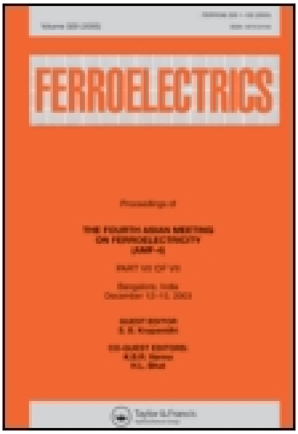

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Yan-Qing Lu [a] , Quan Wang [a] , Yuan-Xin Xi [a] , Zhi-Liang Wan [a] , Xue-Jing Zhang [a] & Nai-Ben Ming [a]

[a] National Laboratory of Solid State Microstructures, Nanjing, 210093, People's Republic of China

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Electro-Optic Spectral Filter Based on Optical Superlattice $LiNbO_3$

YAN-QING LU*, QUAN WANG, YUAN-XIN XI, ZHI-LIANG WAN, XUE-JING ZHANG and NAI-BEN MING

National Laboratory of Solid State Microstructures, Nanjing 210093, People's Republic of China

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Electro-optic (EO) effect of optical superlattice $LiNbO_3$ (OSLLN), a single crystal with periodic ferroelectric domain structure was studied theoretically and experimentally. Because the electro-optic coefficient has different signs in different domains, the refractive index ellipsoid deforms periodically in the presence of an electric field applied along the Y-axis, which results in the coupling between the extraordinary wave and ordinary wave. Under specific conditions, the polarization of a light may be rotated to 90°, which means that the optical material could act as a precise spectral filter. The influence on the transmission spectrum of an OSLLN EO filter when there is another electric field along the Z-direction was also studied. It was demonstrated that the transmission peak could move with the electric field along the Z-axis if the duty cycle of the periodic structure is not 50%. Based on this effect, a tunable filter may be constructed.

Keywords: Optical superlattice; Electro-optic effect; Spectral filter

INTRODUCTION

In the last decades, research attentions on materials with artificial superlattice structure are growing. It has been demonstrated that the optical wave or sound wave in the superlattice may exhibit some novel performances. [1-3] The quasi-phase-matching (QPM) material is a kind of artificial superlattice that has many advantages in nonlinear optical

* Corresponding author. lyqzf@usa.com

frequency conversion applications. Because of the important optical applications, it is also termed as optical superlattice (OSL). Compared with ordinary nonlinear medium, the nonlinear optical coefficient in OSL is periodically varied. For example, in OSL $LiNbO_3$ (OSLLN), the sign of nonlinear coefficient is periodically modulated, thus the reciprocal vector may compensate the phase mismatch during the frequency conversion. This technique is called QPM that has many advantages. [4-6] Up to date, various devices on OSLLN including frequency doubler and optical parametric oscillator have been demonstrated. [7-9] However, besides the nonlinear coefficient, other third-rank tensors including the electro-optic (EO) coefficient are also periodically varied in the OSL, [10,11] which may result in some interesting EO properties.

In this report, the electro-optic effect of the OSLLN was studied. We demonstrated that the OSLLN could act as a precise electro-optic frequency filter that has many applications.

ANALYSIS AND EXPERIMENTS

Figure 1 shows the structure of the OSLLN and the geometrical arrangement for studying its EO effect. If an external field along the Y-axis is applied, the index ellipsoid is deformed. The principal axis X remains unchanged while the Y and Z axes rotate a small angle $\theta \approx \gamma_{51} E \Big/ \left(\frac{1}{n_e^2} - \frac{1}{n_o^2} \right)$ about the X-axis where γ is the electro-optic coefficient and E is intensity of the applied field, n_o and n_e represent refractive indices of the ordinary wave and extraordinary wave respectively. Because of the periodic EO coefficient, the azimuth angle rocks right and left from $+\theta$ to $-\theta$ successively. If the phase retardation of each domain is $\Gamma=\pi$, 3π..., the extraordinary light that is polarized along the Z-axis will be polarized at $\psi=2\theta$ after passing through the first domain. The second domain is oriented at angle $-\theta$, rotating the polarization by 3θ with respect to the original 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

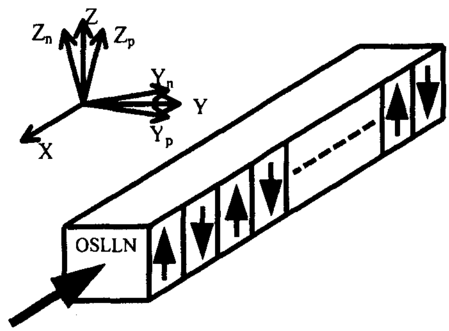

FIGURE 1: Experimental setup for studying the electro-optic effect of OSLLN. X, Y, Z represent the principal axes of original index ellipsoid and $Y_{p,n}$, $Z_{p,n}$ are the perturbed principal axes of the positive domains and the negative domains, respectively. The arrows inside the OSLLN indicate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

$\psi = 4N\theta$, which produces a rotation of polarization. Here we also define the EO coherence length Lc satisfying $Lc = \lambda / 2(n_o - n_e)$, to make π phase retardation between the ordinary wave and the extraordinary wave that is similar to definition of the conherence length in nonlinear frequency conversion. For a 632.8nm laser, Lc is 3.74μm which is achieveable for the current fabrication technique. The solid line in Figure 2 shows the calculated polarization rotation angle of the He-Ne laser as a function of the applied voltage in a 0.5mm-thick sample with 300 domains. The domain thickness is 3.74μm. From the figure, the polarization can be rotated 90° with the applied field of 1.2kv/mm.

For verifying the prediction, a Czochralski grown [12-13] OSLLN sample with the average domain thickness of 4.2μm was selected to do the experiments. The total domain number is 300 and there is a period fluctuation of less than 6%. When a He-Ne laser was shot into the sample, the rotation angle increased with the applied field. A rotation angle of 16.5° was obtained when the field was 1KV/mm. However, for a single domain LN with the same thickness, no remarkable rotation was observed, which means that it is the periodic structure that results in the rotation of the polarization. However, because of the deviation of domain thickness from Lc and the 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. For a commercially available 5cm-long OSLLN with appropriate domain thickness, only a very weak field (28.6V/mm) may make the polarization be rotated to 90°, which is very attractive.

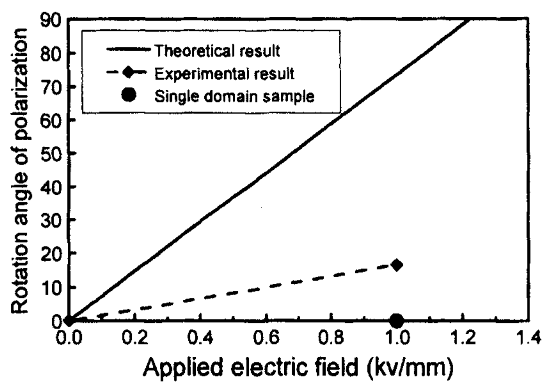

FIGURE 2: The polarization rotation angle as a function of the applied electric field. The solid line and the dashed line correspond to the theoretical result and experiment result, respectively. The experimental result on a single domain LN sample is also displayed in the figure with a round dot.

THEORETICAL RESULTS

Our analyses above are based on the condition that each domain has identical thickness Lc. However, there may be the discrepancy between the actual domain thickness and the designed value in a real sample, thus it is difficult to get the final polarization status from the direct analysis. For solving this problem, the coupled wave method may be employed. When the electric field is applied on a LN crystal along the Y direction, the dielectric impermeability tensor index that is the matrix inverse of dielectric constant could be obtained as:

$\frac{1}{\varepsilon_0}\begin{bmatrix} (1/n_o^2)-\gamma_{22}E & 0 & 0 \\ 0 & (1/n_o^2)+\gamma_{22}E & \gamma_{51}E \\ 0 & \gamma_{51}E & 1/n_e^2 \end{bmatrix}$, where γ is the electro-optic coefficient and E is intensity of the applied field. Considering that $\gamma_{22}E$ and $\gamma_{51}E$ should be much smaller than $1/n_o^2$ and $1/n_e^2$, the dielectric tensor after applying the field then could be written as: $\varepsilon = \varepsilon(0) + \Delta\varepsilon$, where $\varepsilon(0) = \varepsilon_0 \begin{bmatrix} n_o^2 & 0 & 0 \\ 0 & n_o^2 & 0 \\ 0 & 0 & n_e^2 \end{bmatrix}$, $\Delta\varepsilon = -\varepsilon_0\gamma_{51}En_o^2n_e^2 \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 1 & 0 \end{bmatrix}$. As a consequence, the dielectric constant in an OSLLN after applied the electric field is:

$$\varepsilon(x) = \varepsilon(0) + \Delta\varepsilon \cdot f(x) \tag{1}$$

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

Where Δε times a factor f(x) due to the periodic EO coefficient. The function f(x) can be expanded to a Fourier series and written as: $f(x) = \sum_{m=-\infty}^{\infty} G_m e^{-iK_m x}$, where G_m is the m-th order Fourier coefficient; $K_m = \frac{2\pi m}{\Lambda}$ is the m-th order reciprocal vector; Λ is the period that is equal to twice domain thickness L if the duty cycle is 50%.

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

$$\begin{cases} dA_2/dx = -iKA_3\exp(i\Delta\beta x) \\ dA_3/dx = -iK^* A_2\exp(-i\Delta\beta x) \end{cases} \tag{2}$$

with $\Delta\beta = \beta_2 - \beta_3 - K_m$, $K = -\frac{1}{2}\frac{\omega}{c}\frac{n_o^2n_e^2}{\sqrt{n_o n_e}}\gamma_{51}E_2G_m$, $(m = 1,3,5\ldots)$,

where A_2 and A_3 are the amplitudes for the ordinary wave and the extraordinary wave, respectively; β_2 and β_3 are the corresponding wave vectors; Assuming the input light is 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. If the applied filed is not too intensive, the small signal approximation $A_3(x) = A_3(0) = 1$ may be used then the power conversion efficiency from the extraordinary wave to the ordinary wave, i.e. the transmission for the extraordinary wave is:

$$T = \left| A_2(x) \middle/ A_3 \right|^2 = k^2 x^2 \left(\sin(\tfrac{1}{2}\Delta\beta \cdot x) \middle/ (\tfrac{1}{2}\Delta\beta \cdot x) \right)^2 \quad (3)$$

This expression is similar to that of the QPM frequency conversion efficiency, [14] thus the research results for the QPM frequency conversion may also useful for the study on the EO effect. From equation (3), the maximum conversion may be achieved when $\Delta\beta = (\beta_2 - \beta_3) - K_m = 0$, which means the reciprocal vector may also compensate the wave vector mismatch. Similar to the QPM frequency conversion, this condition could also be termed QPM condition.

In general case, the applied field may be intensive, thus the small signal approximation cannot be used. In this case, the transmission is:

$$T = |A_2(W)|^2 = |K|^2 \frac{\sin^2(Sx)}{S^2}, \text{ where } S^2 = |K|^2 + \left(\frac{\Delta\beta}{2}\right)^2 \quad (4)$$

Although there is another dynamical condition $|K|x = \frac{(2u+1)\pi}{2}$ (u=0, 1, 2...), the QPM condition is still a prerequisite for the 100% conversion, thus for a given OSLLN, there are only some discrete transmission peak at a specific temperature. The solid curve in Figure 3 shows the transmission spectrum of an OSLLN with the period number 1000. The thicknesses of the positive domain and the negative domain are 17.7μm and 3μm, respectively. There is a 100% transmission peak at 1556nm that corresponds to the first-order QPM. The dynamical condition is satisfied by applying a 0.75kV/mm field. This result shows that the OSLLN could act as a precise spectral filter.

Besides applying field along Y-direction, the electric field can also be applied along other directions. Here we consider the situation where there is also a field along the Z-axis besides the field along the Y-axis. The Z-direction field does not result in the change of the directions of the principal axes, thus conversion between the extraordinary wave and the ordinary wave is still achievable. However, if the duty cycle of the OSLLN is not 50%, i. e., the domain thicknesses of the positive domains and negative domains are different [15], the whole optical path of a sample will change with the Z-direction field. According to the

QPM condition, the position of transmission peaks should also move with the field. The dashed curve in Figure 3 shows the calculated transmission spectrum of the same sample if one adds another 10kV/mm field along the Z-direction. From the figure, the transmission peak move about 14nm, which means the OSLLN could act as an EO tunable filter. A possible but important application of such a tunable filter is in the wavelength division multiplexing (WDM) optical networks.

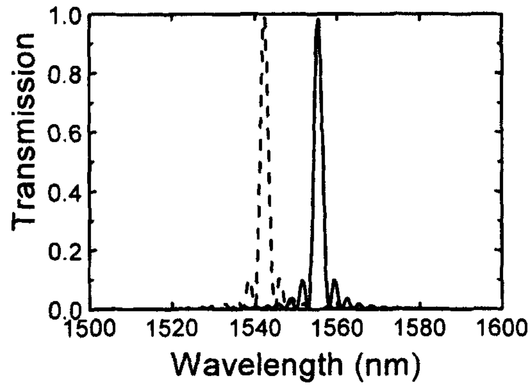

FIGURE 3: The electro-optic transmission spectrum of an OSLLN filter. The dashed line corresponds to the situation where there is another electric field applied along the Z-direction besides the Y-direction field.

CONCLUSIONS

In conclusion, the EO effect of OSLLN was studied theoretically and experimentally. We found that the conversion properties between the extraordinary wave and ordinary wave have similar features to the QPM frequency conversion. Their fundamental equations, *i.e.* coupled wave equations have the similar format and some notions such as coherence length, QPM condition may be extended from the frequency conversion process to this case. Influence of the QPM condition and the applied field along the Y or/and Z direction on the transmission properties has also been studied, which means that the OSLLN may act as a tunable fine spectral filter that has some possible applications.

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