Tunable Šolc-type filter in periodically poled LiNbO$_3$ by UV-light illumination

Jianhong Shi[*], Jinghe Wang, Lijun Chen, Xianfeng Chen[**] and Yuxing Xia

Institute of Optics & Photonics, Physics Department, The State Key Laboratory on Fiber-Optic Local Area Network and Advanced Optical Communication Systems, Shanghai Jiaotong University, Shanghai, China
[*] purewater@sjtu.edu.cn [**] xfchen@sjtu.edu.cn

Abstract: We demonstrate a tunable Šolc-type filter in periodically poled lithium niobate by UV-light illumination in this paper. Due to the photovoltaic effect, a Šolc-type filter in PPLN can be formed without applying an external electric field. Through this mechanism, a tunable wavelength filter by UV-light illumination is realized. A wavelength shift as large as 15nm is observed under 778mW/cm^2 uniform UV illumination. The dependence of wavelength shift on illumination intensity shows a nearly linear relationship and the tuning rate is about 52 mW/cm^2 per nm at 20°C.

©2006 Optical Society of America

References and links

1. I. Šolc , "Birefringent chain filters," J. Opt. Soc. Am. **55**, 621-625 (1965).
2. A. Yariv and P. Yeh, *Optical Waves in Crystal: Propagation and Control of Laser Radiation* (John Wiley & Sons, New York, 1984).
3. D. R. Pinnow, R. L. Abrams, J. F. Lotspeich, D. M. Henderson, T. K. Plant, R. R. Stephens, and C. M. Walker, "An electro-optic tunable filter," Appl. Phys. Lett **34**, 391-393 (1979).
4. J.H. Shi, X.F. Chen, Y.P. Chen, Y.M. Zhu, Y.X. Xia, Y.L.Chen, "Observation of Šolc-like filter in periodically poled lithium niobate," Electron. Lett. **39**,224-225 (2003).
5. X.F. Chen, J.H. Shi, Y.P. Chen, Y.M. Zhu, Y.X. Xia, Y.L.Chen, "Electro-optic Šolc-type wavelength filter in periodically poled lithium niobate," Opt. Lett. **28**, 2115-2117 (2003).
6. Y. M. Zhu, X. F. Chen, J. H. Shi, "Wide-range tunable wavelength filter in periodically poled lithium niobate," Opt. Commun. **228**, 139-143 (2003).
7. Lijun Chen, Jianhong Shi, Xianfeng Chen, Yuxing xia, "Photovoltaic effect in a periodically poled lithium niobate Šolc-type wavelength filter," Appl. Phys. Lett. **88**, 121118 (2006).
8. Y. Q. Lu, Z. L. Wan, Q. Wang, Y. X. Xi, and N. B. Ming, "Electro-optic effect of periodically poled optical superlattice LiNbO$_3$ and its applications," Appl. Phys. Lett. **77**, 3719–3721 (2000).
9. Y. Q. Lu, Y. Y. Zhu, Y. F. Chen, S. N. Zhu, N. B. Ming, and Y. Y. Feng, "Optical properties of an ionic-type phononic crystal," Science **284**, 1822-1824 (1999).
10. L. Arizmendi, "photonic applications of lithium niobate crystals," Phys. Stat. Sol. **201**, 253-283 (2004).
11. B. I. Sturman, V. M. Fridkin, *The photovoltaic and photorefractive effects in noncentrosymmetric materials* (Gordo and Breach Science Publishers, 1992).
12. E. Kratzig and H. Kurz, "photo-induced currents and voltages in LiNbO$_3$," Ferroelectrics **13**, 295-296 (1976).
13. M. Glass, D. von der Linde, T. J. Negran, "High-voltage bulk photovoltaic effect and the photorefractive process in LiNbO$_3$," Appl. Phys. Lett. **25**, 233-235 (1974).
14. M. Simon, St. Wevering, K. Buse and E. Kratzig, "The bulk photovoltaic effect of photorefractive LiNbO$_3$:Fe crystals at high light intensities," J. Phys. D: Appl. Phys. **30**, 144-149 (1997).

1. Introduction

The Šolc filter is well known as a polarization interference filter with birefringent crystals. [1,2] A conventional Šolc filter consists of a stack of identical birefringent plates with folded azimuth angles between crossed polarizers and fanned azimuth angles between parallel polarizers. An electro-optic (EO) tunable Šolc filter can be fabricated by the application of a periodic array of equal and opposite voltages to a thin platelet of LiTaO$_3$. [3]

Recently, we demonstrated an EO Šolc filter by applying an uniform DC electric field along the transverse (Y) axis of a periodically poled LiNbO₃ (PPLN). [4-6] The amplitude of the passband was modulated by the intensity of the external electric field and the passband wavelength could be tuned by temperature. Compared with traditional Šolc filters, [1–3] the PPLN EO Šolc filter takes advantage of one-chip integration with lithium niobate and a simpler electrode structure. Furthermore, we observed that the device may function as a filter even without an external field applied, which we previously attributed to a fabrication defect of the PPLN. [4] In our recent experiment, however, we found that the performance of the non-field applied PPLN Šolc filter is actually due to the bulk photovoltaic effect (PVE) of PPLN. [7] Using the PVE effect, a light controllable Šolc filter can be realized.

In this paper, we demonstrate a passband tunable Šolc-type filter in PPLN by UV-light illumination via PVE. The center wavelength shift of the filter is determined by the UV-light intensity. The center wavelength of the filter changes from 1531.9nm to 1516.9nm when the light intensity reaches 778mW/cm². The relationship between the wavelength shift and the light intensity is almost linear and the tuning rate is about 52mW/cm2 per nm at 20℃.

2. Basic Theory

For lithium niobate crystal with 3m symmetry, in the presence of an external electric field along the Y-axis, the refractive index ellipsoid deforms to make the Y and Z axes rotate a small angle θ about the X-axis. X,Y and Z represent the principal axes of the original index ellipsoid of the lithium niobate crystal. θ is given by: [2]

$$\theta \approx \frac{\gamma_{51}E_y}{(1/n_e^2)-(1/n_o^2)} \tag{1}$$

The new semiaxes are:

$$\begin{cases} n_x^{'} = n_o + \gamma_{22}E_y n_o^3/2 \\ n_y^{'} = n_o - \gamma_{22}E_y n_o^3 / 2 \\ n_z^{'} = n_e \end{cases} \tag{2}$$

And while the electric field is along the Z-axis, the principal axes of the new index ellipsoid remain unchanged. The new semiaxes are: [2]

$$\begin{cases} n_x^{'} = n_o - \gamma_{13}n_o^3 E_z / 2 \\ n_y^{'} = n_o - \gamma_{13}n_o^3 E_z / 2 \\ n_z^{'} = n_e - \gamma_{33}n_e^3 E_z / 2 \end{cases} , \tag{3}$$

Where E_y and E_z are the field intensity, γ_{51}, γ_{22}, γ_{13} and γ_{33} are the EO coefficient of lithium niobate. In PPLN, the spontaneous polarization is periodically reversed by domain inversion. Besides the nonlinear optical coefficient, other third-rank tensors are also modulated periodically due to the periodically reversed ferroelectric domains in PPLN. Among them are the electro-optic (EO) coefficient, [4-6,8] the piezoelectric coefficient [9] and photovoltaic coefficients. [7] Since the structure inversion is in the Z axis alone, only the elements that relate to the Z axis change their sign, which means that γ_{51}, γ_{13}, γ_{33} (for the positive domain) become $-\gamma_{51}$, $-\gamma_{13}$, $-\gamma_{33}$ (for the negative case), and γ_{22} remains the same. In PPLN, because γ_{51} changes its sign in the opposite domains, in the presence of a uniformed electric field along the Y-axis, the Y and Z axes rotate an angle θ in the opposite direction about the X axis in positive and negative domains. Thus, a folded Šolc-type filter is formed. In such filter, each domain acts as a half-wave plate with folded azimuth angles. Figure 1 shows the schematic diagram of a PPLN Šolc filter. A Z-cut PPLN with period Λ and period number N is placed between two crossed polarizer and the light propagates along the X direction.

The fundamental wavelength of such filter is only determined by the phase delay of one wave plate, which is given by:

$$\lambda_v = (n_o - n_e)\Lambda/(2v+1) = \delta n\Lambda/(2v+1), v = 0,1,2,\dots, \tag{4}$$

Where v is the order of the half-wave plate of one domain and is zero in this application. n_o and n_e are the refractive index of lithium niobate. δn is the refractive-index variation. Since the refractive index is temperature dependent, the center wavelength of such filter can be tuned by temperature. [5,6]
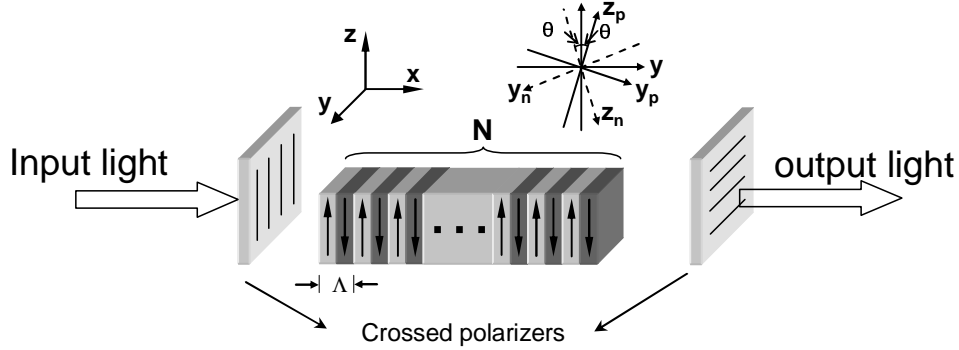

Fig. 1. Schematic diagram of a PPLN Šolc filter

The center wavelength transmissivity of such filter is $T = \sin^2 4N\theta$. Where θ is given by Eq. (1) and N is the period number which is half of the number of the domains.

While a field is applied solely along the Z axis, as can be seen in Eq. (3), there is no θ induced. The only change is the refractive-index variation.

Lithium niobate is a kind of photorefractive crystal. When light propagates through the photorefractive crystal, the PVE can lead an electric field in the presence of photoinduced electrical currents and voltages in the bulk dielectric material. The incident light will ionize impurities in the material and these ionized charges will move in a particular direction inside the crystal without the presence of an external electric field. If the sample is uniformly illuminated and kept in open circuit, then a voltage between the faces is observed. This current density can be described by the following linear equation for a LiNbO$_3$ crystal: [10,11]

$$\begin{bmatrix} J_1 \\ J_2 \\ J_3 \end{bmatrix} = \alpha \begin{bmatrix} 0 & 0 & 0 & 0 & G_{15} & -G_{22} \\ -G_{22} & G_{22} & 0 & G_{15} & 0 & 0 \\ G_{31} & G_{31} & G_{33} & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} E_1E_1^* \\ E_2E_2^* \\ E_3E_3^* \\ E_3E_2^* \\ E_3E_1^* \\ E_1E_2^* \end{bmatrix} \tag{5}$$

Here 1, 2 and 3 correspond to the X, Y and Z axes of the Cartesian system, the X axis parallels the a axis, and the Z axis parallels the c axis of the LiNbO$_3$ crystal. When a light passes through the crystal under different conditions, we have the following:

When the light with Y polarized propagates in the X direction:

$$\begin{bmatrix} J_1 \\ J_2 \\ J_3 \end{bmatrix} = \alpha \begin{bmatrix} 0 \\ G_{22} \\ G_{31} \end{bmatrix} E_2E_2^* \tag{6}$$

When the light with Z polarized propagates in the X direction:

$$\begin{bmatrix} J_1 \\ J_2 \\ J_3 \end{bmatrix} = \alpha \begin{bmatrix} 0 \\ 0 \\ G_{33} \end{bmatrix} E_3 E_3^* \tag{7}$$

When a non-polarized light propagates in the Z direction:

$$\begin{bmatrix} J_1 \\ J_2 \\ J_3 \end{bmatrix} = \alpha \begin{bmatrix} -G_{22}E_1 E_2^* \\ 0 \\ G_{31}E_1 E_1^* + G_{31}E_2 E_2^* \end{bmatrix} \tag{8}$$

The current is very small because of the low conductivity of the pure crystal. After several seconds, the current will cause the charge accumulated at the chip face and establish a field that holds back the current. When the balance is accomplished, there is:

$$J = -\sigma E_{sat}$$
$$\sigma = \sigma_d + \sigma_{ph} I \tag{9}$$

σ is the conductivity of the lithium niobate that includes two parts: the dark conductivity σ_d and the photoconductivity σ_{ph}. I is the light intensity. E_{sat} is the saturation field in the bulk crystal established by PVE.

While the input light is propagated in the X-direction, from the Eq. (5) to Eq. (9), if the input polarizer is put in the Y direction, there will be a field formed in the Y direction. Since G_{22} didn't change sign in opposite domains, this field is uniform, which can enable a Šolc filter based on the former theory. If the input polarizer is set in the Z direction, there is only a field along the Z-axis which can only change the refractive index and can't induce a rocking of the half-wave plates. In our recent experiment, pass peak is observed with the Y direction input polarizer and no filter function is observed with the input polarizer along the Z direction. [7] This experiment proved that the performance of the non-external field applied PPLN Šolc filter is due to the PVE effect. Furthermore, this result means that the PVE effect induced electric field is not negligible in PPLN.

When a light irradiates at the Z face of PPLN, there is an electric field generated by PVE along the Z axis according to Eq. (8) and Eq. (9), Which is:

$$E_{sat\,Z} = -\alpha G_{31} I / \sigma , \tag{10}$$

where I is the light intensity. The refractive-index variation caused by this field can be described as follows based on the above equations:

$$\delta n = n_o' - n_e' = (n_o - n_e) - \frac{1}{2}(n_o^3 \gamma_{33} - n_e^3 \gamma_{13}) E_{sat\,z}$$
$$= (n_o - n_e) + \frac{1}{2}\alpha(n_o^3 \gamma_{33} - n_e^3 \gamma_{13}) G_{31} I / \sigma \tag{11}$$

Since $G_{31}, \gamma_{33}, \gamma_{13}$ change sign in opposite domains, the product of $G_{31}\gamma_{33}$ and $G_{31}\gamma_{13}$ will remain unchanged. Thus, when a PPLN Šolc filter is formed by a light propagate along X axis, the center wavelength of this filter can be tuned by another light irradiate at the Z face according to Eq. (4) and Eq. (11).

3. Experiment and results

Figure 2 shows the schematic diagram of the experimental setup. A single chip PPLN crystal is placed between two crossed polarizers. The input polarizer is parallel to the Y direction and the output polarizer is parallel to the Z direction. The PPLN is Z-cut and an EXFO ASE light source with total power of 9.3mW is used as the light propagates along the X direction. The PPLN in our experiment was fabricated by congruent lithium niobate at the HC Photonics Corp. using the electric-field poling technique. The sample was 28mm long, 5mm wide and

0.5mm thick, which has a period of 20.8μm. An optical spectrum analyzer (OSA) is used as the detector. The light is induced and exported by a couple of collimators with about –2dB insertion loss. Since the filter center wavelength can be easily shifted by temperature, the data is measured at a constant temperature of about 20℃. An EXFO UV source with a wavelength of around 365nm, which is non-polarized, is employed to irradiate the Z-face of PPLN. This UV-light source usually used as spot light curing source and has excellent cold light properties which can reduce the impact of the thermal effect. The intensity of the UV-light is measured by a UV power meter. The radiation time can be controlled by an electronic shutter.
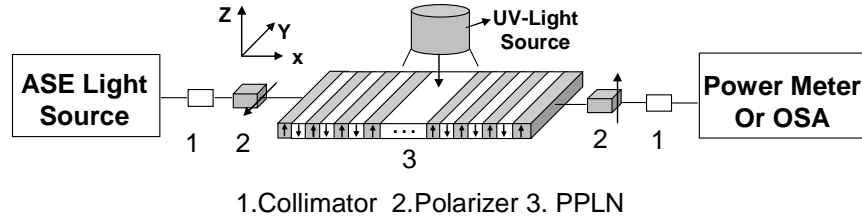

1.Collimator 2.Polarizer 3. PPLN

Fig. 2. Schematic diagram of the experimental setup

Figure 3 shows measured output power against wavelength for the PPLN of period 20.8μm with and without the illumination of the UV-light, respectively. The UV-light intensity is about 143mw/cm². The passband of the filter moves from 1531.9nm to 1529.1nm. It takes several seconds until the spectrum of the filter becomes stable. However, the peak value and the shape of the passband are unchanged. This means that the Y field of the PVE is not changed. This accords with Eq. (8) in that no Y direction field is induced when a non-polarized light propagates in the Z direction.
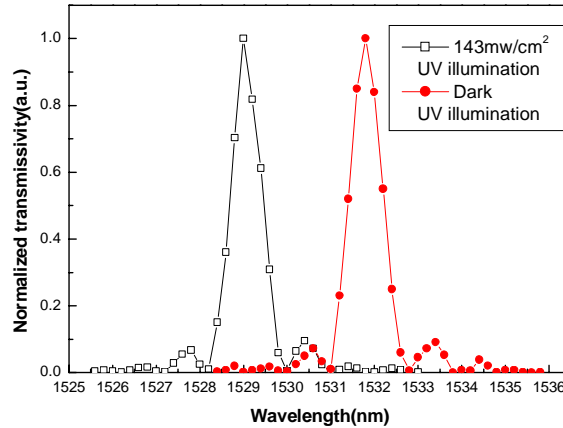

Fig. 3. The spectrum of the PPLN filter under 143mw/cm² UV illumination (empty square symbol) and without UV light illumination (red circle symbol)

The wavelength shift caused by the intensity of the UV incident light is recorded in Fig. 4. When the intensity of UV-light reaches 778mW/cm², a shift of 15nm can be achieved. Further increasing the intensity of UV-light will introduce evident photorefractive damage. According to Eq. (4) and Eq. (11), and taking the following parameters: [5,12]

$$\Lambda = 20.8\mu m, \gamma_{33} = 30.6\,pm/V, \gamma_{13} = 9.6\,pm/V, \alpha G_{31} = 1\,pA/mW$$

The measured data is fitted by a curve where the conductivity σ in the sampled PPLN estimated is about $\sigma = 8.7 \times 10^{-15} + 1.8 \times 10^{-15} I(\Omega/cm)^{-1}$. Where the unit of I is W/cm².The

relationship between the UV-light intensity and the wavelength shift is almost linear. The tuning rate is about 52 mW/cm^2 per nm. Compared with the conductivity σ in Fe-doped lithium niobate, which is $1.5\times10^{-14} + 1.4\times10^{-12}\,I\,(\Omega/cm)^{-1}$ [13,14], the conductivity σ in the sampled PPLN is much smaller.
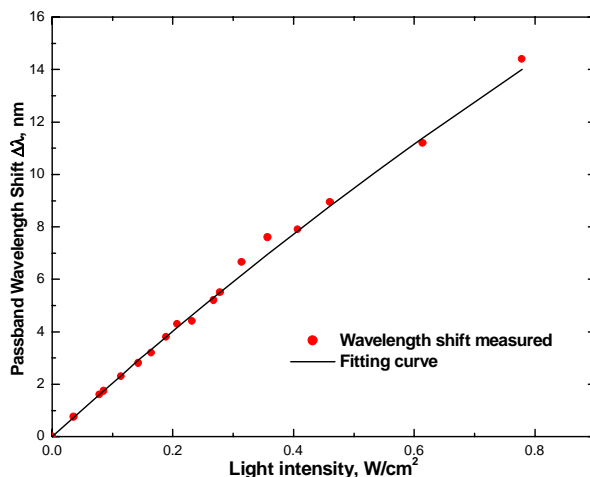

Fig. 4 The center wavelength shift of a PPLN filter: measurement (red dot) and fitting curve (solid line).

4. Conclusion

A UV-light illumination tunable PPLN Šolc filter is demonstrated in this paper. Based on the PVE and EO effect in PPLN, the passband wavelength of a PPLN Šolc filter can be tuned via UV-light illumination on the Z-face of the sampled PPLN. It confirms that in some EO devices, the PVE effect is not negligible. Furthermore, based on the PVE effect, light controllable optical devices are possible.

Acknowledgments