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Optics Communications 228 (2003) 139–143

OPTICS COMMUNICATIONS

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Wide-range tunable wavelength filter in periodically poled lithium niobate

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Received 14 July 2003; received in revised form 25 September 2003; accepted 30 September 2003

Abstract

In this paper, a tunable narrowband spectral filter in periodically poled lithium niobate (PPLN) by temperature is experimentally demonstrated. We observe a shift of transmission spectrum of PPLN Šolc-type filter when the temperature is modified. The tuning rate is measured to be −0.422 nm/°C, which is in agreement with calculation results of the coupled-mode theory.

PACS: 42.79.C; 42.70

Keywords: Optical filters; Optical materials

1. Introduction

The ferroelectric crystals, such as lithium niobate and lithium tantalate, are the very important materials for electro-optical (EO) and nonlinear optical process due to their large EO and nonlinear optical coefficients. With the maturity of room temperature electric-poling technique [1–3], periodically poled ferroelectric crystals, especially periodically poled lithium niobate (PPLN), have attracted much research interest for many years [3–7]. PPLN has been already used commercially for laser frequency conversion. Since the domain structure is modulated periodically in PPLN, it takes an advantage of quasi-phase-matching (QPM) technique to realize the nonlinear optical processes with the largest nonlinear coefficient of the nonlinear optical crystal. Besides the nonlinear optical coefficient, the EO coefficient is also periodically modulated due to the periodically reversed ferroelectric domains in PPLN, which results in some interesting EO properties [8,9]. It is theoretically predicted that alternative positive and negative angle deviation from its original axis in different domains when the external electric field is

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0030-4018/$ - see front matter © 2003 Elsevier B.V. All rights reserved.
doi:10.1016/j.optcom.2003.09.081

applied along transverse direction [8]. Recently, a creditable experimental demonstration of electro-optics Šolc-type filter has been reported [10]. It is also found that Šolc-type wavelength filter exists even without voltage applied [11], which indicates that there should be a small angle between the axis of positive and negative domains after room temperature electric poling process. In a PPLN Šolc-type filter, the central wavelength is determined by the period of domain inversion, and the period is a function of ordinary and extraordinary indices. Because the indices are temperature dependent, the central wavelength of a Šolc-type filter can be shifted by adjusting the working temperature of PPLN.

In this paper, we experimentally demonstrate a PPLN tunable Šolc-type filter in the telecommunication wavelength band (1550 nm) by changing temperature of the PPLN crystal.

2. Theory of tunable PPLN olc-type filter

The experimental observation of PPLN Šolc-type filter indicates that there is a rocking angle $\theta = \theta_1 + \theta_2$ between optical axes of positive and negative domains, and θ_1 (θ_2) is an angle between axis of positive (negative) domain and Z-axis as shown in the inset of Fig. 1. In the scenario of the existence of a rocking angle between domains, PPLN can be regarded as a folded Šolc-type filter. Assuming the input light is polarized along the Z-axis, it will rotate $2\theta_1$ after passing through the first positive domain and rotate $2(2\theta_1 + \theta_2)$ after the first negative domain. So, the polarization angle of the light is $2(\theta_1 + \theta_2) = 2\theta$ from the Z-axis after passing through a first set of positive and negative domains. Thus, after passing through N domains ($N/2$ sets), the rotation angle of polarization will be $N\theta$ with respect to the input plane of polarization. As a result, the light with a fundamental wavelength (2π-wave plate for a period) will rotate its polarization, and totally or partly pass through the output polarizer, while lights with other wavelengths almost keep their polarization directions unchanged.

A more accurate method to analyze the filter is coupled-mode theory. The small deviation angles (θ_1 and θ_2) cause the deformation of the index ellipsoid. The coupled wave equations of the ordinary and extraordinary waves are [12]:

$$\begin{cases} \mathrm{d}A_1/\mathrm{d}x = -\mathrm{i}\kappa A_2\,\mathrm{e}^{\mathrm{i}\Delta\beta x} \\ \mathrm{d}A_2/\mathrm{d}x = -\mathrm{i}\kappa^* A_1\,\mathrm{e}^{-\mathrm{i}\Delta\beta x} \end{cases} \tag{1}$$

with $\Delta\beta = (\beta_2 - \beta_1) - G_m$, $G_m = 2\pi m/\Lambda$, and the coupling constant κ is given by

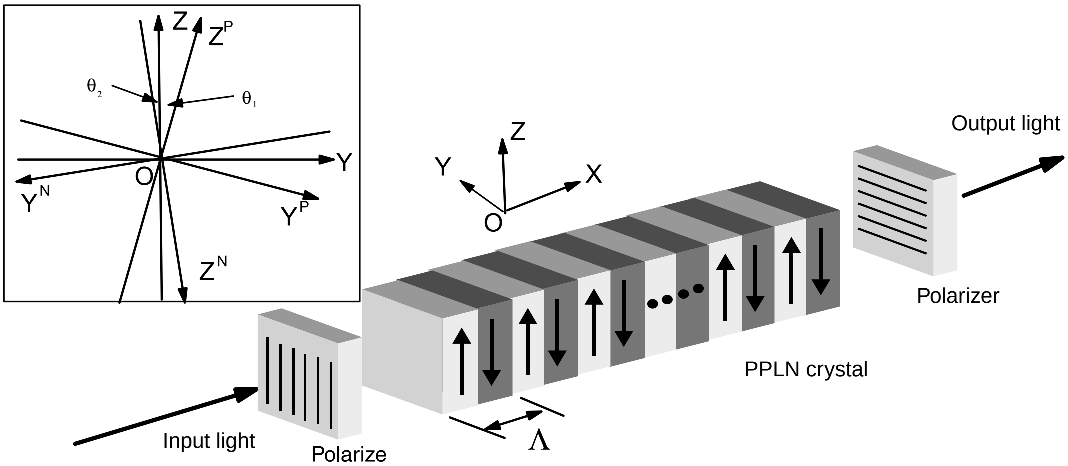

Fig. 1. Experimental setup for tunable PPLN Šolc-type wavelength filter. A PPLN crystal is placed between two crossed polarizers and put into an oven. X, Y, and Z represent the principal axes of the original index ellipsoid. Y^{P} (Y^{N}) and Z^{P} (Z^{N}) are the principal axes of the positive (negative) domains, respectively. θ_1 (θ_2) is a derivation angle between axis of positive (negative) domain and Z-axis.

$$\kappa = -\frac{\omega}{4c}\frac{(n_o^2 - n_e^2)\theta}{\sqrt{n_o n_e}}\frac{\mathrm{i}(1 - \mathrm{e}^{\mathrm{i}2mk\pi})}{m\pi}$$

A_1 and A_2 are the normalized amplitudes of the ordinary wave and the extraordinary wave, respectively; β_1 and β_2 are the corresponding wave vectors. G_m is the mth reciprocal vector, Λ is the period of the PPLN which equals to the sum length of negative domain and the positive domain. The transmission rate of the extraordinary wave is obtained as

$$T = \left|\frac{A_2(x)}{A_1(0)}\right|^2 = |\kappa|^2\frac{\sin^2(Sx)}{S^2}, \tag{2}$$

where $S^2 = |\kappa|^2 + (\Delta\beta/2)^2$. The 100% conversion of the mode energy can be achieved when the QPM condition $\Delta\beta = 0$ is satisfied.

When $\Delta\beta = (\beta_2 - \beta_1) - G_m = 0 \quad (m = 1, 3, 5, \ldots)$, the reciprocal vector totally compensates for the wave vector mismatch between ordinary and extraordinary waves. For a light with wavelength λ_0, the QPM condition is satisfied while the period of domain inversion is $\Lambda_m = m\lambda_0/(n_o - n_e)$. Light at wavelength λ_0 can pass through the filter, but light at all other wavelengths can hardly pass. The transmission of the filter exhibits a $(\sin x/x)^2$ function. Furthermore, the FWHM of the filter is determined by the order of the QPM and the number of the domains. The full width at half maximum of such filter can be estimated by the following equation:

$$\Delta\lambda_{1/2} = 1.60\lambda_0/(2m - 1)N, \tag{3}$$

where m is the order of the QPM.

Because the indices are temperature dependent, the PPLN can be used as a tunable spectral filter. The central wavelength is given by $\lambda_0 = (n_o - n_e) \times \Lambda_1$, where Λ_1 is a first-order period of the PPLN. When the temperature is modified, the fundamental wavelength λ_0 will be shifted according to the above QPM condition while the period of domains is fixed. The wavelength-tuning rate to temperature is

$$\frac{\mathrm{d}\lambda}{\mathrm{d}T} = \Lambda_1 \times \left(\frac{\mathrm{d}n_o(\lambda, T)}{\mathrm{d}T} - \frac{\mathrm{d}n_e(\lambda, T)}{\mathrm{d}T}\right). \tag{4}$$

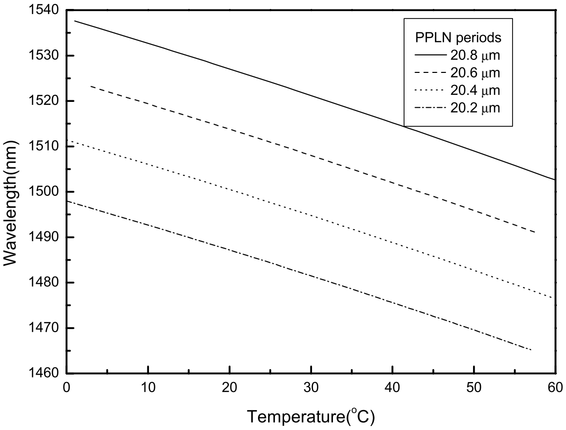

Fig. 2. Calculated results of the central wavelength tuning curves as a function of temperature in PPLNs with their periods of 20.2, 20.4, 20.6 and 20.8 μm. The wavelengths shifts at each period exhibit a near-linear dependence on the temperature.

Fig. 2 shows the calculated results of the central wavelength-tuning curve as a function of temperature in PPLN which four periods of 20.2, 20.4, 20.6 and 20.8 μm. From the figure, the wavelengths shifts at each period exhibit a near-linear dependence on the temperature. The tuning rates are $\frac{\Delta\lambda}{\Delta T} = -0.588$, -0.593, -0.598 and -0.603 nm/°C at periods from 20.2 to 20.8 μm. Therefore, without the necessity of heating the device to high temperature, a wide tuning range can be obtained.

3. Experimental results and discussions

The schematic diagram of the experiment is shown in Fig. 1. We use the EXFO optical test system, which includes a broadband ASE spontaneous source, a tunable laser, a high-speed power and an optical spectrum analyzer (OSA). A PPLN crystal is placed between two crossed polarizers. The PPLN in the experiment is fabricated by the electric-field poling technique at the room temperature. The sample with a dimension of $28 \times 5 \times 0.5$ mm^3 consists with four gratings with the periods from 20.2 to 20.8 μm and the width of 1 mm, and their duty cycle are about 50%. The polarization of the front (end) polarizer is along the $Z(Y)$-axis. The PPLN is put inside an oven whose temperature is controlled with an accuracy of 0.5 °C. The light is propagating along the X-direction.

Measurements are carried out between 14 and 48 °C. When the temperature is higher than 50 °C, no obvious transmission peak is detected for the 20.8 μm period PPLN due to the limitation of wavelength range of the tunable laser and the ASE light source.

The normalized transmission spectra of 20.8 μm period PPLN Šolc-type filter measured by a tunable laser and a power meter at 14 and 38 °C are shown in Fig. 3. When the temperature is changed from 14 to 38 °C, we find a large shift of the transmission spectrum. The central wavelengths are at 1535.755 and 1525.990 nm, respectively. The values of central wavelengths as shown in Fig. 2 at different temperature are calculated from Sellmeier equation [13], which differ from our experimental values. This discrepancy is possibly due to the fact that the refractive index in our experiment may be different with the one in Ref. [13]. The FWHM of the filter can be calculated from Eq. (3), which is determined by the domain number of the PPLN under a first-order QPM condition. For the PPLN we used in the experiment, the period is 20.8 μm and the domain number is about 2692, then $\Delta\lambda_{1/2} = 1.60\lambda_0/N \approx 0.9$ nm, which is in good agreement with the measured result 0.8 nm in our experiment. If the length of the PPLN is as twice as the one we used, the FWHM of the filter can reach to $\Delta\lambda_{1/2} \approx 0.45$ nm. So, narrower spectrum filter can be achieved by employing longer PPLN crystal.

The temperature dependency of the central wavelength is shown in the inset of Fig. 3. We find that the wavelength shift is proportional to the change of temperature. The linear fitting shows that the tuning rate is −0.422 nm/°C, which is smaller than theoretical calculation result of −0.603 nm/°C. The difference between the theoretical and experimental results may arise from the unknown data of the wavelength and temperature dependence of refractive index of our PPLN sample.

Wavelength tuning by temperature is interesting in dense wavelength division multiplexer (DWDM) optical fiber communication system where it can be employed as a tunable filter for all-optical wavelength routing. Based on the above discussions, narrowband filter with wide-range tuning can be implemented by shifting temperature in PPLNs with different periods. For example, a temperature change of 10 °C can shift 4.2 nm of the central wavelength in a 20.8 μm period PPLN. By cascading six PPLNs with different period, wavelength tuning up to 25.2 nm can be achieved. Over 32 channels with wavelength spacing of 100 GH can

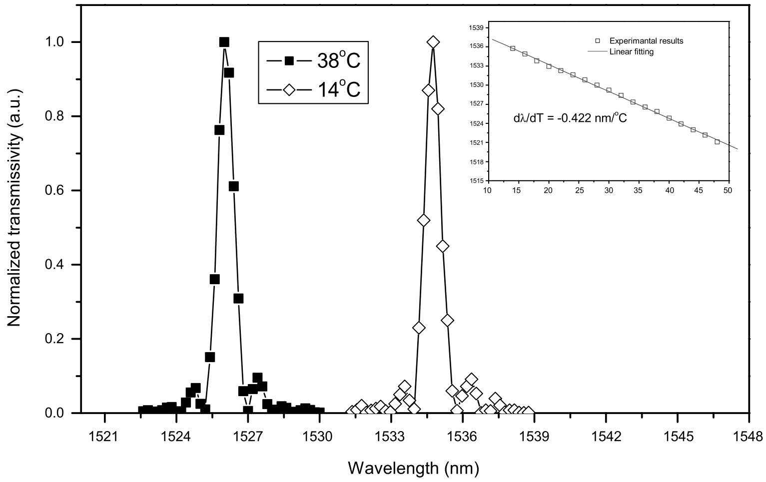

Fig. 3. Transmission spectra of Šolc-type filter measured by a power meter for 20.8 μm period PPLN at different temperature. The curve at right (left) is measured at 14 °C (38 °C), and the center wavelength is 1535.755 nm (1525.990 nm). The inset of Fig. 3 is the temperature dependent of the central wavelength measured by an optical spectrum analyzer. The linear fitting shows that the tuning rate is −0.422 nm/°C.

be arbitrarily filtered in optical crossed connection (OXC).

From Eq. (4), we can rewrite the wavelength tuning rate as

$$\frac{\mathrm{d}\lambda}{\mathrm{d}T} = \frac{\lambda_0}{(n_\mathrm{o} - n_\mathrm{e})} \times \frac{\mathrm{d}(n_\mathrm{o} - n_\mathrm{e})}{\mathrm{d}T}. \qquad (5)$$

Tuning rate $\mathrm{d}\lambda/\mathrm{d}T$ is proportional to derivation of birefringence and inversely proportional to birefringence. So, other ferroelectric crystals, those can be electrically poled, with larger value of $\mathrm{d}\lambda/\mathrm{d}T$ can be dramatically enhance the tuning rate. Lithium tantalate, another important nonlinear optical crystals, has a very small birefringence and large derivation of birefrigence. The tuning rate in lithium tantalite can be calculated as large as 24 nm/°C. This is very interesting for practical applications. But, small birefringence will lead to a long periodicity of domain inversion. In this case, a very long crystal is needed in order to achieve filtering with high transmission efficiency. The issue can be solved by cascading several periodically poled lithium tantalite crystals (PPLTs), each of PPLT has a reasonable length.

4. Conclusions

In conclusion, we have demonstrated a wide-range tunable narrowband wavelength filter in PPLN. We observe that the transmission spectrum of PPLN Šolc-type filter is shifted when the temperature is changed. The dependence of the central wavelength shift on temperature shows a near-linear relationship and tuning rate measured is −0.422 nm/°C. Other ferroelectric materials with small birefringence or large derivation of birefringence will increase the tuning rate. We believe that this tunable Šolc-type wavelength filter may have potential applications in DWDM optical communications.

Acknowledgements

This work was supported by the key program of the fund of technology development in Shanghai, China, under the grant no. 02DJ14001 and the National Science Foundation of China (NSFC) under the grant no. 60007001. Xianfeng Chen's e-mail address is xfchen@sjtu.edu.cn.

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