

Research Article

Šolc-Type Wavelength Filters Based on TE ↔ TM Mode Conversion Utilizing Periodically Poled Ti-Diffused Lithium Niobate Channel Waveguides

Hongsik Jung

Department of Electronic and Electrical Engineering, Hongik University, 121-791 Seoul, South Korea

Correspondence should be addressed to Hongsik Jung, hsjung@wow.hongik.ac.kr

Received 2 November 2009; Accepted 22 January 2010

Academic Editor: Sang-Kook Han

Copyright © 2010 Hongsik Jung. This is an open access article distributed under the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

We have demonstrated the Šolc-type wavelength filters in a 52 mm long periodically poled Ti-diffused lithium niobate channel waveguide which has a domain period of 16.6 μm . At room temperature, the center wavelength and the full-width at half maximum of the filter were about 1272.49 nm and 0.23 nm, respectively. The nearest side-lobe is about 7 dB. New structure of optical add/drop multiplexer (OADM) utilizing Šolc-type TE ↔ TM mode converters was proposed for the first time.

1. Introduction

The development of periodic poled Ti-diffused lithium niobate channel waveguides (Ti:PPLN) utilizing the electric-field poling techniques [1] allows good quality quasiphase-matched (QPM) waveguide devices which can be used in various optical application fields. Among the various periodically poled ferroelectric materials, a periodically poled lithium niobate (PPLN) is particularly attractive for various QPM devices due to its large nonlinear-optic coefficient and easy integration. The main application fields of QPM devices based on periodical poled titanium-diffused optical channel waveguides (Ti:PPLN) are all-optical wavelength conversion [2], optical pulse compression [3], all-optical switching [4], and all-optical logic gate because of their ultrafast nonlinear optical response and high-conversion efficiency. Actually, the electric-field poling of lithium niobate modulates not only the nonlinear optical coefficients but also the electro-optical coefficients due to periodically domain-inversion. These kinds of modulated structures can be used to compensate the phase mismatch between the ordinary and extraordinary wave in birefringent lithium niobate optical channel waveguides.

Recently, the electric-field poling technique allows a new type of narrowband Šolc filter based on PPLN, which

has thousands of birefringent plates [5]. Although the Šolc filter was proposed more than 50 years ago, difficulties with the fabrication technology in making a large number of birefringent plate stacks have prevented the appearance of a practical narrowband Šolc-type wavelength filter [5]. Optical wavelength filtering and polarization mode conversion are key functions in an optical signal processing and communication systems. Optical wavelength filters have attracted much attention in applying to WDM systems due to their constant availability and reliability in the spectrum division and narrowing [6]. Among the diverse optical narrowband wavelength filters, birefringent Šolc-type wavelength filters can allow narrow and tunable spectral band.

Section 2 of this paper reviews the operation principles of a Šolc-type wavelength filters based on TE-TM mode conversion. Section 3 discusses the fabrication processes of Ti:PPLN and some experimental observations including propagation loss, near-field mode patterns, and measurements of second harmonic generation. Section 4 describes the performance of a Šolc-type wavelength filters and Section 5 suggests an add/drop optical multiplexer consisting of Šolc-type TE ↔ TM mode converters and polarization beam splitters (PBS).

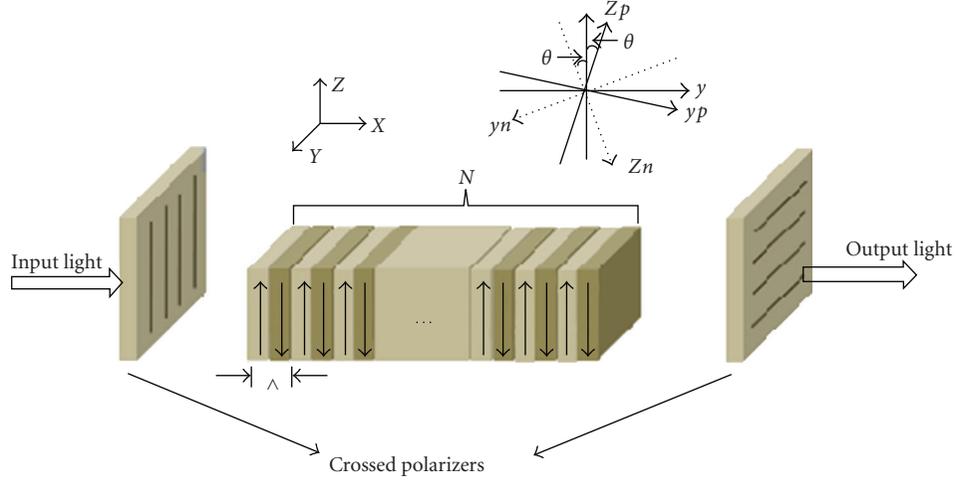


FIGURE 1: The schematic diagram of folded Šolc-type wavelength filter. M couples of half-wave plates are held in two crossed polarizers. The optic axes of the plates aligned at angles $+\theta$ and $-\theta$ with respect to the Z axis in every couple.

2. Operation Principle of Šolc Filters

In a folded Šolc-type wavelength filter, a series of half-wave plates are contained between crossed polarizers as shown in Figure 1. The optical axes of the half-wave plates are alternately aligned at angles of $+\theta$ and $-\theta$ with respect to the plane of polarization of the input light. The angle θ is called the rocking angle because the angle cannot be changed after poling process. The experimental observation of the Šolc-type filter indicates that there is rocking angle θ between the optical axes of the positive and negative domains. Even though the origin of this rocking angle is not clear, the fabricating defect of the PPLN is suspected to cause the rocking angle. Namely, the crystal-axis (namely, Z -axis) is not exactly perpendicular with the crystal surface, the crystal-axis of the negative domain after poling may have a very small deviation angle θ from the crystal-axis of the positive domain [5]. When a rocking angle θ exists between domains, the input light at the center wavelength which is polarized along the Y -axis rotates by an angle of 2θ after passing through the first set of positive and negative domains. The center wavelength λ_o is defined by [7]

$$\lambda_o = \frac{2}{2m+1}(n_o - n_e)d, \quad m = 0, 1, 2, \dots, \quad (1)$$

where n_o and n_e are refractive indices of the ordinary and extraordinary wave, respectively, and d is the domain thickness. Thus, after passing through N domains ($N/2$ sets), the rotation angle of the polarization is $N\theta$. In this case the transmission of power is described by $T = \sin^2(N\theta)$. Therefore, when $N\theta = 90^\circ$ at the filter, the light of wavelength does not experience loss in passing through the crossed polarizer as shown in Figure 1. Light at other wavelengths does not satisfy the above condition and is therefore quickly attenuated at the crossed output polarizer. The transmissivity

T of the Šolc-filter can be expressed by

$$T = \left[\frac{\sin\left(\frac{1}{2}\pi\sqrt{1 + (N \cdot (\Delta\Gamma/\pi))^2}\right)}{\sqrt{1 + (N \cdot \Delta\Gamma/\pi)^2}} \right]^2, \quad (2)$$

where $\Delta\Gamma$ is the change of phase retardation defined by

$$\Delta\Gamma = -\frac{\pi(\lambda - \lambda_o)}{\lambda_o}, \quad (3)$$

where λ_o is the center wavelength of the filter. The FWHM of the filter is proportional to the inverse of the number of domains as given by

$$\lambda_{\text{FWHM}} \cong 1.6 \left\{ \frac{\lambda_m}{[(2m+1)N]} \right\}. \quad (4)$$

Therefore, we can control the bandwidth of filter by changing the length of device. Such a narrow bandwidth is caused by the numerous domains in the Ti:PPLN channel waveguide.

In a lithium niobate crystal, because of the presence of an external electric field along the Y axis, the refractive-index ellipsoid deforms and consequently the Y and Z axes of the Z -cut lithium niobate rotate by a small angle Φ about the X axis. X , Y , and Z represent the principal axes of the original index ellipsoid of the lithium niobate crystal. The rotation angle Φ is given by [8]

$$\Phi \approx \frac{\gamma_{51}E}{(1/n_e^2) - (1/n_o^2)}, \quad (5)$$

where E is the electric field intensity and r_{51} is the off-diagonal electrooptic coefficient. Note that the coefficient r_{51} changes its sign in the negative domains because of the 180° rotation of the crystal structure. Thus, even in the presence of a uniform electric field along the Y axis, the rotation angle of the Y and Z axes changes sign from positive to negative

domains. For a PPLN with alternatively positive and negative domains whose length is given by (1), a folded Šolc-type wavelength filter can be easily formed by application of a uniform electric field along the Y axis. Since the rotation angle Φ given by (5) is proportional to the intensity of the applied voltage, the transmission intensity at a given wavelength can be electrically modulated by the applied electric field. Furthermore, very narrow spectrum filters can be achieved by employment of a longer PPLN crystal since the line width of the transmission spectrum is governed by both the number and order of the half-wave plates.

In general, it is very difficult to predict and adjust the rocking angle θ by only poling to make $N\theta = 90^\circ$ for a given device length. Therefore, the $N\theta$ may be greater or smaller than 90° and eventually transmittance should be degraded. The amount of deficiency and surplus of $N\theta$ can be adjusted to 90° by the rotation angle Φ , applying an external electric field along the Y axis. In this case, the transmission of power can be described by $T = \sin^2(N\theta \pm \Phi)$. A maximum spectral transmittance can be achieved at the condition $N\theta \pm \Phi = 90^\circ$. By the way, the transmission spectrum can correspondingly evolve into a flat-top waveform if higher electric field than $N\theta \pm \Phi = 90^\circ$ is applied, and then eventually a flat-top bandpass Šolc-type wavelength filter can be realized [9, 10].

3. Fabrication Processes of Ti:PPLN and Characterizations

A channel waveguide with a width of $7\ \mu\text{m}$ was fabricated by diffusing $\sim 100\ \text{nm}$ thick Ti stripes on $-Z$ face of a $60\ \text{mm}$ long, $12\ \text{mm}$ wide, and $0.5\ \text{mm}$ thick Z-cut LiNbO_3 substrate along its X -axis [11]. Afterwards, a microdomain inversion structure with a periodicity of $16.6\ \mu\text{m}$ was generated by using an electrical field poling technique with liquid electrodes and annealed to remove the stress happened during electrical field poling [1]. Figure 2 shows periodic domain inversion structure on Ti-diffused channel waveguide in lithium niobate after selective chemical etching. We confirmed the qualities of QPM structure and waveguide in a Ti:PPLN device by the measure of the second-harmonic wave, the propagation loss of waveguide, and near field mode profiles, respectively. Figure 3 shows the second harmonic curve at room temperature. The conversion efficiency was measured to be $473\%/W$ at a wavelength of $1529.80\ \text{nm}$. Such a narrow bandwidth and high conversion efficiency indicate that a good QPM structure was fabricated through the whole length of waveguide. The propagation losses of TM and TE polarization mode at $1529.80\ \text{nm}$ were measured to be 0.03 and $0.01\ \text{dB/cm}$, respectively. At the same time, the near-field mode profiles of Ti:PPLN channel waveguide at the both polarizations in Figure 4 were measured to be $6.83\ \mu\text{m} \times 4.69\ \mu\text{m}$ and be $4.77\ \mu\text{m} \times 3.47\ \mu\text{m}$ for TM and TE polarization modes, respectively. From the waveguide characterization, we confirmed that the fabricated Ti:PPLN channel waveguides can guide TM and TE polarization beam simultaneously with a single-mode profile. The shorter wavelength side ripples of a phase peak as shown in Figure 3 seem to be influenced by slight variation of the refractive index difference between fundamental and second harmonic waves.



FIGURE 2: Periodic domain inversion structure on Ti:LiNbO_3 channel waveguide after selective chemical etching.

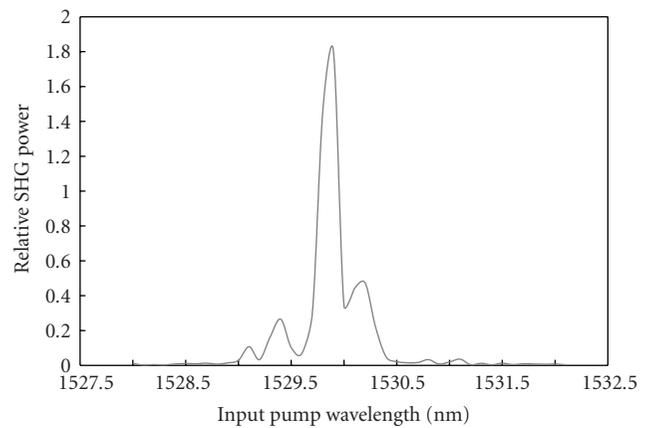


FIGURE 3: Dependence of second harmonic wave power on the pump wavelength.

4. Šolc Filters Performances

The experimental setup to perform the wavelength filtering based on the TE-TM mode conversion of Ti:PPLN channel waveguide is shown in Figure 5. An incident optical wave from a wavelength swept fiber laser based on a semiconductor optical amplifier and a Fabry-Perot tunable filter was collimated and end-fire coupled into polarizer by $\times 10$ objective lens. The polarization direction of input mode was adjusted parallel to the Y -axis and output signal was observed by an optical spectrum analyzer. The optical spectrum of the wavelength swept fiber laser was shown in Figure 5(b). The average power and sweeping frequency of the optical signal were $10\ \text{mW}$ and $15\ \text{kHz}$, respectively. The swept bandwidth of the laser was about $70\ \text{nm}$ (from 1260 – $1333\ \text{nm}$).

The measured transmission spectra of the waveguide-type Šolc-filter based on the Ti:PPLN waveguide are shown in Figures 6 and 7. The transmission spectra were measured at room temperature (25°C). The measured center wavelength and full-width at half-maximum (FWHM) of the filters in Figures 6 and 7 are $1272.49\ \text{nm}$ and $\sim 0.23\ \text{nm}$, and $1272.3\ \text{nm}$ and $\sim 0.24\ \text{nm}$, respectively, which is almost the same as the predicted value in theoretical calculation. The largest sidelobe occurring on the transmission curve was

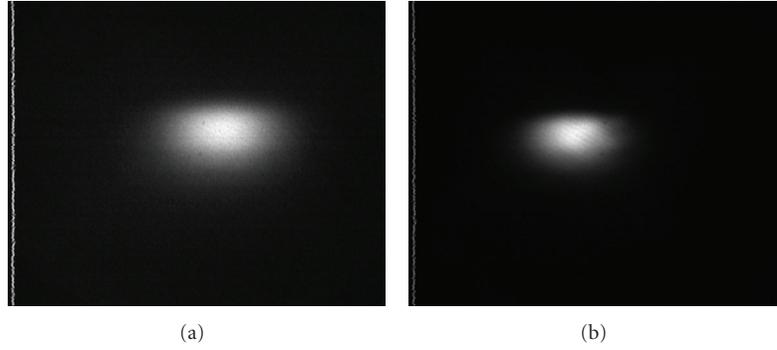


FIGURE 4: TE and TM mode intensity distribution of Ti diffused waveguide at 1550 nm wavelength.

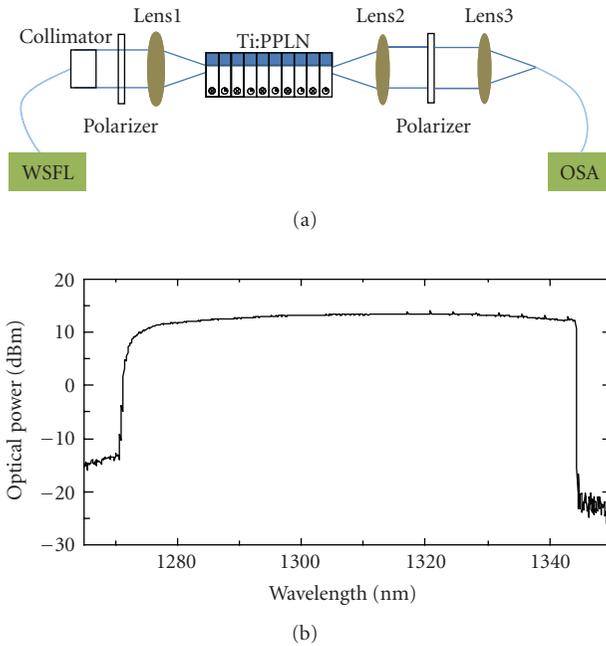


FIGURE 5: (a) Schematic diagram of measurement setup for Ti:PPLN Šolc-type wavelength filter and (b) spectrum of wavelength swept fiber laser (WSFL).

measured about 7 dB below the maximum transmission. A bandwidth of ~ 0.23 nm is narrow enough for use in wavelength filtering in optical communications. The FWHM of the filter is proportional to the inverse of the number of domains as given by (4). Therefore, we can control the bandwidth of the filter by changing the length of Ti:PPLN devices. The normalized transmittance shows less than 10% because the rocking angle θ and entire device length were not enough to convert TE to TM entirely. However, the transmittance can be improved utilizing the rotation angle Φ by application of electric field along the Y-axis of the PPLN.

By the way, the sharp peak of the transmission spectrum of such Šolc-type wavelength filter as shown in Figures 6 and 7 seems to be an obstacle to the application in optical communication and signal processing. In particular, a narrow flat-top band-pass filter, which not only enables

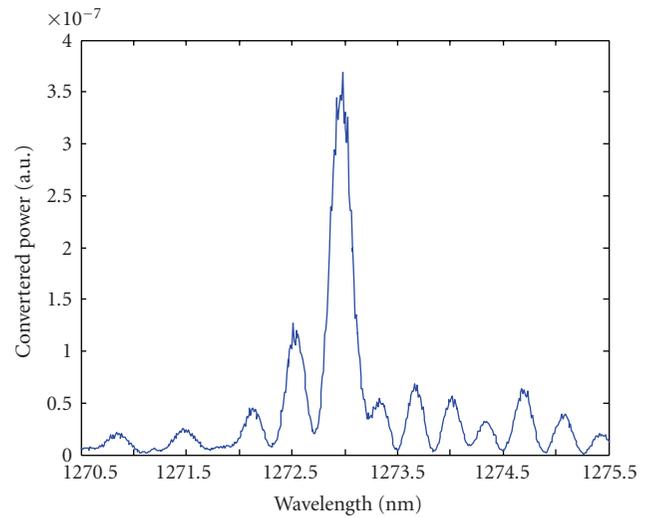


FIGURE 6: Measured transmission power against wavelength for Ti:PPLN Šolc-type wavelength filter with $16.7 \mu\text{m}$ -period: center wavelength (1273 nm), FWHM bandwidth (~ 0.23 nm).

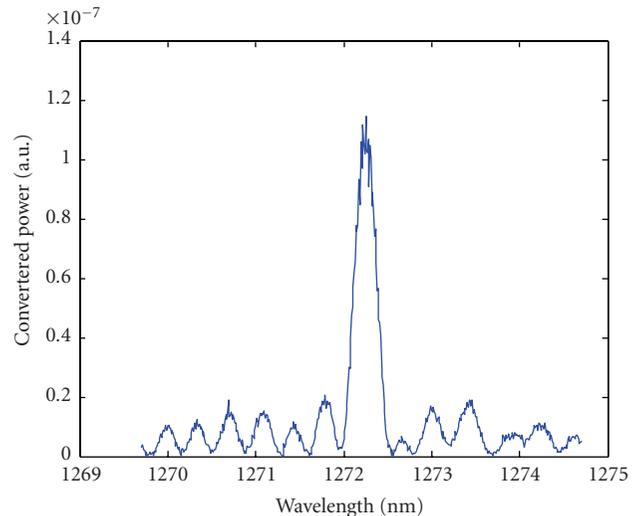


FIGURE 7: Measured transmission power against wavelength for Ti:PPLN Šolc-type wavelength filter with $16.7 \mu\text{m}$ -period: center wavelength (1272.3 nm), FWHM bandwidth (~ 0.24 nm).

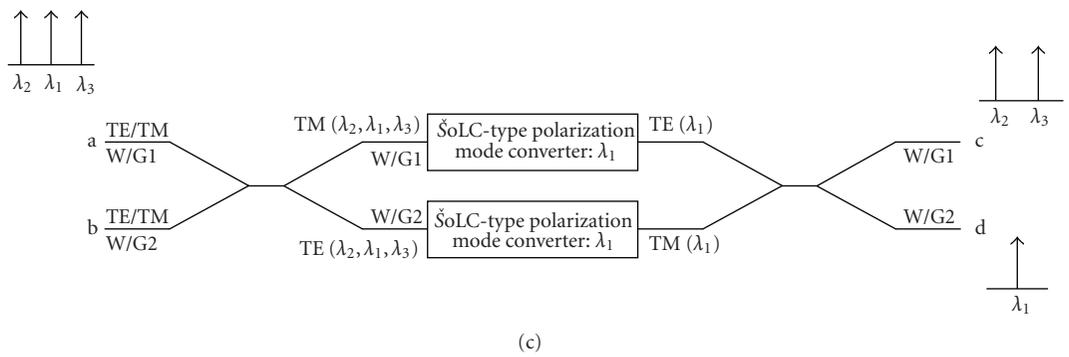
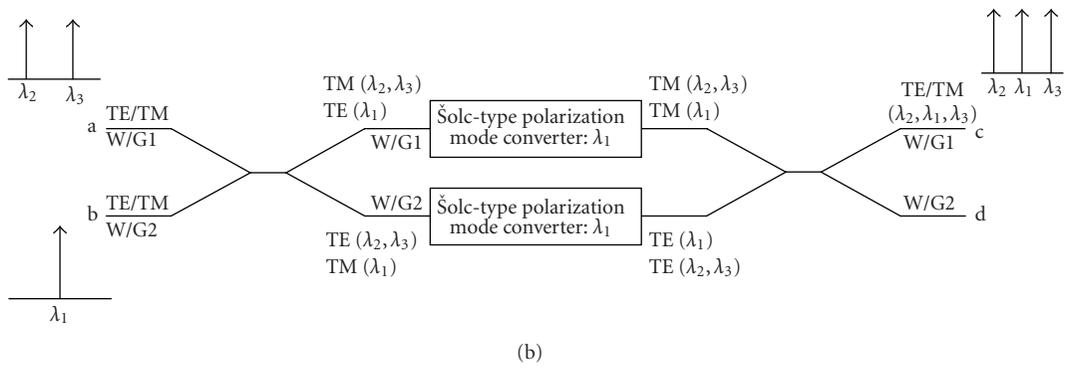
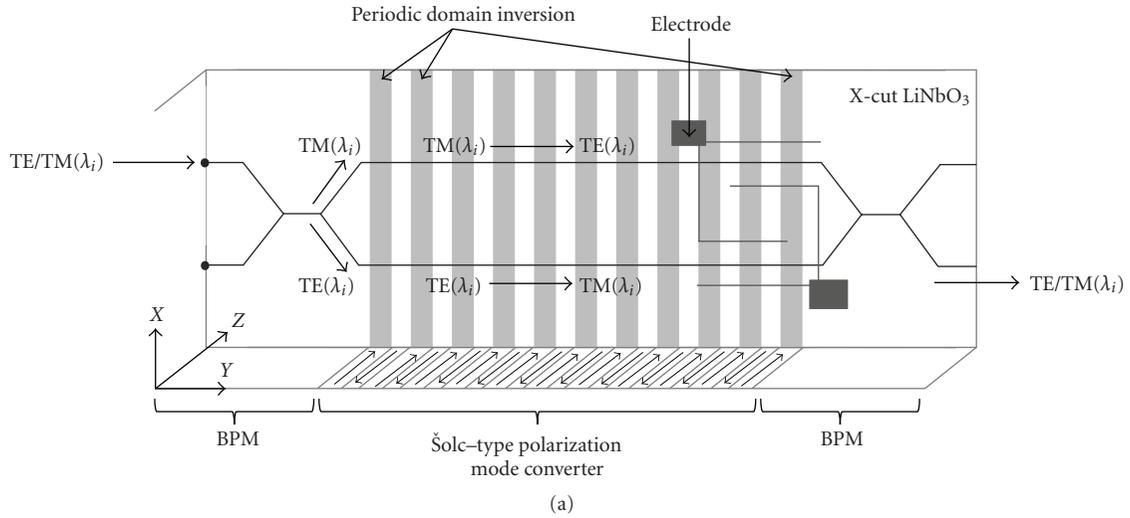


FIGURE 8: (a) OADM layout, and schematic configuration illustrating (b) add and (c) drop operation principles

a particular wavelength channel to pass, is widely needed in wavelength-division multiplexing system. Recently, a flat-top band-pass Solc-type wavelength filter in PPLN waveguide has been successfully proposed [9, 10].

5. Optical Add/Drop Multiplexers Utilizing Ti:PPLN Solc-Filter

The schematic diagram of optical add/drop multiplexer (OADM) as shown in Figure 8(a) was proposed for the first time to the best of our knowledge. It consists of three

sections: two identical polarization beam splitters (PBS) near the input and output ends that are joined by a pair of parallel channel waveguides in which Solc-type polarization mode conversion and wavelength tuning occur. The PBSs based on two-mode interference are basically a kind of passive directional couplers that leave an incident TM component in the straight-through arm, and route an input TE component to the cross-over arm. At the center polarization mode converter (PMC) section, the separated polarized components undergo wavelength dependent Solc-type polarization mode conversion in each of the parallel Ti:PPLN waveguide arms

which has thousands of birefringent plates on Ti diffused channel waveguide.

The lower port (b) on the input side in Figure 8(b) can be used to add the phase-matched wavelength λ_1 . Linearly input polarized lights (λ_2, λ_3) and (λ_1) at the input ports (a) and (b), respectively encounter the first PBS. From input port (a), the decomposed $TM(\lambda_2, \lambda_3)$, $TE(\lambda_2, \lambda_3)$ components enter PMC 1 and PMC 2 through the straight arm of first polarization mode splitter and cross-over arm, respectively. From input port (b), the decomposed $TM(\lambda_1)$ and $TE(\lambda_1)$ components enter the PMC 2 and PMC 1 through the straight and cross-over arm, respectively. If the wavelength of the light, λ_1 , satisfies the phase matching condition, the decomposed components experience Šolc-type polarization mode conversion. The $TM(\lambda_1)$ component in the PMC 2 converts to $TE(\lambda_1)$ polarization and crosses into the upper arm of the second PBS, while the $TE(\lambda_1)$ component in the PMC 1 converts to $TM(\lambda_1)$ and remains in the upper arm as it proceeds through the second PBS. Thus the $TM(\lambda_1)$ and $TE(\lambda_1)$ polarization components recombine and emerge from the output port (c) at the end of substrate. Because the $TE(\lambda_2, \lambda_3)$, $TM(\lambda_2, \lambda_3)$ wavelength polarization components do not satisfy the phase match condition, the $TM(\lambda_2, \lambda_3)$ components in the PMC 1 remain as TM, while the $TE(\lambda_2, \lambda_3)$ components in PMC 2 remain TE and cross into the upper as they proceed through the second PBS. Thus only converted light λ_1 emerges from the upper output (add) port (c) of the OADM with other lights λ_2, λ_3 .

The upper port (a) on the input side in Figure 8(c) can be used to drop the phase matched wavelength λ_1 which then undergoes splitting, Šolc-type polarization mode conversion and recombination successively through its guided-wave propagation path within the structure and emerges at the lower output port (d), leaving all unconverted light to exit through the upper output port (c).

6. Conclusions

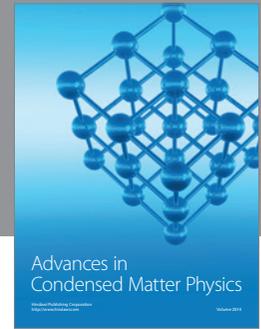
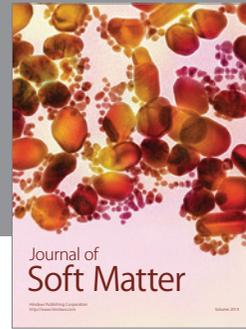
We have demonstrated the Ti:PPLN channel waveguide Šolc wavelength filter which has a domain period of $16.6 \mu\text{m}$. We observed that the FWHM, $\sim 0.23 \text{ nm}$ of wavelength filter was narrow enough for use in an optical filter for all-optical wavelength switching. From a practical point of view, the optical waveguide-type PPLN Šolc wavelength filter is more useful than bulk-type Šolc filters. Among the various waveguide-type PPLNs, the Ti:PPLN waveguide is the most promising device for the Šolc filter because it can support both TE and TM polarization modes simultaneously with single-mode profile and low-insertion loss. The new configuration of optical add/drop multiplexer (OADM) utilizing Šolc-type polarization mode converters was proposed for the first time to the best of our knowledge. We believe that the Šolc-type wavelength filter and polarization mode converter based on a Ti:PPLN channel waveguide will be a very useful optical device for a future tunable wavelength filter in optical communication.

Acknowledgment

This work was supported by the Korea Research Foundation Grant funded by the Korean Government (MOEHRD, Basic Research Promotion Fund) (KRF-2008-521-D00305) and by 2010 Hongik University Research Fund.

References

- [1] Y. L. Lee, H. Suche, G. Schreiber, R. Ricken, V. Quiring, and W. Sohler, "Periodical domain inversion in singlemode Ti : MgO : LiNbO₃ channel waveguides," *Electronics Letters*, vol. 38, no. 15, pp. 812–813, 2002.
- [2] M. H. Chou, I. Brener, M. M. Fejer, E. E. Chaban, and S. B. Christman, "1.5- μm -band wavelength conversion based on cascaded second-order nonlinearity in LiNbO₃ waveguides," *IEEE Photonics Technology Letters*, vol. 11, no. 6, pp. 653–655, 1999.
- [3] M. A. Arbore, O. Marco, and M. M. Fejer, "Pulse compression during second-harmonic generation in aperiodic quasi-phase-matching gratings," *Optics Letters*, vol. 22, no. 12, pp. 865–867, 1997.
- [4] T. Suhara and H. Ishizuki, "Integrated QPM sum-frequency generation interferometer device for ultrafast optical switching," *IEEE Photonics Technology Letters*, vol. 13, no. 11, pp. 1203–1205, 2001.
- [5] J. Shi, X. Chen, Y. Chen, Y. Zhu, Y. Xia, and Y. Chen, "Observation of Šolc-like filter in periodically poled lithium niobate," *Electronics Letters*, vol. 39, no. 2, pp. 224–225, 2003.
- [6] I. Šolc, "Birefringent chain filters," *Journal of the Optical Society of America*, vol. 55, pp. 621–625, 1965.
- [7] S. J. B. Yoo, "Wavelength conversion technologies for WDM network applications," *Journal of Lightwave Technology*, vol. 14, no. 6, pp. 955–966, 1996.
- [8] C. Y. Huang, C. H. Lin, Y. H. Chen, and Y. C. Huang, "Electro-optic Ti:PPLN waveguide as efficient optical wavelength filter and polarization mode converter," *Optics Express*, vol. 15, no. 5, pp. 2548–2554, 2007.
- [9] K. Liu, J. Shi, and X. Chen, "Electro-optical flat-top bandpass Šolc-type filter in periodically poled lithium niobate," *Optics Letters*, vol. 34, no. 7, pp. 1051–1053, 2009.
- [10] K. Liu, J. Shi, Z. Zhou, and X. Chen, "Electro-optic Šolc-type flat-top bandpass filter based on periodically poled lithium niobate," *Optics Communications*, vol. 282, no. 6, pp. 1207–1211, 2009.
- [11] A. Yariv and P. Yeh, *Optical Waves in Crystal: Propagation and Control of Laser Radiation*, John Wiley & Sons, New York, NY, USA, 1984.



Hindawi

Submit your manuscripts at
<http://www.hindawi.com>

