Light-enhanced electro-optic spectral tuning in annealed proton-exchanged periodically poled lithium niobate channel waveguides

Y. Y. Lin, Y. F. Chiang, Y. C. Huang, A. C. Chiang, and S. T. Lin

Department of Electrical Engineering, Institute of Photonics Technologies, National Tsinghua University, Hsinchu 30013, Taiwan

Y. H. Chen

Institute of Optical Sciences, National Central University, Jhongli City, Taoyuan 32001, Taiwan

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We report the observation of light-enhanced electro-optic spectral tuning in annealed proton-exchanged, asymmetric domain-duty-cycle periodically poled lithium niobate (PPLN) channel waveguides for second-harmonic generation. The spectral tuning rate was increased rapidly from 0.07 nm/(kV/mm) to a saturated value of 0.32 nm/(kV/mm) in a 30%/70% domain-duty-cycle PPLN waveguide when the fundamental pump power near 1534 nm was increased from 0.6 to 46 mW. The second-harmonic laser power at 767 nm was identified to be the source enhancing the spectral tuning. © 2006 Optical Society of America

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Among various nonlinear wavelength conversion techniques, quasi-phase-matched (QPM) nonlinear wavelength conversion[1] is known to have high efficiency and excellent flexibility. In particular, waveguide-based QPM wavelength converters have demonstrated unprecedented, conversion efficiency[2] in recent years. To date, the most widely used QPM nonlinear crystal is periodically poled lithium niobate (PPLN).[3] Since lithium niobate is also a good electro-optic (EO), acousto-optic, and piezoelectric material, it is possible to integrate multiple material properties into a single PPLN device to enhance its functionalities. For example, the EO property of lithium niobate has been used for demonstrating simultaneous amplitude modulation and second-harmonic generation (SHG) in a monolithic PPLN crystal.[4] An electrode-coated asymmetric-duty-cycle PPLN crystal was also employed for tuning the wavelength of an optical parametric oscillator.[5]

Most published works for EO tuning in QPM materials were related to bulk PPLN crystals. To lower the tuning voltage, one approach is to reduce the bulk-crystal dimension to an optical-waveguide size. For example, Watts *et al.*[6] demonstrated EO tuning of phase mismatch of a SHG built upon an asymmetric-duty-cycle periodically poled lithium tantalate (PPLT) waveguide. The nonideal spectral tuning rate, 0.025 nm/(kV/mm), reported by Watts *et al.* was attributed to a nearly 50%/50% domain-duty cycle in the PPLT waveguides. Usually, impurity diffusion is necessary to form a high-index waveguide channel in a lithium niobate or lithium tantalite crystal. The material properties, such as the EO and nonlinear optical coefficients, could be affected by those impurities. In this Letter, we investigate the EO tuning of SHG phase mismatch in several asymmetric-duty-cycle PPLN waveguides. To our surprise, the spectral tuning rate in an annealed proton-exchanged (APE) PPLN waveguide can be greatly enhanced by laser intensity in the waveguide, as will be reported below.

EO tuning of the SHG phase mismatch in bulk PPLN crystals with an asymmetric-duty cycle has been studied both in theory and experiment with an externally applied electric field along the crystallographic z direction.[7] For a PPLN crystal exhibiting photorefractive effects, an internal z-component field alternating with domain orientation is also present under laser illumination.[8] By taking the total tuning field as the superposition of the external and internal electric fields, one can derive from the phase-matching condition that the total EO tuning of the fundamental wavelength for the first-order QPM SHG process in a PPLN waveguide is expressed by

$$\Delta\lambda_{\omega} = \Delta\lambda_{\mathrm{in},\omega} + \Delta\lambda_{\mathrm{ex},\omega}, \tag{1}$$

where

$$\Delta\lambda_{\mathrm{in},\omega} = -\alpha(r_{33,2\omega}n_{e,2\omega}^{3} - r_{33,\omega}n_{e,\omega}^{3})E_{\mathrm{in}}(L_2 + L_1) \tag{2}$$

is the EO wavelength tuning due to the z-component internal field in the $+z$ crystal domain E_{in} and that in the $-z$ domain $-E_{\mathrm{in}}$, and

$$\Delta\lambda_{\mathrm{ex},\omega} = \alpha(r_{33,2\omega}n_{e,2\omega}^{3} - r_{33,\omega}n_{e,\omega}^{3})E_{z,\mathrm{ex}}(L_2 - L_1) \tag{3}$$

is the wavelength tuning due to an externally applied field $E_{z,\mathrm{ex}}$ along z. In Eqs. (1)–(3), the subscripts ω and 2ω denote the parameters associated with the fundamental and SHG waves, respectively, r_{33} is the relevant EO coefficient in bulk lithium niobate, α is a reduction factor of the bulk EO coefficient in APE lithium niobate, n_e is the effective extraordinary refractive index in the waveguide, and L_1 and L_2 are $+z$ and $-z$ domain lengths, respectively, in a QPM period. For a PPLN waveguide, n is the mode index of the guided wave, which is close to the bulk value for most cases (difference within 10^{-3}–10^{-2}).[9] Savati-

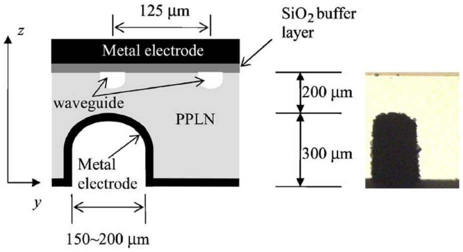

Fig. 1. (Color online) Cross-sectional view of the electrode-coated PPLN waveguide (left, schematic; right, photograph). To reduce the EO tuning voltage, a 300 μm deep trench was cut on the back side of the waveguide.

nova *et al.*[10] have reported a maximum r_{33} value of 20.4 pm/V at 633 nm in an APE lithium niobate waveguide. Given $r_{33}=30.8$ pm/V at 633 nm in bulk $\mathrm{LiNbO_3}$,[11] the maximum value of α is therefore ~66%.

The PPLN crystals in our experiment were fabricated from z-cut congruent lithium niobate wafers by using the standard lithographic patterning and electric-field poling technique.[3] The grating period of the PPLN crystals was 15 μm. The APE waveguides were fabricated on the +z surface of the PPLN wafer. To reduce the EO tuning voltage, we used a dicing saw (DISCO 2H/6T) with a 150 μm blade width to cut a 300 μm deep and 150–200 μm wide trench along x on the back side of the APE waveguides, as shown by the cross-sectional view of the PPLN crystal in Fig. 1. We first deposited a 1 μm thick $\mathrm{SiO_2}$ buffer layer above the PPLN waveguides and then coated the ±z surfaces of the sample with 0.2 μm thick NiCr metal electrodes. The $\mathrm{SiO_2}$ buffer layer and the top metal electrode increased the waveguide loss at the fundamental wavelength from 0.39 to 0.48 dB/cm. The laser source of the fundamental wave was an external-cavity diode laser (ECDL) amplified through an erbium-doped fiber amplifier (EDFA), generating ~60 mW cw laser power between 1530 and 1560 nm.

For our first PPLN-waveguide sample, the domain-duty cycle was estimated to be 65%/35%, obtained by averaging the domain image of the sample under a microscope. The SHG interaction length in the PPLN waveguide was 3 cm. Figure 2 shows the normalized SHG tuning curves with 1.3 mW pump power from the ECDL (open circles) and 43 mW pump power from the EDFA (filled circles). The measured normalized SHG conversion efficiency was $24\%/(\mathrm{W/cm^2})$, which is smaller than a nominal value due to the asymmetric-domain-duty cycle. The agreement between the experimental data and the theoretical sinc curves in Fig. 2 indicates good uniformity in the PPLN waveguide. The high-power tuning curve is shifted in the fundamental wavelength by 0.12 nm relative to the low-power one due to the photorefractive effect described by Eq. (2). In the following investigation, we always waited until the wavelength shift $\Delta\lambda_{\mathrm{in},\omega}$ settled to a steady-state value so that under an externally applied electric field the measured wavelength shift was only relevant to Eq. (3). The steady-state condition was verified by reversing the polarity of the applied voltage and observing an equal amount of wavelength shift to the other side of the steady-state tuning curve.

Figure 3 shows the measured $\Delta\lambda_{\mathrm{ex},\omega}$ versus $E_{z,\mathrm{ex}}$ at 1.5 mW (open circles) and 40 mW (solid circles) fundamental-wave powers in the PPLN waveguide. The phase-matching wavelength is shifted linearly with $E_{z,\mathrm{ex}}$, as expected from Eq. (3). However, the EO wavelength tuning was increased with elevated fundamental-wave power. For the low-power data, the continuous line plots the theoretical curve, Eq. (3), fitted with the refractive indices $n_{e,\omega}=2.152$, and $n_{e,2\omega}=2.2033$.[12] By linearly interpolating the bulk r_{33} values at 633 nm and 3.39 μm in Ref. 11, we obtained $r_{33,\omega}=29.9$, $r_{33,2\omega}=30.66$ pm/V, and found $\alpha=56\%$ for the continuous line. Alternatively, by applying Miller's rule[13] from the r_{33} value at 633 nm, we obtained $r_{33,\omega}=26.5$, $r_{33,2\omega}=29.2$ pm/V, and found $\alpha=32\%$ for the continuous line. The dashed line in Fig. 3 is a linear fitting curve to the high-power data. The EO spectral tuning rate, defined to be $\Delta\lambda_{\mathrm{ex},\omega}/E_{z,\mathrm{ex}}$, for the solid line is 0.075 nm/(kV/mm), whereas that for the dashed line is 0.23 nm/(kV/mm), which is about three times the low-power value.

To repeat the observation, we further fabricated a 2 cm long APE PPLN waveguide with a 70%/30% domain-duty cycle. Figure 4 plots the measured spec-

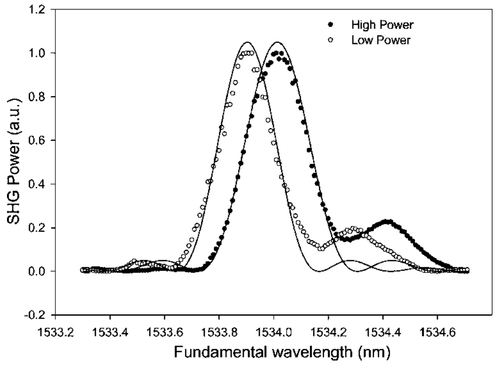

Fig. 2. SHG tuning curves at low (1.3 mW) and high (43 mW) pump powers in the 65%/35% duty-cycle PPLN waveguide. The wavelength shift between the high-power and the low-power curves is due to the photorefractive internal field [see Eq. (2)].

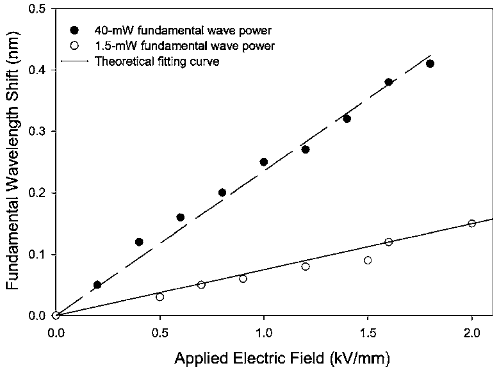

Fig. 3. Fundamental-wavelength shift versus applied electric field with 1.5 mW (open circles) and 40 mW (filled circles) fundamental-wave power in the 65%/35% duty-cycle PPLN waveguide. The wavelength shift is apparently larger with 40 mW pump power in the waveguide.

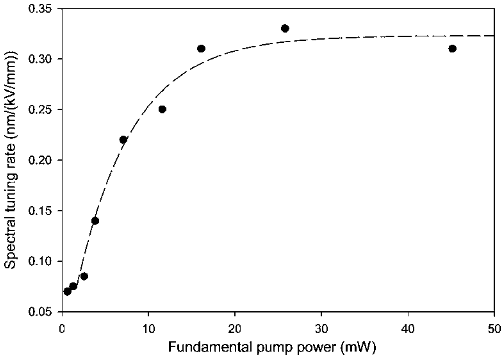

Fig. 4. EO tuning rate versus fundamental-wave power for the 70%/30% duty-cycle PPLN waveguide. The tuning rate was enhanced more than four times when the fundamental-wave power was increased from 0.6 to 46 mW.

tral tuning rate versus the fundamental power for this crystal sample. Again, the tuning rate is evidently dependent on the pump power. The spectral tuning rate was initially pinned at 0.07 nm/(kV/mm) for a fundamental-wave power below 2 mW. When the fundamental-wave power was increased from 2 to 40 mW, the spectral tuning rate grew rapidly and saturated at 0.32 nm/(kV/mm). The tuning rate of this waveguide sample is approximately 1.38 times that of the previous sample, which agrees well with the ratio of the two domain length difference $L_1 - L_2$, as expected from Eq. (3).

In Eq. (3), the domain length difference $L_1 - L_2$ is fixed for a given PPLN crystal and cannot be changed by the laser power or by the applied electric field. If the light-enhanced EO tuning rate implies a power-dependent r_{33}, the nonlinear coefficient d_{33} and the SHG efficiency could also depend on the laser power, regardless of the domain-duty cycle. We therefore measured the SHG conversion efficiency as a function of the pump power for our 50%/50% and 70%/30% duty-cycle PPLN waveguide samples. According to Eq. (2) and Fig. 2, the laser power in a PPLN waveguide can induce an internal electric field and detune the SHG phase-matching wavelength. After carefully compensating for the detuned wavelength in our measurement, we found that the SHG conversion efficiencies for both samples stayed fairly constant over the range of our pump power. Therefore the nonlinear coefficient d_{33} and thus the EO coefficient r_{33} do not depend on the laser power in the waveguide. To determine whether the pump power at 1.5 μm or the SHG power at 0.7 μm is responsible for the enhanced EO tuning rate, we conducted a pump–probe experiment by first measuring the tuning rate with 1.5 mW pump power at the 1534 nm phase-matching wavelength in the 70%/30% duty-cycle PPLN waveguide and remeasuring it by copropagating 43 mW laser power at a detuned wavelength (1551 nm) into the same waveguide. We found that the EO tuning rate stayed at the low value of 0.07 nm/(kV/mm) with or without the presence of the 43 mW power at 1551 nm. Therefore the SHG laser at 767 nm is responsible for the enhanced EO tuning rate in an asymmetric-duty-cycle PPLN waveguide. With 40 mW pump power at 1534 nm, there was approximately 1.5 mW power at 767 nm in the lithium niobate waveguide.

To estimate the uncertainty in the domain-duty cycle of our PPLN samples, we also performed an EO tuning experiment by selecting an ~50%/50% duty-cycle PPLN waveguide sample and found a one-sixth spectral tuning rate measured for the 65%/35% duty-cycle PPLN waveguide. Therefore we inferred an uncertainty of ±2.5% in estimating the domain-duty cycle. In addition, to avoid any mistake in calculating the external field $E_{z,\mathrm{ex}}$, we also reproduced Figs. 3 and 4 by using 500 μm thick PPLN waveguide samples with no cutting trenches on the opposite side of the waveguides.

In conclusion, we have observed a power-dependent EO spectral tuning in APE PPLN waveguides for SHG. The spectral tuning rate increased from 0.07 nm/(kV/mm) to a saturated value of 0.32 nm/(kV/mm) when the fundamental pump power was varied from 0.6 mW to 40 mW in a 70%/30% duty-cycle PPLN waveguide. The enhanced EO spectral tuning rate is useful for applications employing APE PPLN waveguides. Although the mechanism of the light-enhanced EO tuning in a PPLN waveguide is not yet known, we identified that the SHG laser near 700 nm is responsible for the abnormally large EO spectral tuning.

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