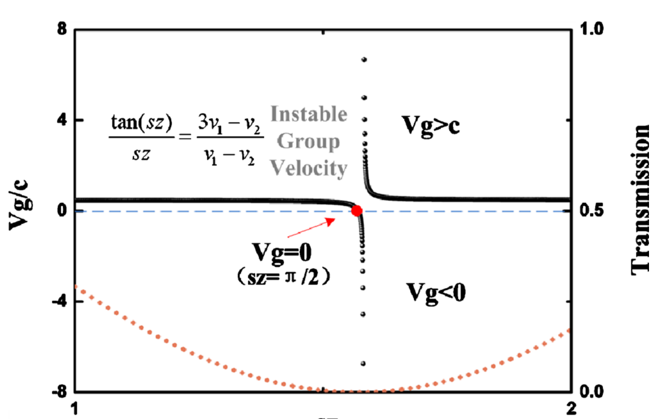

FIG. 1. (Color online) Theoretical results on the group velocity as a function of sz using Eq. (9), where $v_1=1.3567\times10^8$ and $v_2=1.4035\times10^8$. The dotted line represents the corresponding transmission.

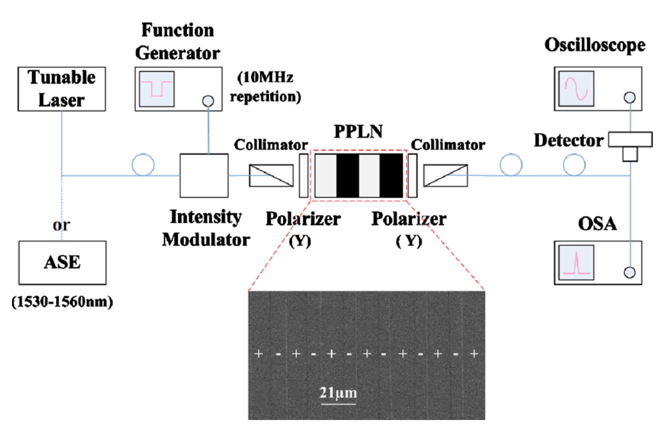

FIG. 2. (Color online) Experimental setup for slowing light signals. A PPLN crystal, which is Z cut, is placed between two parallel Y-oriented polarizers. The light propagates along the X direction, and a uniform electric field is applied along the Y axis of the PPLN sample. ASE and OSA.

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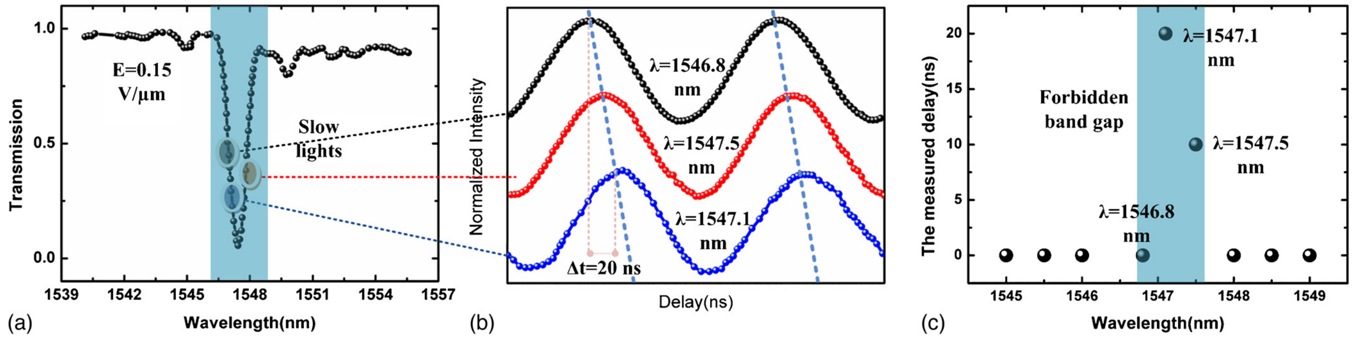

FIG. 3. (Color online) (a) presents the experimental results of the transmission spectrum after the PPLN sample at an electric field of 0.15 V/μm. (b) presents the signal waveforms at different wavelengths inside the band gap and the amplitude of the waveforms are normalized to unity. The loss in amplitude can be obtained from (a). (c) shows the measure delay with respect to wavelength.

$$A_2(z) = \exp[-i(\Delta\beta/2)z][\cos(sz) + i\Delta\beta/(2s)\sin(sz)], \quad (5)$$

with $s^2=\kappa\kappa^*+(\Delta\beta/2)^2$. Considering $E_{1,2}=A_{1,2}(z)\exp[i(\beta_{1,2}z-\omega t)]$, the phase of EW is derived as

$$\Phi_2(z) = \frac{\pi}{\Lambda}z + \frac{(3\beta_2-\beta_1)}{2}z + \arctan\left[\frac{\Delta\beta}{2s}\tan(sz)\right]. \quad (6)$$

The inverse of the effective group velocity of EW is given by[14,26]

$$\frac{1}{V_g} = \frac{dk}{d\omega} = \frac{1}{z}\frac{d\Phi}{d\omega} = \frac{3v_1-v_2}{2v_1v_2} + \frac{1}{1+\frac{\Delta\beta^2}{4s^2}\tan^2(sz)}\left[\frac{v_2-v_1}{2v_1v_2}\frac{\tan(sz)}{sz} + \frac{\Delta\beta}{2}\left(\frac{\tan sz}{sz}\right)'\right], \quad (7)$$

where v_1 and v_2 are the group velocity of OW and EW in the medium of lithium niobate, respectively. And the transmission of EW is

$$I_2 = \left[\cos^2(sz) + \frac{\Delta\beta^2\sin^2(sz)}{4s^2}\right]. \quad (8)$$

For quasiphase matching condition (where $\Delta\beta=0$) and the effective group velocity of EW is

$$V_g = \frac{2v_1v_2}{3v_1-v_2+(v_2-v_1)\frac{\tan(sz)}{sz}}, \quad (9)$$

if $sz=\pi/2+m\pi$, $m=0,1,2\ldots$, V_g approaches 0, seeming that the light is brought to a complete standstill. However, as the transmission declines to zero, it cannot be considered as an approach for storing lights. The group velocity V_g exceeds c and can even become negative by choosing an appropriate "sz," A negative group velocity of light has been demonstrated, though it seems counterintuitive.[27] The detailed variation in the group velocity as a function of sz is shown in Fig. 1, which also reveals a critical point that is very interesting, where the group velocity is extremely sensitive to sz. This critical point satisfies the equation of $3v_1-v_2+(v_2-v_1)(\tan(sz)/sz)=0$. In the vicinity of this solution, small change of the electric field or the wavelength causes large change of the group velocity or the delay of a signal. There is one flow that the instable point locates at where the transmission is extremely lossy.

In the experiment, we fabricated a periodically poled grating in a z-cut $LiNbO_3$ crystal with a dimension of 30 mm (L)×10 mm (W)×0.5 mm (T). The corresponding grating period of the PPLN is 21 μm. The scheme designed to measure the group velocity of light near the band edges of the transmission spectrum was shown in Fig. 2. A high-voltage source with the maximum of 1.5 kV is used to generate the electric field along the transverse direction of PPLN. An optical test system is employed in our experiment,

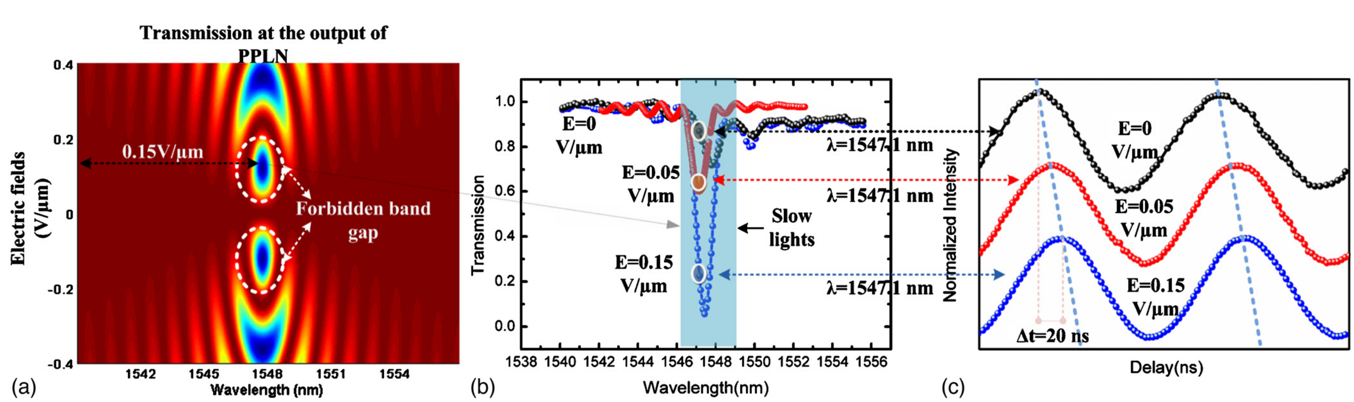

FIG. 4. (Color online) (a) presents the simulation results of the transmission spectrum as a function of the external electric fields at the output of the PPLN. (b) presents the experimental results of the transmission spectrum after the PPLN sample at electric fields of 0, 0.05, and 0.15 V/μm, and the amplitude of the waveforms are normalized to unity. The loss in amplitude can be obtained from (b). (c) presents the signal waveforms of a light at 1547.1 nm at different electric fields.

which includes a broadband amplified spontaneous emission (ASE) source with an output wavelength ranging from approximately 1530 to 1560 nm, as well as an optical spectrum analyzer (OSA) for observing the transmission spectrum. The light signal was launched from a tunable laser modulated by an intensity modulator with a function generator, and the output light signal was observed by a photoelectric detector connected with an oscilloscope.

By use of the above experimental setup, we observed the slow light at the room temperature. Many studies have demonstrated that the group velocity of light exhibits strong dispersion near the band edges in photonic band crystal resulted from Bragg reflection.[5–9,14] Our scheme here engendered a forbidden band using folded dielectric axes structures when electric fields exceed zero.[17,18] The formation of this forbidden band can be described as follows: when a uniform electric field is applied along the Y axis of PPLN, based on the electro-optic effect, the optical axis of each domain is alternately aligned at the angles $+\theta$ and $-\theta$ with respect to the plane of polarization of the input light. The angle θ is called the rocking angle and is proportional to electric field intensity.[24] For wavelength which satisfies the case that each domain serves as a half-wave plate with respect to it, after passing through the stack of half-wave plates, the optical plane of polarization of such wavelength rotates continually and emerges finally at an angle of $2N\theta$, where N is the number of plates. Therefore, when $2N\theta=90°$ at the filter output, light of the wavelength experiences giant loss in passing through the analyzer which is parallel to the polarizer, and a forbidden band gap can be formed.[17]

A light signal near the band edge can be delayed or advanced by adjusting electric fields and wavelengths. Figure 3(a) presents the transmission spectrums at a given electric field of 0.15 V/μm observed by the OSA. Near the band gap a light at 1546.8, 1547.5, and 1547.1 nm was launched from a tunable laser. This continuous wave was modulated by an intensity modulator as well as a function generator with a frequency of 10 MHz. Figure 3(b) presents the signal waveforms at different wavelengths observed by an infrared photodetector. The delay can be as large as 20 ns, which is 1/5 of the period of the signal with a frequency of 10 MHz. Wavelength off the band gap was also investigated. Figure 3(c) shows the measured delay with respect to wavelength, indicating the delay only experience dramatic variation near the bottom of the forbidden gap.

Figure 4(a) presents the theoretical transmission spectrum as a function of the external electric fields, which suggests that a light can be trapped in a forbidden band gap or released out of it by simply modulating the electric fields. Figure 4(b) presents the experimental transmission spectrums at electric fields of 0 and 0.15 V/μm, showing a dip for zero applied field while the theory in Fig. 4(a) shows that such a gap shouldn't exist. The deviation between the experimental result and the theoretical result is due to an initial domain angle existing in such a periodically poled structure which may be caused by the strain-optic effect[28] produced in the process of polarization or the photovoltaic effect[29] engendered by the input light. Figure 4(c) presents the signal waveform at electric fields of 0, 0.05, and 0.15 V/μm, where the delay also approaches 20 ns. As the length of the sample is 3 cm, a light without slowing process will spend about 0.2 ns in passing through this PPLN sample. The effective group velocity here can be about 1.5×10^6 m/s and the effective group index can be about 200. The large effective group index facilitated the exclusion of the impact resulted from the classical Pockels EO effects which are too weak to produce such an amount.

In summary, a method was demonstrated for slowing light signals. The group velocity of a light near the filter band gap can be delayed via changes in electric field strength or wavelength, which are attractive for EO signal processing and all-optical signal processing. A negative group velocity or that exceeds c helps to investigate physics on fast light.

This research was supported by the National Natural Science Foundation of China (Grant Nos. 60508015 and 10574092), the National Basic Research Program "973" of China (Grant No. 2006CB806000), and the Shanghai Leading Academic Discipline Project (Project No. B201).

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