High quality buried waveguides in stoichiometric $LiTaO_3$ for nonlinear frequency conversion

M. Marangoni, M. Lobino and R. Ramponi

Dipartimento di Fisica - Politecnico di Milano, and Istituto di Fotonica e Nanotecnologie del CNR, Piazza Leonardo da Vinci 32, 20133 Milan, Italy
marco.marangoni@polimi.it

E. Cianci, V. Foglietti

Istituto di Fotonica e Nanotecnologie del CNR, sezione di Roma, via Cineto Romano 42, 00156 Rome, Italy

Abstract: High-quality buried optical-waveguides were fabricated by reverse-proton-exchange in periodically-poled stoichiometric lithium tantalate. Experimental results show excellent fiber-mode matching, losses below 0.3 dB/cm and almost non-critical conditions for a quasi-phase-matched second-harmonic generation process from telecom wavelengths. The interaction length of 2.5 cm is the highest so far reported for lithium tantalate waveguides.

OCIS codes: (190.4390) Nonlinear optics, integrated optics (130.3130) Integrated optics materials; (230.7370) Waveguides; (230.4320) Nonlinear optical devices.

References and links

1. M. L. Bortz, S. J. Field. , M. M. Fejer, D. W. Nam, R. G. Waarts, and D. F. Welch, "Noncritical quasi-phase-matched second harmonic generation in an annealed proton-exchanged $LiNbO_3$ waveguide," IEEE Trans. Q. Electron. **30**, 2953-2960 (1994).
2. S. Yi, S. Shin, Y Jin, and Y, Son, "Second harmonic generation in a $LiTaO_3$ waveguide domain-inverted by proton exchange and masked heat treatment," Appl. Phys. Lett. **68**, 2493-2495 (1996).
3. K. Yamamoto, K. Mizuuchi, K. Takeshige, Y. Sasai, and T. Taniuchi, "Characteristics of periodically domain inverted $LiNbO_3$ and $LiTaO_3$ waveguides for second harmonic generation," J. Appl. Phys. **70**, 1947-1951 (1991).
4. M. Houé, and P. D. Towsend, "An introduction to methods of periodic poling for second-harmonic generation," J. Phys. D **28**, 1747-1763 (1995).
5. K. R. Parameswaran, R. K. Route, J. R. Kurz, R. V. Roussev, M. M. Fejer, and M. Fujimura, "Highly efficient second-harmonic generation in buried waveguides formed by annealed and reverse proton exchange in periodically poled lithium niobate," Opt. Lett. **27**, 179-181 (2002).
6. M. L. Bortz, and M. M. Fejer, "Annealed proton-exchanged $LiNbO_3$ waveguides," Opt. Lett. **16**, 1844-1846 (1991).
7. S. Fouchet, A. Carenco, C. Daguet, R. Guglielmi, and L. Riviere, "Wavelength dispersion of Ti induced refractive index change in $LiNbO_3$ as a function of diffusion parameters," IEEE J. Lightwave Technol. **5**, 700-708 (1987).
8. M. H. Chou, I.. Brener, M. M. Fejer, E. E. Chaban, and S. B. Christman, "1.5-micron-band wavelength conversion based on cascaded second-order nonlinearity in $LiNbO_3$ waveguides," IEEE Photonics Technol. Lett. **11**, 653-655 (1999).
9. T. Pertsch, R. Iwanow, R. Schiek, G. I. Stegeman, U. Peschel, F. Lederer, Y. H. Min, and W. Sohler, "Spatial ultrafast switching and frequency conversion in lithium niobate waveguide arrays," Opt. Lett. **30**, 177-179 (2005).
10. B. Agate, E. U. Rafailov, M. Sibett, S. M. Saltiel, P. Battle, T. Fry, and E. Noonan, "Highly efficient blue-light generation from a compact, diode-pumped femtosecond laser by use of a periodically poled KTP waveguide crystal," Opt. Lett. **28**, 1963-1965 (2003).
11. K. Mizuuchi, T. Sugita, K. Yamamoto, T. Kawaguchi, T. Yoshino, and M. Imaeda, "Efficient 340-nm light generation by a ridge-type waveguide in a first-order periodically poled $MgOLiNbO_3$," Opt. Lett. **28**, 1344-1346 (2003).
12. K. Kitamura, Y. Furukawa, K. Niwa, V. Gopalan and T. E. Mitchell, "Crystal growth and low coercive field 180° domain switching characteristics of stoichiometric $LiTaO_3$," Appl. Phys. Lett. **73**, 3073-3075 (1998).

#9711 - $15.00 USD Received 22 November 2005; revised 23 December 2005; accepted 29 December 2005

13. T. Hatanaka, K. Nakamura, T. Taniuchi, H. Ito, Y. Furukawa and K. Kitamura, "Quasi-phase-matched optical parametric oscillation with periodically poled stoichiometric $LiTaO_3$, " Opt. Lett. **25**, 651-653 (2000).
14. G. Marcus, A. Zigler, D. Eger, A. Bruner, and A. Englander, "Generation of a high-energy ultrawideband chirped source in periodically poled $LiTaO_3$," J. Opt. Soc. Am. B, **22**, 620-622 (2005).
15. M. Marangoni, R. Osellame, R. Ramponi, S. Takekawa, M. Nakamura, and K. Kitamura, "Reverse-proton-exchange in stoichiometric lithium tantalate," Opt. Express **12**,. 2754-2761 (2004).
16. S. Tanzilli, H. De Riedmatten, W. Tittel, H. Zbinden, P. Baldi, M. De Micheli, D.B. Ostrowsky, and N. Gisin, "Highly efficient photon-pair source using periodically poled lithium niobate waveguide," Electron. Lett. **37**, 26-27 (2001).
17. J. Olivares and J. M. Cabrera, "Guided modes with ordinary refractive index in proton exchanged $LiNbO_3$ waveguides," Appl. Phys. Lett. **62**, 2468-2471 (1993).
18. M. Nakamura, S. Higuchi, S. Takekawa, K. Terabe, Y. Furukawa and K. Kitamura, "Refractive Indices in Undoped and MgO-Doped Near-Stoichiometric $LiTaO_3$ Crystals," Jpn. J. Appl. Phys. **41**, 465-467 (2002).
19. M. Lobino, M. Marangoni, R. Ramponi, E. Cianci, V. Foglietti, S. Takekawa, M. Nakamura, K. Kitamura, "Optical-damage free guided second-harmonic-generation in 1% MgO-doped stoichiometric-lithium-tantalate," Opt. Lett., accepted for publication.

1. Introduction

In the early 90's, congruent lithium tantalate (LT) was a strong competitor of congruent lithium niobate (LN) in the fabrication of optical waveguides for frequency conversion devices, in particular for the realization of compact coherent sources in the blue region [1,2]. With respect to LN the main advantages were the wider range of transparency toward the ultraviolet region, the higher optical damage threshold, but, most of all, the possibility of achieving quasi-phase-matching by selective proton-exchange followed by rapid thermal annealing [3] (technique not applicable to LN). With the advent of the electric-field poling technique for ferroelectric domain reversal [4], the performances of LN waveguides started growing exponentially [5], because of the higher nonlinearity of the material, the availability of larger substrates and of well consolidated techniques for fabricating highly homogenous waveguides, either by proton-exchange [6] or by Ti: indiffusion [7]. LN waveguides became thus the leading choice for nonlinear applications, most of all in the field of all-optical devices for telecom applications [8,9] (for the duplication in the blue region, significant alternatives are also KTP [10] and micro-machined LN waveguides [11]).

The interest for LT has again increased in the past few years due to the development and optimization of the Chochralsky growth with stoichiometric composition [12]. With the addition of 1% MgO doping, the stoichiometric composition allows an optical damage threshold much higher than LN, which makes periodically-poled stoichiometric LT (PPSLT) an extremely interesting choice for nonlinear applications, like, e.g., optical parametric amplifiers and generators, frequency doublers, etc. [13,14]. In such works, however, only bulk configurations were used.

In this paper we present some of the first results that we obtained in the nonlinear regime in PPSLT waveguides fabricated by reverse-proton-exchange (RPE). Such technique was recently demonstrated to be suitable for the realization of high optical quality buried waveguides [15]. The attention is here focused on a particular waveguide design that allows nearly non-critical phase-matching conditions in a second harmonic generation process from telecom wavelengths. Such configuration, even if not optimized for the highest normalized efficiency, presents extremely interesting linear features as to fiber-mode matching and attenuation, which could be successfully exploited for the realization of, e.g., efficient single photon-pair light-sources [16].

2. Waveguides fabrication and linear characterization

A set of waveguides having widths from 6 to 10 μm were fabricated on a 25 mm long PPSLT sample with five periods ranging from 17.7 to 18.5 μm. The fabrication parameters are the

#9711 - $15.00 USD Received 22 November 2005; revised 23 December 2005; accepted 29 December 2005

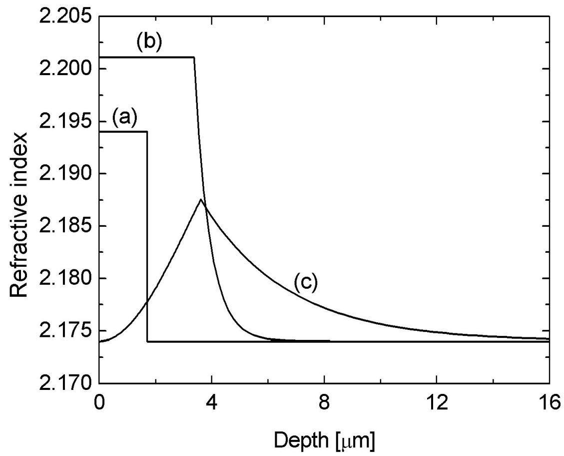

Fig. 1. Refractive index profile of the waveguide after proton-exchange (a), annealing (b) and reverse-exchange (c).

following: 1 h 47 m of proton exchange at 280° C in pure benzoic acid, 3 h of annealing at 350 °C in air, 25 h of reverse-exchange at 350° C in an euthectic melt of $LiNO_3$, KNO_3, and $NaNO_3$. Figure 1 shows the refractive index profile after each fabrication step, as determined by m-lines spectroscopy on the planar waveguide realized on the opposite side of the sample.

After proton-exchange the profile of the extraordinary refractive index (i.e., the only one increased by the proton-exchange process [17]) is step-like, with a 1.7 μm depth and a 0.02 index change. In such conditions the waveguide losses are quite high (> 1.2 dB/cm at λ=1.55 μm) and the nonlinearity of the material reduced by the high proton concentration. The subsequent three hours of annealing strongly modify both shape and dimensions of the refractive index profile, which can be roughly approximated by a step-exponential curve with a maximum index change of 0.027 and a full 1/e depth of 3.91 μm. In such conditions the waveguide supports two modes at λ=1.55 μm with asymmetric field profiles. With the reverse-exchange step, lithium ions diffuse from the euthectic melt inside the sample, and the

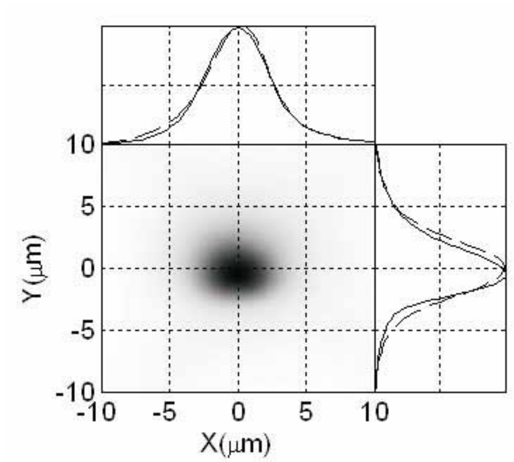

Fig. 2. Intensity profile of the fundamental mode at λ=1.55μm. Top and right boxes report respectively the horizontal and vertical cross-sections of the waveguide mode (solid lines) as compared to that of a fiber (dashed line).

#9711 - $15.00 USD Received 22 November 2005; revised 23 December 2005; accepted 29 December 2005

index profile reduces its area while becoming smoother on the surface side and enlarged on the substrate side. The resulting 1/e depth of the index profile is ~4.66 μm and the maximum index change roughly 0.013 (this value corresponds to the intersection between the step-exponential curve caused by the annealing process with a gaussian-like curve generated at the surface by the income of lithium ions, as described in detail in Ref. 15).

With the above fabrication and optical parameters all channel waveguides were found to be single-mode at λ=1.55 μm. The intensity profile of the mode of the 10 μm wide channel is reported in Fig. 2, together with its horizontal and vertical cross-sections (solid lines in the up and right boxes). Both sections are highly symmetric and very well matched to those of a standard fiber mode (dashed lines), so that coupling losses of only 0.08 dB are estimated. By directly measuring insertion losses in various channels, and by subtracting estimated coupling and Fresnel losses, we determined propagation losses ranging from 0.2 to 0.3 dB/cm, which is a quite satisfactory result.

3. Nonlinear characterization

As a pump laser source we employed a cw extended-cavity laser-diode with broad wavelength tunability and output power as high as 2.5 mW in the wavelength range used in the experiments (Agilent 81600 B). The emitted radiation was coupled into the waveguides by standard polarization maintaining fibre with a power penalty of ~0.6 dB, mostly due to Fresnel losses at the input facet of PPSLT. Tuning curves like that reported in Fig. 3 were obtained by measuring the second harmonic generation efficiency as a function of the fundamental wavelength. The curve, which refers to the 10 μm wide channel of the 18.3 μm poling period, presents a ~440 pm FWHM. By considering both material and waveguide dispersion (the former one being calculated from Sellmeier curves reported in Ref. 18, the second one from the above reported refractive index profile) this value corresponds to an

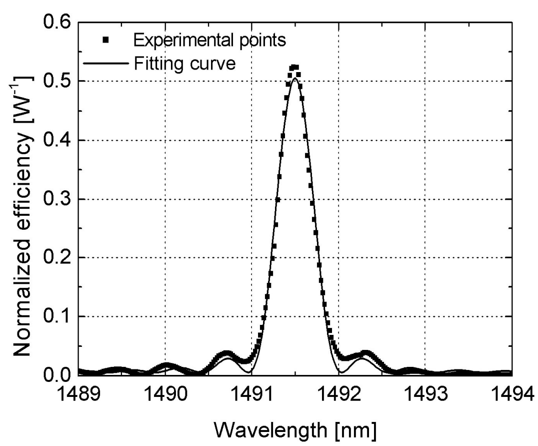

Fig. 3 Second harmonic generation efficiency normalized to the input pump power as a function of wavelength. The curve refers to a 10 μm wide channel and to a Λ = 18.3 μm poling period.

interaction length of ~25 mm, thus equal to the sample length. Slightly larger curves, up to 1000 pm in the worst cases, were obtained for smaller channels, indicating more critical phase-matching conditions. This was confirmed by the measurement of phase-matching wavelength versus channel width, reported in Fig. 4. For narrow channels phase-matching wavelength rapidly increases with channel-width, which implies a strong dependence of the phase-matching condition on waveguide geometry, and thus on waveguide homogeneity. For wider channels the homogeneity constraints are reduced, and a rather satisfactory non-critical

#9711 - $15.00 USD Received 22 November 2005; revised 23 December 2005; accepted 29 December 2005

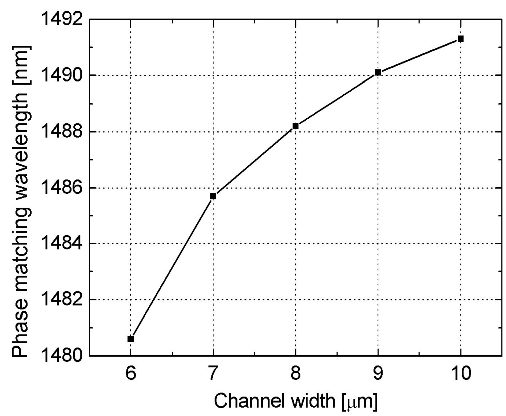

Fig. 4 Phase matching wavelength versus channel width.

phase-matching condition is achieved for the 10 μm width.

From the peak of the tuning curve a normalized second harmonic generation efficiency of 8.4 % $W^{-1}cm^{-2}$ was calculated. By taking into account that SLT exhibits at telecom wavelengths a nonlinear coefficient of 10.6 pm/V [19], this efficiency corresponds to a rather large interaction area, equal to 70 μm^2. The consistency of such result was verified by a direct measurement of the intensity profile of the second harmonic mode, which is reported in Fig. 5. The profile clearly corresponds to the TM_{00} mode and exhibits, as well as the fundamental mode, a highly symmetric behaviour. The numerical superposition of the profiles of Fig. 2 and Fig. 5 gives an effective interaction area of 80 μm^2, in good agreement with the expected value. This result attests that the waveguiding region exhibits full nonlinearity, which is not trivial if detrimental effects due to proton exchange are considered.

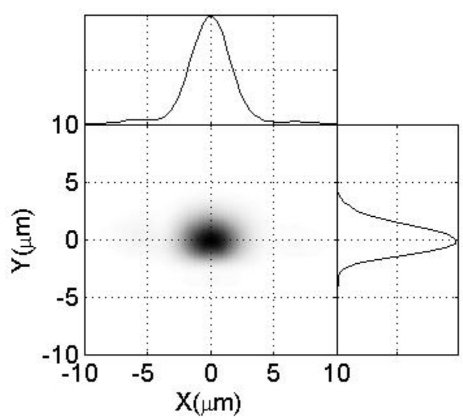

Fig. 5 Intensity profile of the second harmonic mode together with its horizontal (top box) and vertical (right box) cross-sections

5. Conclusions

High quality buried waveguides with nearly circular mode profiles at the fundamental and second harmonic wavelengths and with extremely low coupling and propagation losses have been fabricated by reverse-proton-exchange in PPSLT. The configuration here proposed provides the highest nonlinear interaction length reported up to now in LT waveguides, equal to 2.5 cm, further improvable with longer samples. Experimental data show that by the

#9711 - $15.00 USD Received 22 November 2005; revised 23 December 2005; accepted 29 December 2005

annealing and reverse-exchange processes the nonlinear coefficient of PPSLT is fully restored with respect to typical proton-exchanged waveguides. The waveguides obtained, although not designed for the highest possible conversion efficiency, are suitable for the realization of different devices such as efficient single photon-pair light-sources or nonlinear devices requiring a short-wavelength pump/signal field to be coupled. In the former case the extremely low coupling losses are far more important than high conversion efficiency, while in the latter case the excellent circularity of the waveguide modes prevents light to be coupled into undesired high-order modes.

Acknowledgments

The authors wish to acknowledge Prof. Kitamura and co-workers of the National Institute for Materials Science (Tsukuba – Japan) for kindly supplying the substrates. This study was partially supported by the FIRB project "Miniaturized Systems for Electronics and Photonics".

#9711 - $15.00 USD Received 22 November 2005; revised 23 December 2005; accepted 29 December 2005