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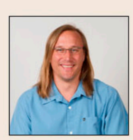

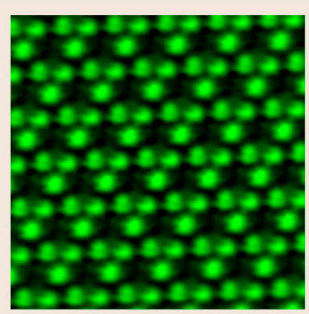

Electro-optic effect of periodically poled optical superlattice $LiNbO_3$ and its applications

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The electro-optic effect of periodically poled optical superlattice $LiNbO_3$ (PPLN) was studied. Because of the periodic electro-optic (EO) coefficient, the reciprocal vector of the periodic structure can be used to compensate for the phase mismatch between the ordinary and extraordinary waves, which is similar to the nonlinear optical frequency conversion process. If the quasi-phase-matching condition is satisfied, polarization of a light propagated in PPLN can rotate linearly with the applied electric field, which shows that PPLN may be used as a precise spectral filter or an EO switch.
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In recent years, more and more research attention has been paid to periodically poled optical superlattice $LiNbO_3$ (PPLN) because of its outstanding nonlinear optical properties.[1–3] The origin of the attractive characteristics is the periodic nonlinear coefficient caused by the periodic domain structure, thus the reciprocal vector may compensate the phase mismatch during the frequency conversion processes. This technique, called quasi-phase-matching (QPM), has many advantages compared to the conventional birefringence phase matching.[4–6] To date, various related devices have been demonstrated.[7–9] However, besides the nonlinear coefficient, other third-rank tensors are also modulated periodically due to the periodic ferroelectric domains in PPLN. Among them, there are the piezoelectric coefficient and electro-optic (EO) coefficient.[9–11] As a consequence, it is natural to ask the question: what will happen if the EO coefficient modulation is considered? Answering this question is important in the interest of fundamental physics and also has practical applications.

In this letter, we demonstrate that if an electric field is applied along the *Y*-axis of PPLN, coupling between the extraordinary wave and ordinary wave is established. Under the QPM condition, the polarization of light propagating in the crystal could be modulated by the applied electric field. Based on this effect, a novel EO filter may be developed.

$LiNbO_3$ (LN) is a ferroelectric crystal with the symmetry of 3 m. In the negative domain, the crystal structure rotates 180° about the *X* axis, thus the electro-optic coefficients change subsequently under this operation. It is easy to demonstrate that all elements of the electro-optic tensor have different signs in different domains.

Figure 1 shows the geometrical arrangement for studying the EO effect. In the presence of an external field along the *Y* axis, the index ellipsoid deforms to make the *Y* and *Z* axes rotate a small angle

$$\theta \approx \frac{\gamma_{51} E}{(1/n_e^2) - (1/n_0^2)}$$

about the *X* axis,[12] where *E* is the field intensity; γ_{51} is the *EO* coefficient; n_0 and n_e represent the refractive indices of the ordinary wave and extraordinary wave, respectively.

With consideration of the periodic electro-optic coefficients, the dielectric constant of PPLN with an electric field along the *Y* axis thus can be written as:

$$\epsilon = \epsilon(0) + \Delta\epsilon f(x), \tag{1}$$

where

$$\epsilon(0) = \epsilon_0 \begin{bmatrix} n_0^2 & 0 & 0 \\ 0 & n_0^2 & 0 \\ 0 & 0 & n_e^2 \end{bmatrix}$$

is the original dielectric tensor,

$$\Delta\epsilon = -\epsilon_0 \gamma_{51} E n_0^2 n_e^2 \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 1 & 0 \end{bmatrix}$$

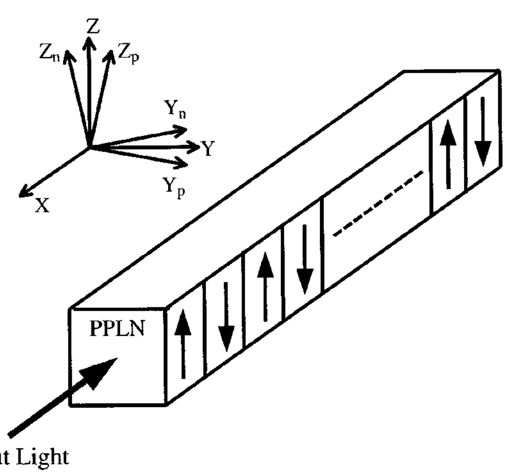

FIG. 1. Experimental setup for studying the electro-optic effect of PPLN. *X*, *Y*, and *Z* represent the principal axes of the original index ellipsoid and $Y_{p,n}$, $Z_{p,n}$ are the perturbed principal axes of the positive domains and the negative domains, respectively. The arrows inside the PPLN indicate the spontaneous polarization directions.

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is the dielectric tensor change. In PPLN, a factor $f(x)$ should be included where

$$f(x)=\begin{cases}+1 & \text{if } x \text{ is in the positive domains}\\ -1 & \text{if } x \text{ is in the negative domains.}\end{cases} \quad (2)$$

The change of the dielectric tensor could be viewed as a disturbance, thus the coupled wave equations of the ordinary and extraordinary waves may be obtained as:

$$\begin{cases} dA_2/dx=-iKA_3 \ \exp(i\Delta\beta x)\\ dA_3/dx=-iK^*A_2 \ \exp(-i\Delta\beta x)\end{cases}, \quad (3)$$

with

$$\Delta\beta=(\beta_2-\beta_3)-G_m, \quad G_m=\frac{2\pi m}{\Lambda},$$

$$K=-\frac{\omega}{2c}\frac{n_0^2 n_e^2\gamma_{51}E}{\sqrt{n_0 n_e}}\frac{i(1-\cos m\pi)}{m\pi}, \quad (m=1,3,5\ldots),$$

where A_2 and A_3 are the amplitudes of the ordinary wave and the extraordinary wave, respectively; β_2 and β_3 are the corresponding wave vectors. G_m is the mth reciprocal vector, Λ is the modulation period that is equal to twice domain thickness L if the duty cycle is 50%. Assuming the input light is an extraordinary wave by putting a vertical polarizer in front of the sample, the initial condition at $x=0$ is given by $A_3(0)=1$, $A_2(0)=0$. For studying the conversion from the extraordinary wave to ordinary wave, another horizontal polarizer should be put at the back of the sample as an analyzer. If the field is not intensive or the crystal length is short, the coupling between the extraordinary wave and the ordinary wave will be weak. In this case, the weak coupling approximation $A_3(x)=A_3(0)=1$ may be used and the power conversion efficiency from the extraordinary wave to the ordinary wave, i.e., the transmission for the extraordinary wave of this filter, is:

$$T=\left|\frac{A_2(x)}{A_3}\right|^2=K^2x^2\left(\frac{\sin(\Delta\beta\cdot x/2)}{\Delta\beta\cdot x/2}\right)^2. \quad (4)$$

This expression is similar to that of the QPM frequency conversion efficiency,[13] thus the research results for the QPM frequency conversion may be helpful in the study of the EO effect. From Eq. (4), the maximum conversion is achieved when $\Delta\beta=(\beta_2-\beta_3)-G_m=0$, which means the reciprocal vector may also compensate for the wave vector mismatch. Similar to QPM frequency conversion, this condition could be called a QPM condition. Defining the coherence length $L_c=\lambda/2(n_0-n_e)$, the QPM condition is satisfied for a given light of wavelength λ if each domain thickness is L_c or its multiple.

In the general case, for a given static field, the weak coupling approximation cannot be used, the transmission rate is thus obtained as:

$$T=\left|\frac{A_2(x)}{A_3(0)}\right|^2=|K|^2\frac{\sin^2(Sx)}{S^2},$$

where

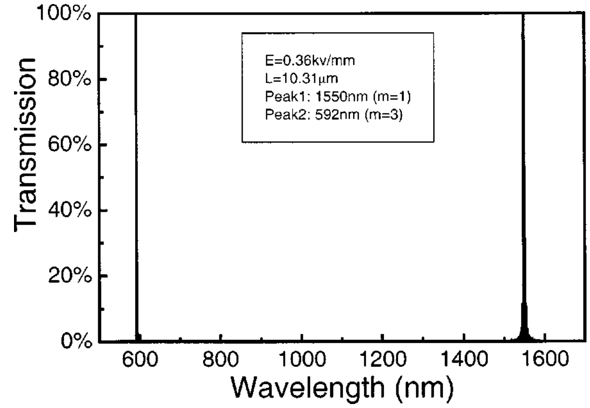

FIG. 2. Calculated electro-optic transmission spectrum of a PPLN filter.

$$S^2=|K|^2+\left(\frac{\Delta\beta}{2}\right)^2. \quad (5)$$

Besides the QPM condition, the dynamical condition $|K|x=[(2u+1)\pi/2](u=0,1,2,\ldots)$ should also be satisfied for 100% conversion to occur. Figures 2 and 3 show the influence of these two conditions on the transmission efficiency. For a sample with the domain thickness of 10.31 μm and the period of 500, the first-order QPM condition corresponds to the wavelength of 1550 nm. From Fig. 2, if the dynamical condition is satisfied by applying a 0.36 kV/mm field, there is a transmission peak at 1550 nm that corresponds to 100% conversion from the extraordinary wave to the extraordinary wave. Besides this peak, there is another one at 592 nm that is due to the phase compensation of the third-order reciprocal vector. The corresponding concept in

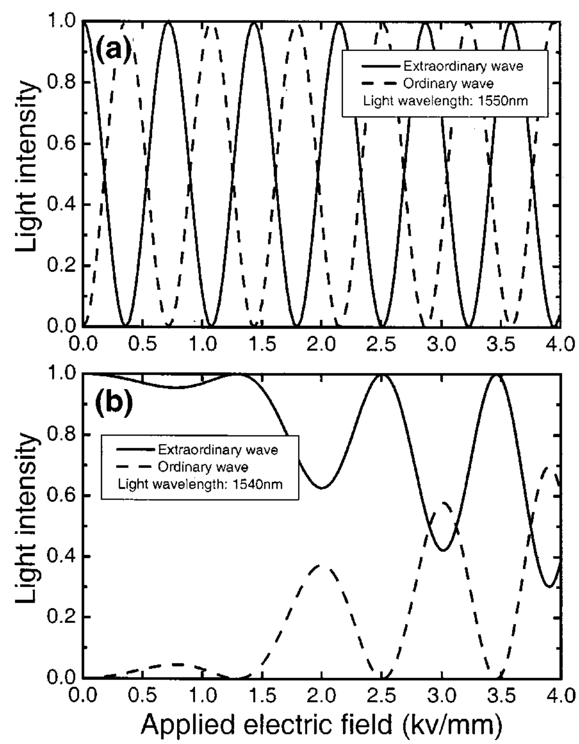

FIG. 3. Power exchange relations between the extraordinary wave and the ordinary wave when (a) the QPM condition is satisfied and (b) the QPM condition is not satisfied. The solid line and the dashed line correspond to the intensity-varying curve of the two waves along the propagation direction, respectively.

the frequency conversion process is the *m*th-order QPM.[13] The width of the 592 nm peak is narrower than that of the 1550 nm peak. In fact, the calculated transmission bandwidth for *m*th-order QPM is $\Delta\lambda_{1/2} \approx 1.60(\lambda/2mN)$, where λ is the center wavelength and N is the period number. Since increasing m and N may decrease bandwidth, a precise spatial filter could be achieved. The influence of the dynamical condition may be obtained by studying the relation between the transmission and the applied electric field. Figure 3 shows the results. The power of the two waves is exchanged periodically in a sinusoidal fashion if the QPM condition is satisfied, as shown in Fig. 3(a). This effect may be useful for EO modulation or switching. On the other hand, the power relation of the two waves is complicated if the QPM condition is not satisfied, which is shown in Fig. 3(b).

From the theoretical results above, the QPM condition governs the passing frequency for a spectral filter based on PPLN. If the QPM condition is satisfied, the dynamic condition determines the transmission ratio of the passing light. Only when the dynamic condition is also satisfied, the polarization of the input extraordinary wave can rotate 90° and totally pass the analyzer. As for the polarization status changing of the light in the crystal along its propagation route, a simple theoretical analysis can give the details.

As we know, the principal axis X remains unchanged while the Y and Z axes rotate a small angle θ about the X axis after applying the field. The azimuth angle of the new Z axis thus rocks right and left from $+\theta$ to $-\theta$ successively due to the periodic EO coefficient, assuming each domain thickness is L_c to satisfy the QPM condition. In this case, each domain acts as a half-wave plate. For a 632.8 nm He–Ne laser, L_c is 3.74 μm which is achievable with current fabrication techniques. For an input extraordinary wave that is polarized along the Z axis, it will be polarized at $\psi = 2\theta$ 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 N periods is $\psi = 4N\theta$, which produces a rotation of polarization. The solid line in Fig. 4 shows the calculated polarization rotation angle of the He–Ne laser as a function of the applied voltage in a sample with 300 domains. The domain thickness is 3.74 μm thus satisfying the QPM condition. From this figure, the polarization rotation angle is proportional to the intensity of the applied field. If an analyzer is employed, the transmission rate of this filter should exhibit a sinusoidal relationship with the applied field, which agree well with Fig. 3(a). The polarization of the input light can be rotated 90° with an applied electric field of 1.2 kV/mm. In this case, the input light can totally pass through the filter.

To verify these predictions, a PPLN crystal with an average domain thickness of 4.2 μm and the period fluctuation of less than 6% was used to do the experiment. The sample was fabricated using the Czochralski method.[14,15] The total domain number is 300. When a He–Ne laser was passed through the sample, the rotation angle increased with the applied field. A polarization rotation angle of 16.5° was obtained when the field was 1 kV/mm as shown in Fig. 4. However, for a single domain LN crystal with the same thickness, no remarkable polarization rotation was observed, which means that it is the periodic structure that is responsible for the rotation. However, perhaps because of the deviation of domain thickness from L_c and domain thickness fluctuation, the measured rotation angle was smaller than the theoretical prediction. One method that may improve the sample quality is using the electric-poling technique instead.[6] For a commercial available 5-cm-long PPLN, only a 27.6 V/mm field may make the polarization rotate by 90°, which is very attractive.

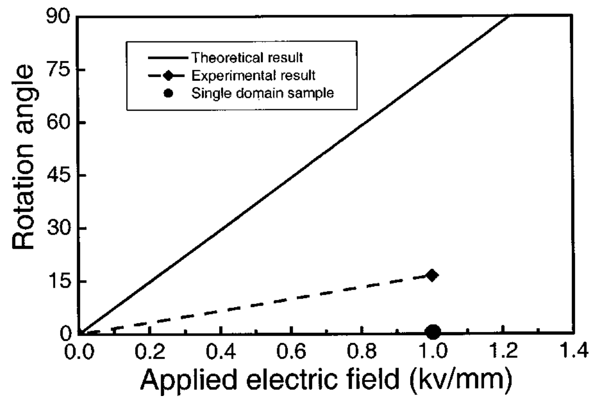

FIG. 4. Polarization rotation angle as a function of the applied electric field. The solid line and the dashed line correspond to the theoretical result and experimental result, respectively. The experimental result on a single domain LN sample is also displayed in the figure with a round dot.

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