Electromagnetically induced transparency-like transmission in periodically poled lithium niobate with a defect

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Electromagnetically induced transparency (EIT)-like transmission is observed in an electro-optic (EO) tunable periodically poled lithium niobate (PPLN) with a central defect. When an electric field is applied, light satisfying the phase matching condition keeps its original polarization, although it experiences polarization rotation then turns back. Therefore the corresponding light always may pass though freely but with an EO tunable phase and dispersion. On the other hand, light with a neighboring wavelength is blocked. An EIT-like spectrum is thus obtained with tunable group delay. A low-voltage bulk phase shifter with over two orders of magnitude larger index change is obtained. © 2011 Optical Society of America

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Electromagnetically induced transparency (EIT) is a quantum interference effect that reduces light absorption over a narrow spectral region [1,2]. EIT gives rise to greatly enhanced nonlinear susceptibility in the spectral region of induced transparency of the medium and is associated with steep dispersion [3]. More advanced techniques based on EIT even allow for the storage of optical data in matter. As a result, EIT has attracted a lot of attention. Because EIT occurs in a coherently driven atomic system, the experimental handling of these setups is rather hard and the setups must typically be cooled down to liquid helium temperatures and/or magnetic fields must be applied [4,5]. Consequently, classical equivalents of EIT were introduced by using coupled microresonators [6], electric circuits [7], a waveguide side-coupled to resonators [8] and metallic structures to overcome many of the basic limitations of EIT on bandwidth and decoherence [6]. EIT-like effect therefore has potential applications in optical communications and quantum information processing. People are pursuing new approaches to obtain EIT-like transmission in new material systems. Since artificial periodic microstructure and birefringence have been induced in many linear and nonlinear optical processes, it would be also interesting to see how they could contribute in an EIT-like system.

Lithium Niobate is a versatile birefrigent crystal with large electro-optic (EO) and nonlinear optical coefficients [9] and a wide transparency range. Besides, microstructures, for example, periodic ferroelectric domain structures in lithium niobate can ameliorate kinds of frequency conversion processes [10,11]. Up to date, Lithium Niobate has been already used in a series of photonic applications.

In this Letter, we propose a periodically poled lithium niobate (PPLN) with defect in the middle position to realize EIT-like effect and tunable group delay. External DC electric fields along the y-axis are applied to the sample and the beam with the same polarization state as the input wave is emitted at the EO quasi-phase-matching (EOQPM) point. The characteristic of the spectrum is similar to EIT-like effect. Related mechanism and future applications are also discussed.

Figure 1 shows the schematic diagram of a PPLN containing a central defect. The length of the defect is twice that of the domain so the defect could be considered as two domains with the same spontaneous polarization direction. The sample could also be viewed as two sections of PPLN with the same length bonding together.

Assume the light propagates along the crystal's X axis and an external field is applied along the Y axis. In this case, the principal axis X remains unchanged while the Y and Z axes rotate a small angle θ about the X axis due to the EO effect [12,13]. The azimuth angle of the new Y axis thus rocks right and left from $+\theta$ to $-\theta$ successively due to the periodic EO coefficient, as long as the domain thickness satisfies the EOQPM condition. In this case, the reciprocal vector compensates the wave vector mismatch between the ordinary and extraordinary waves. Although PPLN is normally used for nonlinear quasi-phase-matching (NQPM) frequency conversion, the reciprocal vector designed here cannot satisfy the NQPM condition. And, we may set the input polarization along Y axis to further suppress the phase mismatched nonlinear processes. In the first PPLN section, the input Y-polarized wave will rotate 2θ angle after passing through the first domain. The second domain is oriented at angle $-\theta$, making an angle of 3θ with respect to the incoming polarization. At the output face of this domain, the polarization will be rotated by 6θ and oriented at azimuth angle 4θ. The final azimuth angle after the first N-periods of PPLN is $4N\theta$, producing a rotation of

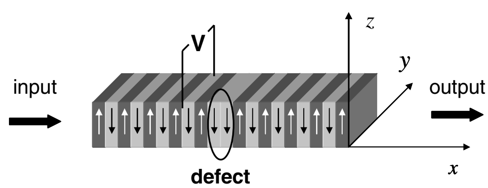

Fig. 1. Schematic diagram of a PPLN with defect. External electric fields are applied along the y-axis. The position in the circle represents a defect with doubled domain thickness.

polarization. Owing to the defect, the spontaneous polarization direction of the first domain in the second PPLN section is the same as the last domain in the first PPLN section, so is the azimuth angle of the new Y axis. After passing through the first domain of the second section, the polarization will be oriented at $(4N\theta - 2\theta)$ as analyzed above. The polarization will be rotated along the opposite direction in the second section. Because the second section has the same length as the first one, a $-4N\theta$ total rotation thus makes the final polarization fully recovered. The output wave will be still the ordinary wave at the wavelength satisfying the EOQPM condition. We may describe this process using Jones matrix calculus [14,15]. Each domain of the PPLN can be taken as a rotated retardation plate and can be described by matrixes showing the phase retardation and the azimuth angle. The matrix of the entire sample is just the product of the matrixes of all domains:

$$T = \prod_{n=1}^{2N} R(\theta_n) W_n R(-\theta_n), \qquad (1)$$

where $R(\theta_n)$ and W_n are the rotation matrix and the intrinsic Jones Matrix of n-th domain. θ_n is the corresponding azimuth angle with opposite signs in different domains. $R(\theta_n)$ and W_n can be expressed as

$$R(\theta_n) = \begin{pmatrix} \cos\theta_n & \sin\theta_n \\ -\sin\theta_n & \cos\theta_n \end{pmatrix}, \qquad (2)$$

$$W_n = \begin{pmatrix} \exp(-in_y\omega l_n/c) & 0 \\ 0 & \exp(-in_z\omega l_n/c) \end{pmatrix}, \qquad (3)$$

where n_y and n_z are the refractive indices of the ordinary and extraordinary waves. ω is the angular frequency and c is the speed of light in vacuum. l_n is n_{th}-domain's thickness. The duty cycle of the sample is set as 50%. As a result, they have same value except that the defect thickness is doubled.

Assume the input Y-polarized beam has the field of E_{in}, the output light at the end of the crystal is given by

$$E_{\text{out}} = T \cdot E_{\text{in}}. \qquad (4)$$

Then the final transmittance after passing through a parallel analyzer could be easily obtained. Figure 2 shows the numerical simulation results about the spectral response and dispersion. We set the wavelength which satisfies the QPM condition at 1550 nm. According to the Sellmeier equations of lithium niobate [16], the domain thickness of the sample is designed at $\Lambda = 10.24\,\mu$m at room temperature 25 °C and the defect thickness is $2\Lambda = 20.48\,\mu$m. The sample length is about 10 mm and the electric field is set at 360 V/mm for simulation. An ordinary wave is injected. A polarizer is placed at the outlet end that only allows the ordinary wave to pass through. According to our analysis above, the input wave at 1550 nm will be transmitted completely. For the input wave at the wavelength which has a slight offset from the phase matching point, the transmittance will be decreased. Figure 2(a) shows the spectral response which testifies our analysis. The spectrum exhibits a narrow transparency peak in the center of a broader transmission dip, which is similar to the EIT-like transmission spectrum. To verify our hypothesis, we also calculate the dispersion of our structure. Figure 2(b) shows the result. The dispersion varies abruptly at the vicinity of phase matching point. The shape of the dispersion curve is also similar to the variation of the real part of susceptibility which determines the refractive index with the wavelength in EIT atomic system. In conclusion, our structure may realize an EIT-like transmission in an anisotropic material, which to our knowledge, has rarely been reported before.

Associated with the large dispersion introduced by EIT-like effect, tunable group delay may also be realized in our designed structure. As we know, tunable group delay has attracted much research interest during the past decade because of its key role in realizing all-optical networks and high-speed optical information processing [17]. For example, it could be made into optical delay lines [18] which could become the building blocks of optical memory provided the variable delay approaches the time occupied by multiple data bits. This application would facilitate contention resolution at busy network nodes without involving optical to electrical data conversion.

According to the Jones matrix calculus illuminated above, we can derive the variation of output light phase from the Jones vector. Then the group delay could be obtained from the first order derivative of the phase to the frequency afterward. The dispersion is the first order derivative of the group delay to the wavelength in the same way. We calculated the group delay varying with the wavelength when the electric field is 360 V/mm, which is described by Fig. 3(a). The variation tendency is symmetrical at both sides of the EOQPM point. Group delay at this point is lower than other wavelength. That's because that lithium niobate is a uniaxial negative crystal. The group velocity of the ordinary wave is smaller than the extraordinary wave. At the phase matching point, the injected wave is first converted into extraordinary wave and then changed back into the ordinary wave, which reduces corresponding group delay. The difference between the maximum and minimum value of group delay is no more than 2.5 ps. Figure 3(b) shows the results of the variation of group delay when the electric field changes. Group delay decreases as the electric field is higher. That is because, when no electric field is applied, the ordinary wave propagates through the sample directly, without any transformation. When the electric

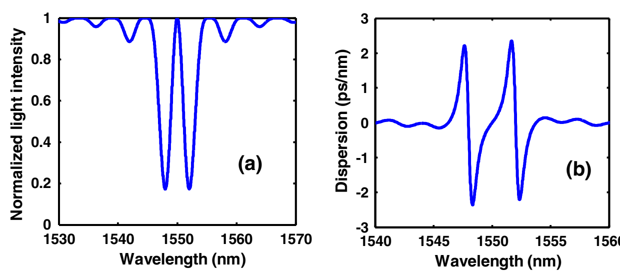

Fig. 2. (Color online) Normalized light intensity (a) and the dispersion (b) versus the wavelength. ($E = 360$ V/mm).

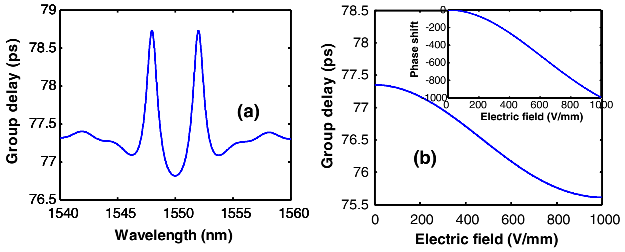

Fig. 3. (Color online) Group delay versus the wavelength (a) and the electric field (b).The inset figure shows the phase retardation of the ordinary wave versus the electric field.

field is applied, the ordinary wave will be converted into the extraordinary wave in a given period of time. So group delay decreases when the electric field is applied. The difference between the maximum and minimum value of the group delay is about 2 ps. However, if we convert the group delay into phase retardation that is shown in the inset of Fig. 3(b), the phase decreases similarly when the applied electric field becomes higher. ~1000 radian phase change occurs at ~1000 V/mm field. Assume a 0.5 mm sample width along y axis, ~1.6 V voltage change is able to generate a π-phase-shift. This is quite sensitive in comparison with normal EO effect. Normally the EO phase-shift is due to the deformation of index ellipsoid, either based on ordinary wave or extraordinary wave. The EO induced change of index itself is quite small for inorganic crystals like lithium niobate, which is normally around 10^{-4} level even if a 1 kV/mm field is applied. However, the mechanism of our PPLN EO phase shifter is different. Although the final polarization does not change, we actually utilize the crystal's intrinsic birefringence, which is in $10^{-1} \sim 10^{-2}$ level. This is similar to liquid crystal's EO effect but with much faster response. In other words, 2–3 orders of magnitude phase-shift enhancement is expected. In our simulation, a 0.5 mm wide sample is considered, which still has much room to further lower the half-wave voltage. This feature would be very attractive for various low-voltage EO modulators and interferometers.

Although a Mach–Zehnder modulator may only need π-phase change, some other applications still need large group delay over tens of picoseconds. It can be seen from Fig. 3 that the difference between the maximum and minimum value of the group delay is not very large. The delay is dominated by the index difference between the ordinary wave and the extraordinary wave, which is approximately 0.08. So the time difference propagating through a 1 cm long sample is about 2.5 ps. Obviously the delay value can be enhanced by increasing the length of the sample. It can be anticipated that if the length of the sample increases to 4 cm, the variation of group delay may increase to 10 ps approximately. However, the increment still might not be enough for some applications. In addition, long PPLN samples are hard to fabricate and very expensive. To overcome this problem, inducing a cavity structure might be a good solution. The cavity structure may increase the tunable group delay to a more desired level. We believe that would be a great improvement for many technical applications.

In conclusion, we proposed a PPLN with a central defect with doubled thickness to realize EIT-like effect. External electric fields are applied along the y axis. When the EOQPM condition is satisfied, the injected ordinary wave is firstly converted to the extraordinary wave and then converted back. The output wave still keeps its original polarization. If a parallel analyzer is introduced, the spectrum will exhibit a narrow transparency peak in the center of a broader transmission dip, which is similar to the EIT transmission spectrum. We also calculated the dispersion and group delay. The group delay and the phase of the ordinary wave both show interesting EO tuning features. Approaches to further improve the delay value are discussed. Promising applications in low-voltage EO modulator and tunable phase array are expected.

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