Electro-optic Ti:PPLN waveguide as efficient optical wavelength filter and polarization mode converter

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Abstract: We report the first experimental demonstration of electrically controlled Šolc-type optical wavelength filters and TE-TM mode converters based on Ti-diffused periodically poled lithium niobate (Ti:PPLN) waveguides. A maximum mode conversion efficiency or a peak spectral transmittance of ~99% in the telecom C-L bands was obtained from a 9-mm long, 21.5-21.8-μm multiple-grating Ti:PPLN waveguide device with a switching voltage of as low as 22 V or 0.99 V×*d*(μm)/*L*(cm), where *d* is the electrode separation and *L* is the electrode length. The spectral range of this device can be tuned by temperature at a rate of ~0.758 nm/°C.

OCIS codes: (230.2090) Electro-optical devices; (120.2440) Filters; (230.7380) Waveguides, channeled; (060.4510) Optical communications

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1. Introduction

Optical wavelength filtering and polarization mode conversion in an optical waveguide system are two essential functions of an optical signal processing or communication system. In contemporary optical fiber communication systems, wavelength-division multiplexing (WDM) has become a popular technique for achieving high capacity data transmission. Dense wavelength division multiplexing (DWDM) creates greater demand for more narrow-line light sources in the telecommunication bandwidth, which is obviously costly in practical use. In view of this, optical filters have recently attracted much attention and are becoming more widely used in WDM and DWDM systems due to their ability and reliability in terms of spectral dividing and narrowing. A popular technique for fabricating an optical filter is to utilize a multilayer optical thin-film coating, which offers fixed spectral filtering of an optical signal. Although optical filters fabricated utilizing the thin-film coating technology have been found to be indispensable in most optical systems, they operate passively and provide little flexibility. It is desirable to have active optical filters with tunable spectral bands and controllable optical data transmission. Šolc filters [1] are a kind of narrowband birefringence filter whose spectral transmission characteristics can be angle or electro-optically tuned via a prescribed phase-retardation-matching condition related to the crystal birefringence. Conventionally, this phase-matching condition can be satisfied by using finger-type or interdigital electrodes to periodically modulate the relevant electro-optic coefficients in a birefringence electro-optic (EO) crystal [2, 3]. Recently, Šolc-type filters with simple uniform electrodes in periodically poled lithium niobate (PPLN) bulk crystals were demonstrated [4]. The superior EO property of such PPLN Šolc filters has been applied successfully to a low-voltage Q-switched solid-state laser [5] and to an optical parametric oscillator (OPO) [6].

In this work, we extended our previous effort to the designing and implementing of highly efficient Šolc-type optical wavelength filters in EO Ti-diffused PPLN (Ti:PPLN) waveguides in the telecom C-L bands. Compared with the bulk Šolc-type quasi-phase-matched (QPM) filter [4], the waveguide filter can have a much lower working voltage (down to the TTL level) and better compatibility with most optical communication devices. Since a Šolc filter is itself a polarization filter, the EO Ti:PPLN waveguide device disclosed in this paper can effectively work as a transverse-electric ↔ transverse-magnetic (TE↔TM) mode converter as well as a high-speed amplitude modulator when driven by an AC modulating field. Since PPLN is known to be a popular QPM material for nonlinear frequency conversion, the integration of our device with PPLN-waveguide optical frequency mixers (OFM) [7] appears to be a promising way to increase the data transmission capacity of an optical communication system.

2. Theoretical description

Consider a PPLN waveguide whose domain period Λ satisfies

$$\Lambda = m\frac{2\pi}{\beta_o - \beta_e},\ m=1, 3, 5\ldots, \quad (1)$$

where β_o and β_e are the propagation constants of two prescribed waveguide modes with *ordinary* and *extraordinary* polarizations, respectively, propagating in the waveguide axial direction x. In view of the PPLN waveguide configuration, the ordinary and extraordinary modes are the TE and TM modes, respectively. In the presence of an external electric field

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E_y along the crystallographic y axis, the perturbed part of the dielectric tensor of the crystal becomes periodic along the x direction, because the relevant Pockels coefficient r_{51} changes its sign in opposite PPLN domains, given by

$$\Delta\varepsilon(x,y,z) = -\varepsilon_o r_{51}(y,z)E_y(y,z)n_o^2(y,z)n_e^2(y,z)\begin{bmatrix}0 & 0 & 0\\ 0 & 0 & 1\\ 0 & 1 & 0\end{bmatrix}g(x) = \sum_{m\neq 0}\Delta\varepsilon_m(y,z)e^{-iK_m x}\ , \qquad (2)$$

where ε_0 is the vacuum permittivity, $n_o(y,z)$ and $n_e(y,z)$ are the refractive index distribution functions of the TE and TM modes in the waveguide, respectively, $g(x)$ is a square-wave function of period Λ, with amplitude between ±1 along x, $\Delta\varepsilon_m(y,z)$ is the m^{th}-harmonic Fourier coefficient of the periodic dielectric perturbation, and $K_m \equiv 2m\pi/\Lambda$ is the m^{th}-order grating vector of the periodically perturbed structure. For the limit of weak perturbation, we have neglected all the diagonal terms in Eq. (2). In the case of a well-diffused $LiNbO_3$ waveguide as used in this work, the waveguide fabrication process has only minor effect on the magnitude of the EO coefficients [8] and produces only a small surface index change on the order of 10^{-2} [9]. Thus the $r_{51}(y,z)$, $n_o(y,z)$, and $n_e(y,z)$ of the waveguide can be approximated by the bulk value r_{51}, the effective refractive index $n_{o,eff}$ of the TE mode, and the effective refractive index $n_{e,eff}$ of the TM mode, respectively. The power conversion between the two polarization modes in this periodically modulated dielectric structure can be solved by using Eq. (2) in the co-directional coupled-mode theory [10]. The power coupling efficiency in such a device with a length of L is

$$\eta_o(L) = |\kappa|^2 L^2 \operatorname{sinc}^2\left(\sqrt{|\kappa|^2 + (\Delta\beta/2)^2}\,L\right), \qquad (3)$$

where $\Delta\beta = (\beta_o - \beta_e) - K_m$ is the wave-vector mismatch of the coupling process and κ is the coupling coefficient. This is given by

$$|\kappa| = \frac{2}{\lambda_0}\frac{n_{o,eff}^2 n_{e,eff}^2 r_{51}|E_y|}{\sqrt{n_{o,eff}n_{e,eff}}}\frac{\sin(m\pi D)}{m}\vartheta\ , \qquad (4)$$

where λ_0 is the wavelength of the mode fields, D is the domain duty cycle of the PPLN crystal, and ϑ is the overlap efficiency of the mode fields and the modulating field, defined by

$$\vartheta = \int e_o^*(y,z)e_y(y,z)e_e(y,z)\,dydz\ , \qquad (5)$$

where $e_o(y, z)$, $e_e(y, z)$, and $e_y(y, z)$ are the normalized transverse field profiles of the o wave, e wave, and modulating field, respectively. At $\Delta\beta = 0$, Eq. (3) is reduced to

$$\eta_o(L) = \sin^2(|\kappa|L)\,. \qquad (6)$$

The switching voltage for such a polarization mode converter is the voltage necessary to vary $\eta_o(L)$ between 0 and 1. Assuming the electrode separation for applying E_y is d, the switching voltage according to Eq. (6) is therefore

$$V_{EO} = \frac{1}{\vartheta}\frac{\lambda_0}{4}\frac{\pi}{\sin(\pi D)}\frac{\sqrt{n_{o,eff}n_{e,eff}}}{r_{51}n_{o,eff}^2 n_{e,eff}^2}\frac{d}{L} \qquad (7)$$

for $m = 1$.

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3. Experimental result and discussion

We first fabricated an array of low-loss channel waveguides optimized for guiding single TE and TM modes in a 1.5-cm long, 1.2-cm wide, and 0.5-mm thick z-cut $LiNbO_3$ wafer by using the Titanium thermal diffusion method. Although the proton exchanged (PE) technique is often adopted for fabricating a PPLN waveguide due to its relatively low temperature (<400°C) process, the Ti-diffused $LiNbO_3$ waveguides were employed in this work because of their ability to guide both TE and TM modes and their lower waveguide losses (<0.2 dB/cm). An array of 95-nm thick, 7.5-μm wide Ti strips with a 100-μm period was first fabricated on the –z surface of the $LiNbO_3$ crystal using the standard lithographic and lift-off processes. Since the high-temperature Ti diffusion process will form a domain-inverted layer on the +z surface of a $LiNbO_3$ crystal [11], we use the –z surface for Ti diffusion. In this manner we avoid subsequent difficulty in relation to electric field poling when fabricating the PPLN gratings. We further coated the +z surface of the lithium niobate substrate with a thin layer of SiO_2 to prevent the crystal domain from inversion during high-temperature diffusion. The sample was then loaded in a loosely covered sapphire boat and heated in a 3-zone furnace to 1035°C for 12 hours with a constant oxygen flow. There was some $LiNbO_3$ powder surrounding the sample in the sapphire boat for reducing the Li_2O out-diffusion problem [12]. After fabricating the Ti waveguides, we fabricated four 1-cm long, 1-mm wide PPLN gratings with periods Λ= 21.5, 21.6, 21.7, and 21.8 μm in the $LiNbO_3$ sample using the standard electric-field poling technique. According to Eq. (1) and the refractive indices estimated from Refs. [13, 14], the four periods 21.5, 21.6, 21.7, and 21.8 μm are expected to be phase-matched to the four telecom C-L-band wavelengths 1.561, 1.568, 1.575, and 1.582 μm, respectively, at 39.5°C. In our design, there are eight waveguide channels in each PPLN grating section. To apply a *y*-component electric field over all waveguide channels, we fabricated interleaved-comb electrodes along the waveguide sides with a 20-μm insulation width. Figure 1 shows a microscopic image of a portion of the –z surface of the EO Ti:PPLN waveguide device. One can clearly see the arrangement of the electrodes relative to the waveguides and the PPLN gratings. The HF etched +*z* surface is also visible in the image, showing a duty cycle of the PPLN domains of between 40-50%. In contrast to the use of a finger-type or interdigital electrode in an ordinary $LiNbO_3$ waveguide mode converter [2, 3], the interleaved-comb electrode configuration permits the use of the full PPLN waveguide length (~9mm in this work) for mode coupling and there is negligible waveguide loss due to the electrode coating. The end faces of the EO Ti:PPLN waveguide sample were optically polished but not coated with any anti-reflection layers. The performance of the EO Ti:PPLN waveguide device was then characterized by using an external cavity laser (ECL) followed by an erbium-doped fiber amplifier (EDFA) in the C-L bands. The output of the EDFA was butt coupled into the Ti:PPLN waveguide by using a single-mode fiber. Figure 2 shows the far-field intensity profiles of the TE and TM modes measured at the output of the Ti:PPLN waveguide, indicating single-transverse-mode guiding of the waveguide for both TE and TM polarizations. The propagation loss of the Ti:PPLN waveguide was measured, using the Fabry-Perot method [15], to be around 0.17 dB/cm, and was of no obvious difference between the TE and TM modes. To measure the spectral-filtering and mode-conversion characteristics of the device, we installed the Ti:PPLN waveguide crystal in a temperature controlled oven between an in-line polarizer at the input end and a polarization beam splitter (PBS) at the output end. The transmission axis of the in-line polarizer is aligned in parallel to the PPLN *y* axis, while the PBS allows for simultaneously monitoring of the transmitted powers of both the TE and TM modes. The TE-TM mode conversion efficiency measured in this work can be defined as

$$\eta_c = \frac{P_{TE\leftrightarrow TM}}{P_{TE} + P_{TM}}, \tag{8}$$

where $P_{TE\leftrightarrow TM}$ is the measured power of the converted polarization mode, and P_{TE} and P_{TM} are the transmitted powers of the TE and TM modes, respectively after the PBS.

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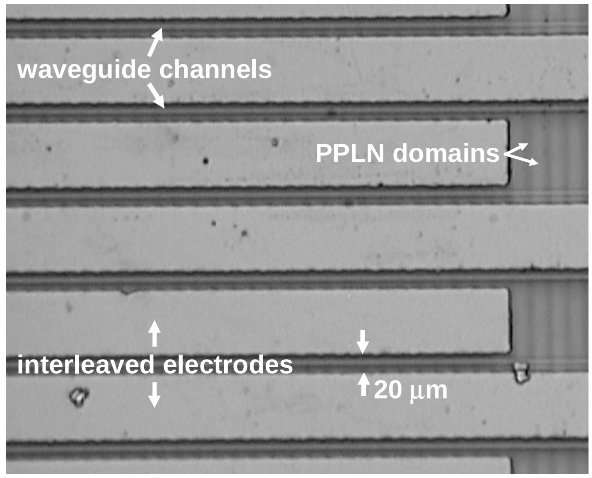

Fig. 1. Microscopic image of the –z surface of the EO Ti:PPLN waveguide device, showing the arrangement of the electrodes relative to the waveguides and the PPLN gratings. The HF etched +z surface is also visible in the image, indicating a duty cycle of the PPLN domains of between 40-50%.

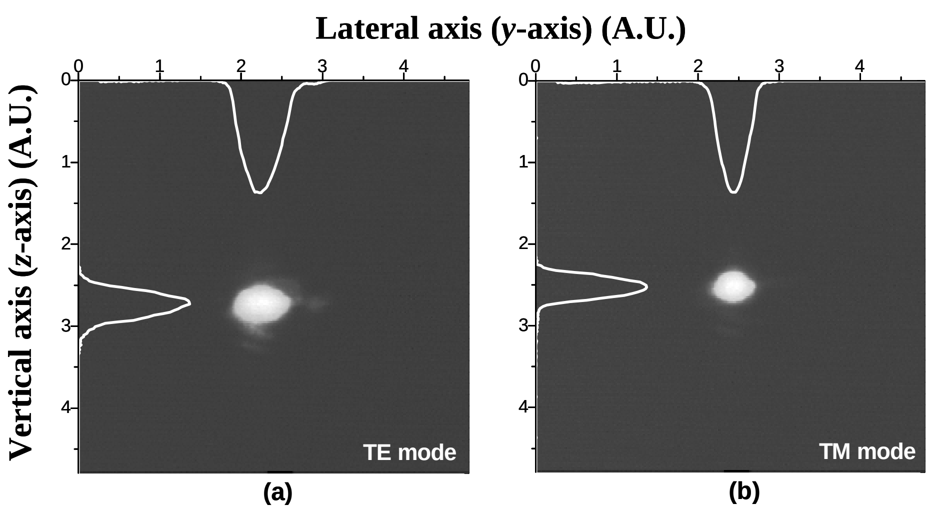

Fig. 2. Far-field intensity profiles of the (a) TE and (b) TM waveguide modes measured at the output of the Ti:PPLN waveguide. The intensity profiles indicate single-transverse-mode guiding of the waveguide for both TE and TM polarizations.

Figure 3 shows the mode conversion efficiency versus the EO tuning voltage for the 21.5-μm-period Ti:PPLN waveguide measured at the phase-matching wavelength 1.561 μm, at 39.5°C, indicating a maximum efficiency of ~99% at a driving voltage of 22V. The experimental data agree very well with the theoretical fitting curve described by Eq. (6). The measured switching voltage corresponds to a normalized value of 0.99 V×d(μm)/L(cm) or 0.63 V×λ_0(μm)d(μm)/L(cm), where λ_0 = 1.561 μm, d = 20 μm, and L = 9 mm, for this work. When comparing the experimental results with Eq. (8), we estimate an overlap efficiency ϑ of ~0.4, which implies some room for further optimization [16]. However, to the best of our knowledge, we have demonstrated the lowest normalized switching voltage, 0.63

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$V \times \lambda_0$(µm)d(µm)/L(cm), for an EO Šolc-type waveguide filter/mode converter built on a $LiNbO_3$ substrate [2, 3]. Figure 4 shows the transmission spectra of the Ti:PPLN-waveguide filters with the four PPLN grating periods between 21.5-21.8-µm at 39.5°C under an applied voltage of 22 V. It can be seen from the plots that the experimental data are in good agreement with the theoretical fitting curves. The spectral bandwidth for each waveguide filter is approximately 2.6 nm.

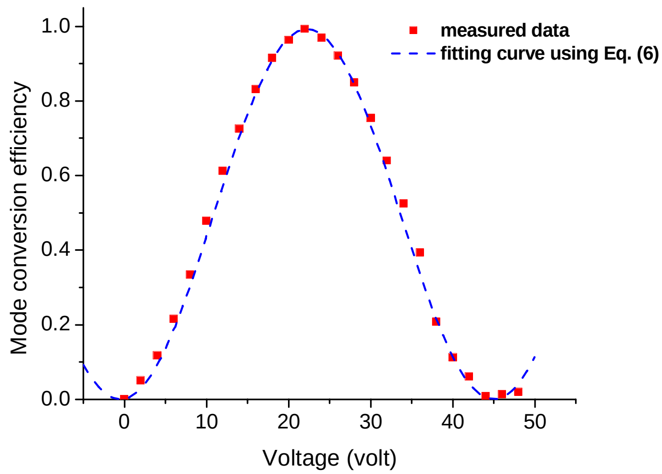

Fig. 3. Mode conversion efficiency versus the EO tuning voltage for the 21.5-µm-period Ti:PPLN waveguide measured at the phase-matching wavelength 1.561 µm at 39.5°C. Nearly 100% conversion efficiency is obtained.

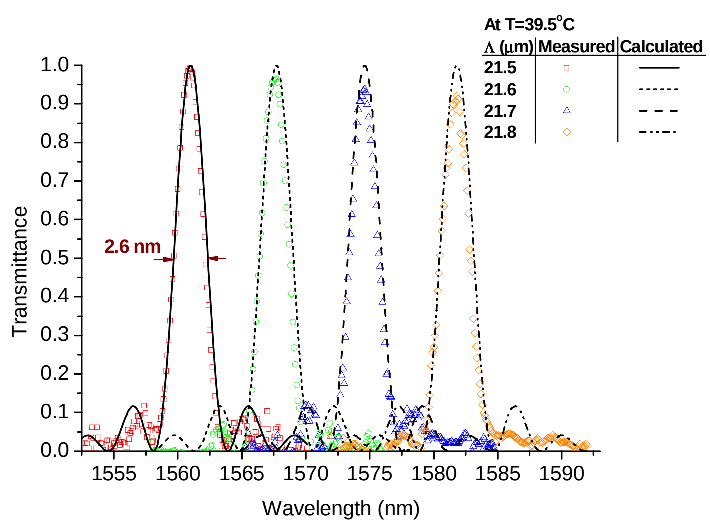

Fig. 4. Transmission spectra of the 21.5-21.8-µm-period EO Ti:PPLN-waveguide wavelength filters at 39.5°C under an applied voltage of 22 V. The transmission bandwidth is ~2.6 nm for each spectral curve.

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Temperature variation is often adopted for tuning the phase-matching wavelengths of a QPM wavelength converter. Similarly, the transmission spectrum of an EO PPLN filter can be tuned by varying the temperature of the PPLN crystal. Figure 5 illustrates that a ~21.2-nm tuning range over a 28°C temperature range can be obtained with the 21.5-μm-period EO Ti:PPLN waveguide, indicating a tuning rate of $d\lambda/dT \sim -0.758 \ \ nm/^{o}C$. The multi-grating design of our PPLN filter can further extend the spectral range of the operation to cover the whole C-L bands in optical communications.

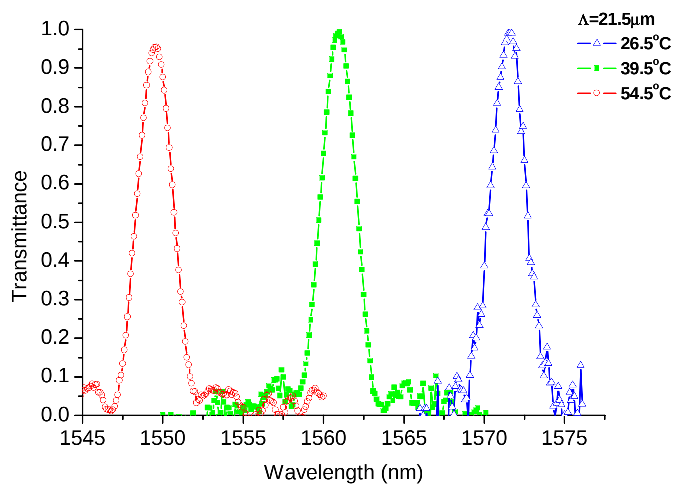

Fig. 5. Temperature-tuned transmission spectra for the 21.5-μm-period EO Ti:PPLN waveguide filter. A tuning rate of ~0.758 nm/°C was obtained.

4. Conclusion

We have successfully developed electro-optic Šolc-type wavelength filters and mode converters based on Ti-diffusion waveguides in a PPLN crystal. The demonstrated device has multiple waveguide channels in different-period PPLN gratings for transmitting optical signals at different wavelengths in the telecom C-L bands. We achieved a maximum mode conversion efficiency or a peak spectral transmittance of ~99% with a ~2.6 nm bandwidth from this 9-mm long Ti:PPLN waveguide device under a fairly low switching voltage of 22 V or 0.99 V×d(μm)/L(cm). A temperature tuning rate of ~0.758 nm/°C for the EO PPLN filter/polarization-mode converter was also demonstrated over the telecom C-L bands. With the maturity of the technology of fabricating long PPLN waveguide devices [11], it should be possible to demonstrate a 5-cm long EO Ti:PPLN wavelength filter having a TTL-level switching voltage and ~0.4-nm transmission bandwidth, which complies with the 50GHz International Telecommunication Union wavelength grid.

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