Šolc-type wavelength filters based on TE↔TM mode conversion utilizing periodically poled Ti-diffused lithium-niobate channel waveguides

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

Keywords- **Šolc-type wavelength filter, Ti:PPLN, polarization mode conversion, periodic poling, lithium-niobate (LiNbO₃), optical channel waveguide, optical add/drop multiplexer(OADM)**

I. INTRODUCTION

The development of periodic poled Ti-diffused lithium niobate channel waveguides (Ti:PPLN) utilizing the electric-field poling techniques[1] allow good quality quasi phased 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 [6]. 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 [7]. Among the diverse optical narrowband wavelength filters, birefringent Šolc-type wavelength filters can allow narrow and tunable spectral band.

Section II of this paper reviews the operation principles of a Šolc-type wavelength filters based on TE-TM mode conversion. Section III 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 IV describes the performance of a Šolc-type wavelength filters and section V suggests an add/drop optical multiplexer consisting of Šolc-type TE↔TM mode converters and polarization beam splitters (PBS).

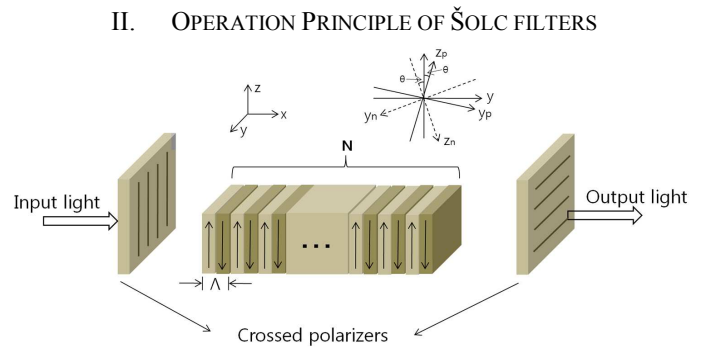## II. OPERATION PRINCIPLE OF ŠOLC FILTERS

Fig. 1. Set-up for a PPLN Šolc-type wavelength filter

In a folded Šolc-type wavelength filter a series of half-wave plates are contained between crossed polarizers as shown in Fig. 1. The optical axes of the half-wave plates are alternately aligned at angles of +θ and −θ with respect to the plane of polarization of the input light. The angle θ is called the rocking angle because the angle can't 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 such that 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 [8]

$$\lambda o = \frac{2}{2m+1}(n_o - n_e)d, \qquad m = 0, 1, 2, - - - \quad (1)$$

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 $N\theta=90^o$ at the filter, light of wavelength does not experience loss in passing through the crossed polarizer as shown in Fig. 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

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

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

$$\Delta\Gamma = -\pi(\lambda - \lambda_0)/\lambda_0 \quad (3)$$

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

$$\lambda_{FWHM} \cong 1.6\{\lambda_m/[(2m+1)N]\} \quad (4)$$

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, if an external electric field along the Y axis is applied 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 [9]

$$\Phi \approx \frac{r_{51}E}{\left(\frac{1}{n_e^2}\right) - \left(\frac{1}{n_o^2}\right)} \quad (5)$$

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 eq. (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 eq. (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 $N\theta=90^o$ 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 $N\theta \pm \Phi=90^o$.

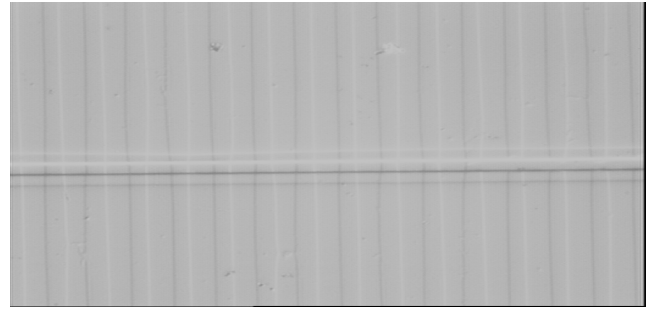### III. FABRICATION PROCESSES OF TI:PPLN AND CHARACTERIZATIONS

Fig. 2. HF-etched Ti:PPLN surface after domain-inversion

A channel waveguide with a width of 7μm was fabricated by diffusing ~100nm thick Ti stripes on –Z face of a 60mm long, 12mm wide, and 0.5mm thick Z-cut LiNbO₃ substrate along its X-axis. Afterwards, a micro-domain inversion structure with a periodicity of 16.6μm was generated by using an electrical field poling technique with liquid electrodes and annealed to remove the stress happened during electrical field poling. Fig. 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. Fig. 3 shows the second harmonic curve at room temperature. The conversion efficiency was measured to be 473%/W at a wavelength of 1529.80nm. 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 1529.80nm were measured to be 0.03 and 0.01dB/cm, respectively. At the same time, the near-field mode profiles of Ti:PPLN channel waveguide at the both polarization were measured to be 6.83μm x 4.69μm and be 4.77μm x 3.47μm for TM and TE polarization mode, 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 Fig. 3 seem to be influenced by slight variation of the refractive index difference between fundamental and second harmonic waves.
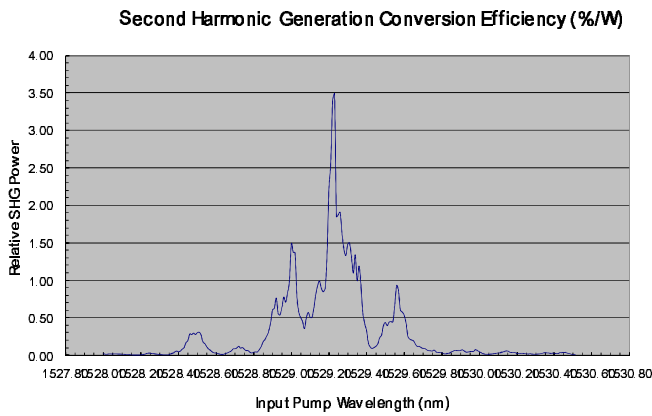

Fig. 3. Second-harmonic generation curve for Ti:PPLN

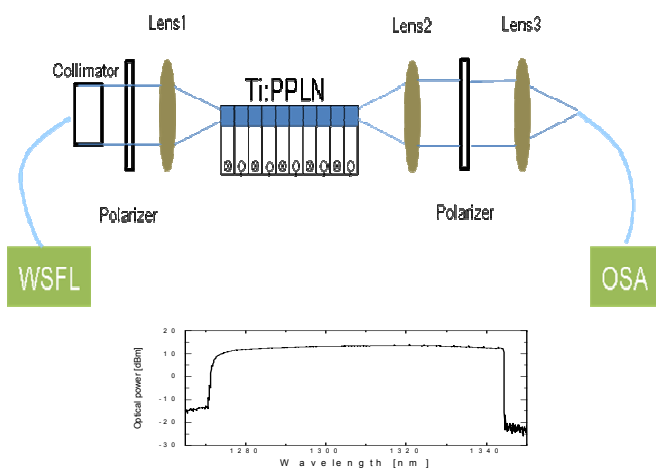## IV.   ŠOLC FILTERS PERFORMANCES

Fig. 4. Measurement set-up of Ti:PPLN Šolc-type filter

The experimental setup to perform the wavelength filtering based on the TE-TM mode conversion of Ti:PPLN channel waveguide is shown in Fig. 4. 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 x10 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 Fig. 4. The average power and sweeping frequency of the optical signal were 10mW and 15 KHz, respectively. The swept bandwidth of the laser was about 70nm (from 1260-1333nm).
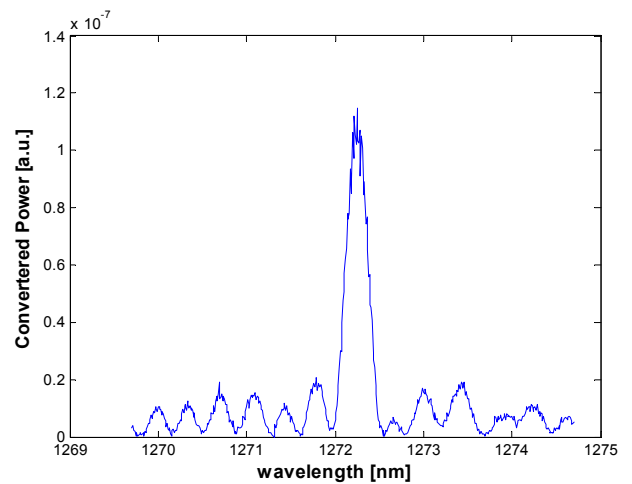
(a)
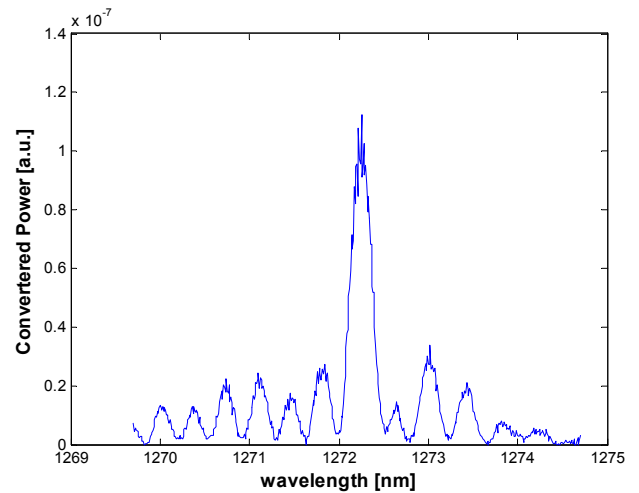
(b)

Fig. 5. Measured transmission optical power versus wavelength of Ti:PPLN Šolc-filter at center wavelength (a) 1272.49nm and (b) 1272.3nm, respectively

The measured transmission spectra of the waveguide-type Šolc-filter based on the Ti:PPLN waveguide are shown in Fig. 5 (a) and (b). 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 Fig. 5 (a) and (b) are 1272.49 nm and ~0.23nm, and 1272.3nm and ~0.24nm, respectively, which is almost the same as the predicted value in theoretical calculation. The largest sidelobe occurring on the transmission curve was measured about 7dB below the maximum transmission. A bandwidth of ~0.23nm is narrow enough for use in wavelength filtering in optical communications. The FWHM of the filter is proportional to the inverse of number of domains as given by eq. (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.

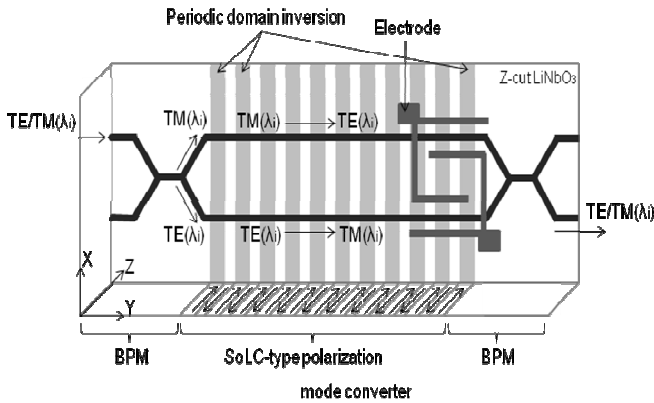## V. OPTICAL ADD/DROP MULTIPLEXERS UTILIZING TI:PPLN ŠOLC-FILTER

Fig. 6. Schematic diagram of optical add/drop multiplexer (OADM) consisting of Šolc-type polarization mode converters and polarization beam splitters

The schematic diagram of optical add/drop multiplexer (OADM) as shown in Fig. 6 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 Šolc-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 Šolc-type polarization mode conversion in each of the parallel Ti:PPLN waveguide arms which has thousands of birefringent plates on Ti diffused channel waveguide.

VI. CONCLUSION

We have demonstrated the Ti:PPLN channel waveguide Šolc wavelength filter which has a domain period of 16.6μm. We observed that the FWHM, ~0.23nm 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 mode 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.

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