Periodically poled $LiNbO_3$ ridge waveguides on silicon for second harmonic generation

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ABSTRACT

Nonlinear periodically poled ridge $LiNbO_3$ waveguides have been fabricated on silicon substrates. Components are micromachined with a precision dicing machine and/or by grinding or polishing steps. They show efficient second harmonic generation at telecommunication wavelengths with normalized conversion reaching 600%/W in a 20mm long device. Influence of geometrical non uniformities of waveguides due to fabrication process is asserted. Components characteristics are studied notably their robustness and tunability versus temperature.

Keywords : Nonlinear optics, periodically poled $LiNbO_3$, ridge waveguides, wavelength conversion

1. INTRODUCTION

Due to its large second order optical nonlinear coefficient (d_{33} = 25 pm/V), efficient and fast nonlinear conversion at low power is possible over short distance in Periodically Poled Lithium Niobate (PPLN) thanks to quasi-phase-matching. Such functionalities are useful to realize optical sources or can play a key role inside wavelength multiplexing systems for optical telecommunications. Particularly, ridge PPLN waveguides [1] with high index contrast can optimize the performances with the combination of strong light confinement, good mode overlap and unaltered nonlinear coefficient of guiding core. Such structures can overpass nonlinear PPLN waveguides fabricated with standard techniques such as proton [2] exchange or titanium-in-diffusion [3]. In addition, PPLN ridge type waveguides can be hybridized with silicon wafers to open up new functionalities for the development of silicon photonics.

In this work we developed ridge-type PPLN components on silicon wafers to efficiency frequency double telecom wavelengths. The fabrication technique is based on wafer bonding and micromachining. Two fabrication methods are implemented.

2. DESIGN

To determine the poling period to achieve quasi-phase matching for second harmonic in a ridge PPLN waveguide at telecom wavelengths λ_p a commercial software is used. The effective indices of the fundamental modes of the pump, n_ω and of the SHG signal, $n_{2\omega}$ are determined. Quasi-phase matching is obtained when the poling period Λ satisfies the following relation:

$$\Lambda = \frac{\lambda_p}{2\left(n_{2\omega} - n_\omega\right)} \quad (1)$$

Figure 1 presents the calculated poling period versus the dimension of a square ridge congruent $LiNbO_3$ waveguide separated from a silicon substrate by a silica layer. Three curves for pump at telecom wavelengths are considered. In order to benefit from the high d_{33} non-linear coefficient associated with an extraordinary polarized light in $LiNbO_3$, TM polarizations are assumed for the pump and the SHG signal. Moreover, even though waveguides can be multimode only phase matching between fundamental guided modes are taken into account.

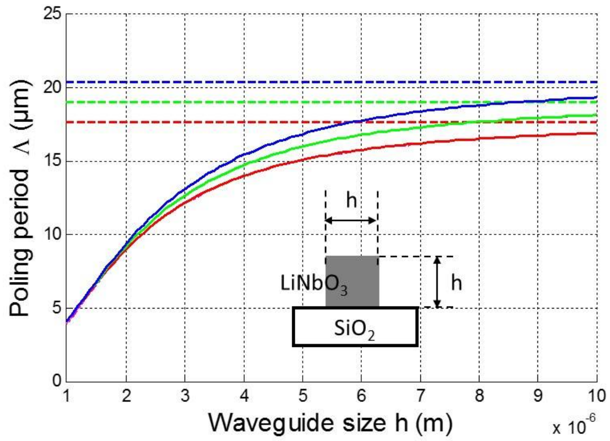

Fig. 1. Poling period for quasi-phase-matched SHG between fundamental modes in a congruent $LiNbO_3$ square ridge waveguide on silica for three different pump wavelengths (continuous line from bottom to top : λp=1500nm, 1550nm and 1600nm) at room temperature. Dotted horizontal lines indicate poling period at the three wavelengths in bulk $LiNbO_3$.

We observe in Fig. 1 that the poling period for quasi-phase-matching becomes smaller as the waveguide section is decreased. For the present study fabricated waveguides have cross sections of about 8µm*8µm which correspond to a poling period Λ close to 17.5µm for a pump wavelength at 1550nm. Waveguides with smaller cross section are expected to provide higher SHG conversion efficiencies thanks to a better confinement but it is at the expense of more stringent conditions for fabrication and light coupling. This choice of waveguide geometry is thus a trade-off in order to release some tolerances for the fabrication and also facilitate light coupling with optical fibers.

To characterize the second harmonic effect it is usual to determine the normalized conversion efficiency η_{SHG} defined in the low conversion regime (undepleted pump) in a waveguide of length *l* for a quasi-phase-matched configuration [4, 5].

$$\eta_{SHG} = \frac{p_{2\omega}}{p_{\omega}^2} = \frac{4}{\pi c^3 \varepsilon_0} \frac{\Gamma \omega^2 d_{eff}^2 l^2}{s\, n_{2\omega} n_{\omega}^2} Sinc^2(\frac{\Delta k\, l}{2}) \qquad (2)$$

Where P_{ω} and $P_{2\omega}$ are the pump and SHG signal power, respectively. Γ is the overlap integral of the SHG and pump mode, d_{eff} is the effective nonlinear coefficient equal to d_{33} , *S* is the effective cross section of the waveguide and the phase mismatched is given by :

$$\Delta k = \frac{4\pi\left(n_{2\omega} - n_{\omega}\right)}{\lambda_p} \qquad (3)$$

3. FABRICATION

The first stage of the fabrication is to periodically pole a 500µm thick commercial z-cut congruent $LiNbO_3$ wafer, supplied by Gooch & Housego, by application of an intense electric field at room temperature [6, 7]. In a second stage, a typical 300nm thick SiO_2 layer is deposited by ICPECVD onto one face of the poled wafer followed by the sputtering of a 200nm thick layer of gold. A high flatness silicon wafer is also coated with a 200nm thick gold layer. The metalized faces of both the PPLN and silicon wafers are then placed into contact and pressed in a wafer bonding machine. The bonding process is realized at room temperature which prevents mechanical stress that could occur due to the dissimilar temperature coefficients of the two wafers. At this stage, a typical 1 mm thick structure composed of a silicon substrate bonded to a PPLN wafer is obtained. Two methods are then implemented to form the ridge waveguides. The first one (method 1) is to thin down the heterostructure by grinding and polishing. This method was used earlier to realize adhered nonlinear ridge waveguides [1, 8] where epoxy was used to bond PPLN wafers onto $LiNbO_3$ substrates. This process leads to components with remarkable characteristics. Multiple Nonlinear components with a common thickness can thus be realized on the same substrate. In order to extend this work to silicon photonics compatible components and at the same time gain some flexibility we also developed another process (method 2) which is entirely based on the use of the precision saw. In this case both the thinning and the ridge dicing are realized with the precision saw.

Figure 2 presents a SEM image of a 10*10 μm^2 cross section waveguide realized with this technique latter method. Both side of the ridge are curved due the small radius of curvature of each corner of the blade. By optical profilometry a 3-4 nm RMS roughness is measured for the ridges faces. Such a surface quality ensures low propagation losses. Moreover, no input and output faces polishing is necessary. One additional advantage of using the dicing technique to realize the ridge compared to the polishing technique is to avoid the appearance of some periodic undulation at the surface of the ridge. Indeed, since –z and +z faces have disparate mechanical properties, when PPLN surface is polished a periodic corrugation given by the periodic poling appears at the surface. This notably increases the propagation losses and can even give parasitic Bragg diffraction. When the top surface of the ridge is instead cut with a precision sawing machine no such corrugation is present. This is illustrated in figure 3 where line profiles have been taken with an optical profilometer for a ridge waveguide realized by polishing and by precision dicing. An undulation of 40nm amplitude with a period corresponding to the poling period clearly appears at the surface of the polished waveguide while precision dicing gives a flat surface. Several ridge waveguides where diced from the hybrid wafers realized with method 2. Waveguides are either 16 mm or 20mm long but different cross sections are targeted to demonstrate the versatility of the developed fabrication technique but also to see their influence on the SHG process.

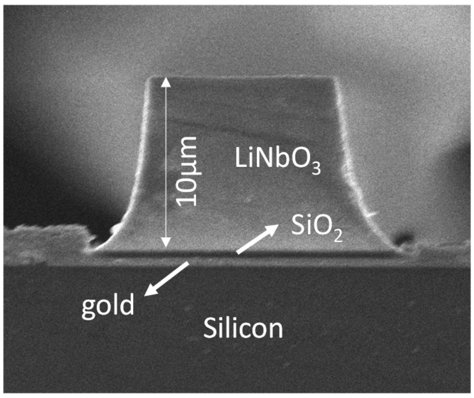

Fig. 2. SEM image of a 10µm by 10µm ridge waveguide realized by precision dicing

4. CHARACTERIZATION

An optical set-up is then used to characterize the waveguides in term of SHG generation. The optical source is an external cavity CW laser tunable between 1500nm and 1600nm for the pump beam. The maximum output power is 10mW. The laser output is attached to a fibered lens to form a spatially collimated beam. The light is linearly polarized and focused with an IR coated microscope objective at the input face of the waveguide under test. The waveguides are placed on a temperature regulated mount controlled by a Peltier element. Output light is then imaged via a second microscope objective onto a vidicon camera to optimize the coupling. For SHG characterization a longpass dichroic mirror is placed at the output in order to separate the SHG signal from the unconverted pump beam. Each beam is measured separately either with powermeters or onto cameras to analyze the guided mode distribution. This set-up allows measurements of the conversion efficiency of the SHG process and is also used to evaluate the transmittivity of the waveguide.

SHG spectral response of the PPLN waveguides are first analyzed over the whole spectrum of the laser source. Several second harmonic peaks are observed in the analyzed spectral range. Each peak is linked to a different transverse mode profile. The peak appearing at the shortest pump wavelength corresponds to the fundamental TM_{00} mode while other peaks are higher order modes of the waveguide. Indeed since the waveguide is multimode phase matching conditions can be fulfilled for different mode combinations as shown in ref [9]. Excitation of higher order modes can be minimized by carefully adjusting the size and the alignment of the injected beam [10]. Consequently, the energy of the guided beam mainly propagates in the fundamental mode which is favorable to obtain high conversion for frequency doubling.

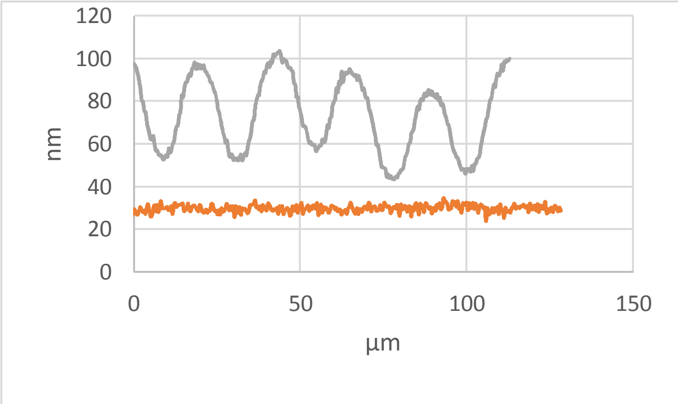

Fig. 3. Profiles measured at the top surface of a PPLN ridge with an optical profilometer for a waveguide thinned by polishing or by precision dicing.

Spectral response of SHG corresponding to TM_{00} modes is then considered further in the text. Figure 4 presents the SHG efficiency as a function of pump wavelength measured in a 16 mm long sample with a poling period of 17.5µm at a temperature of 24°C and a cross section of about 50 μm^2 realized by the method 2. The efficiency greater than 200%/W at 1546.5nm shows that micromachining is a viable solution to carve the ridge waveguides. The measured spectral response has strong similarities with the theoretical response given by a Sinc function which is also a clear indication that quasi-phase- matching is well maintained. Note that the noisy SHG signal is due to the Fabry-Perot effect present in the waveguide, an antireflection coating is in development to minimize this effect. The optimum wavelength is 1545.9nm and a 1nm FWHM is measured for the central peak width which has to be compared of the one estimated (0.65nm) for a perfect waveguide of similar cross section. A linear change of the waveguide thickness of 150nm over the component length could explain this wider response. Tight tolerances have thus to be fulfilled by the fabrication process for the periodic poling but also for the waveguide geometrical uniformity to maintain quasi-phase-matching conditions along propagation. We can however conclude that the fabrication technique based on precision saw for thinning and carving is a viable technique to produce waveguides with good uniformity.

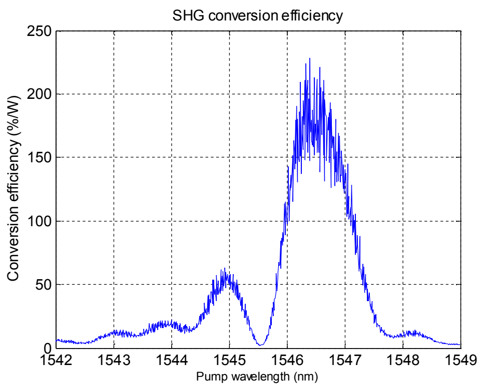

Figure 4: Second harmonic conversion efficiency in a ridge PPLN waveguide entirely realized by precision dicing.

In order to show the correlation between the uniformity of the waveguide and the SHG efficiency additional characterizations have been realized. For this study, waveguides have been fabricated by the more mature process consisting in thinning the $LiNbO_3$ layer by grinding and polishing (method 1). The hybrid wafer is then characterized with a reflectometer in order to evaluate the thickness of the $LiNbO_3$ layer. The thickness mapping is presented in figure 5 for a processed 4 inches diameter wafer with four poling periods of 17.5µm (P1), 17µm(P2), 16.5µm(P3) and 16µm(P4). Note that the four rectangular poled areas are clearly visible because they are slightly less resistant to polishing compare to the surrounding –Z oriented area as mentioned earlier, as a consequence, poled regions are thinner. The nonuniformity thickness in the poled area is about 1µm over the full surface. This is detrimental to maintain the quasi-phase matching of the nonlinear conversion. A theoretical analysis shows that to reach at least half the optimal theoretical conversion efficiency the total thickness variation must be less than 200nm if we consider a 20mm long waveguide. Such ridge waveguides have then been diced with the precision saw in the more uniform regions of the wafer. Conversion efficiency responses are presented in figure 6 for two ridge waveguides of section 7µm*7µm cut in regions P2 (fig. 6a) and P1 (fig. 6b). Both responses are again close to Sinc functions which is a first sign of fairly maintain quasi-phase-matching conditions. Note that central wavelengths are in accordance with the two different poling periods (see Fig. 1). Structures are however not optimal as witnessed by the slightly asymmetric wavelength responses and differing maximum efficiency as well as response bandwidth between the two ridge waveguides. We presume that it is mainly caused by a varying waveguide geometry. However, while further improvement is possible, the conversion efficiency of 600%/W is near the theoretical one which validates the fabrication technique.

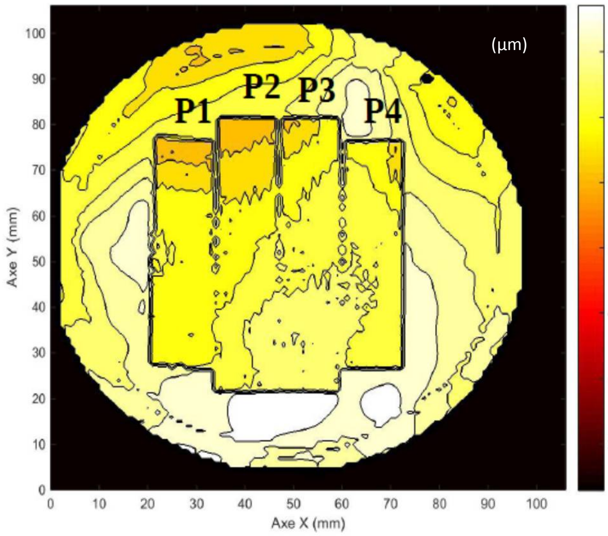

Figure 5: Mapping of the $LiNbO_3$ thickness of a 4 inches diameter hybrid structure

While previous measurements have been performed with components stabilized at 24°C, we may wonder if the component can sustain temperature changes. This would bring fine tuning of the convertion wavelength. Such a question arises since there is a large difference between the thermal expansion coefficients of silicon ($2.6\ 10^{-6}$ °C^{-1}) and $LiNbO_3$ ($13\ 10^{-6}$ °C^{-1}) [11]. The temperature controller based on a Peltier element allows sample temperature stabilization in the 15°C to 60°C range. No component failure occurs even though several temperature cycles were performed in this temperature range. The thin and narrow waveguides carved on the same silicon substrate thus do not suffer excessive strain over this temperature range. Note that a 500µm thick silicon substrate gold bonded to a 500µm thick $LiNbO_3$ wafer breaks under the same temperature test. The change in central wavelength due to the waveguiding effect is clearly observed corresponding to wavelength shift of 0.126 nm/°C for the analyzed waveguide.

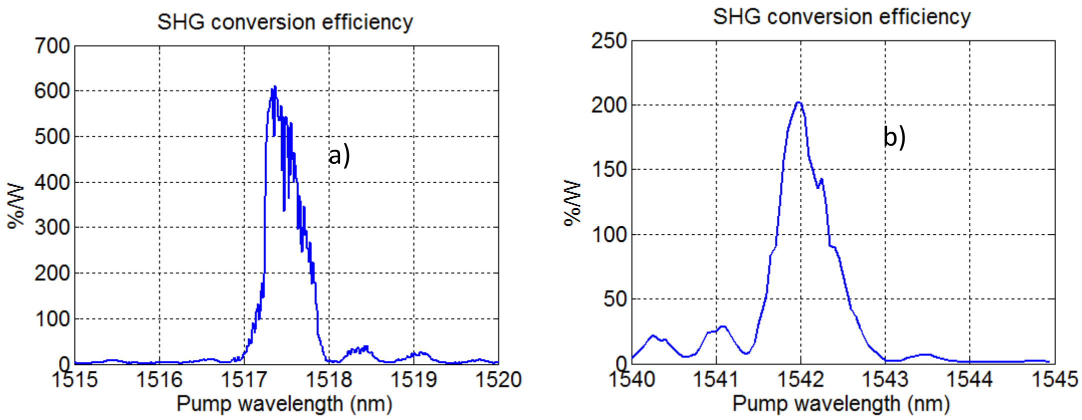

Figure 6: Conversion efficiency responses in two square 7µm*7µm, 20mm long ridge waveguides with poling periods of 17µm (a) and 17.5µm (b).

5. CONCLUSION

In conclusion, we have developed hybrid guided optics components to realize efficient SHG at telecommunication wavelengths. The components, based on PPLN waveguides bonded onto silicon substrates are realized by two methods based either on a combination of polishing and precision dicing or solely based on dicing. High conversion efficiency and frequency response in accordance with theory shows that the developed fabrication techniques are viable to realize nonlinear components compatible with the silicon photonics.

REFERENCES

[1] Kurimura, S., Kato, Y., Maruyama, M., Usui, Y. and Nakajima, H., "Quasi-phase-matched adhered ridge waveguide in LiNbO3," Applied Phys. Letters **89**, 191123 (2006).

[2] Chou, M. H., Brener, I., Fejer, M. M., Chaban, E. E. and Christman, S. B., "1.5-m-band wavelength conversion based on cascaded second-order nonlinearity in LiNbO3 waveguides," IEEE photon. Technol. Lett. **11**, 653655 (1999).

[3] Lee, Y. L., Suche, H., Min, Y. H., Lee, J. H., Grundkotter, W., Quiring, V. and Sohler, W., "Wavelength- and time-selective all-optical, channel dropping in periodically poled Ti:LiNbO3 channel waveguides," IEEE Photon. Technol. Lett. **15**, 978980 (2003).

[4] Kajzar,F. and Swalen,J.D.,[Organic thin films for waveguiding nonlinear optics], CRC Press, 181 (1996).

[5] Rustagi, K. C., Mehendale, S.C., Meenakshi, S., "optical frequency conversion in quasi-phase-matched stacks of nonlinear crystals," IEEE journal of quantum electronics **18**, 1029-1041, (1982)

[6] Myers, L. E., Eckardt, R. C., Fejer, M. M., Byer, R. L., Bosenberg, W. R. and Pierce, J. W., "Quasi-phase-matched optical parametric oscillators in bulk periodically poled LiNbO3," JOSAB **12**, 2102-2116 (1995).

[7] Courjon, E., Courjal, N., Daniau, W., Lengaigne, G., Gauthier-Manuel, L., Ballandras, S. and Hauden, J., "Lamb wave transducers built on periodically poled Z-cut LiNbO3 wafers," J. Appl. Phys. **102**, 114107 (2007).

[8] Kou, R., Kurimura, S., Kikuchi, K., Terasaki, A., Nakajima, H., Kondou, K. and Ichikawa, J., "High-gain, wide-dynamic-range parametric interaction in Mg-doped LiNbO3 quasi-phase-matched adhered ridge waveguide," Optics Express **19**, 11867 (2011)

[9] Park, J. H., Kang, T.Y., Ha, J.H. and Lee, H.Y. "Spatial mode behavior of second harmonic generation in a ridge-type waveguide with a periodically poled MgO-doped lithium niobate crystal," Japanese Journal of Applied Physics **53**, 062201 (2014)

[10] Devaux, F., Lantz, E., Chauvet, M. "3D-PSTD for modelling second harmonic generation in periodically poled lithium niobate ridge-type waveguides" JOSAB (accepted for publication).

[11] Pignatiello, F., De Rosa, M., Ferraro, P. ,Grilli, S., De Natale, P.,Arie, A., De Nicola, S. , "Measurement of the thermal expansion coefficients of ferroelectric crystals by a moiré interferometer", Optics Communications 277, 14-18 (2007).