High conversion efficiency single-pass second harmonic generation in a zinc-diffused periodically poled lithium niobate waveguide

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Abstract: We report a modified technique for the fabrication of zinc-diffused channel waveguides using z-cut electric-field periodically poled $LiNbO_3$. Unlike previous work, the diffusion was carried out using metallic zinc at atmospheric pressure. By optimizing the thermal diffusion parameters, channel waveguides that preserve the existing periodically poled domain structures, support both TE and TM modes, and enhance photorefractive damage resistance were obtained. Nonlinear characterisation of the channel waveguides was investigated via second harmonic generation of a 1552nm laser with a maximum conversion efficiency of $59\%W^{-1}cm^{-2}$ at 14.6ºC. Using a pulsed source a second harmonic conversion efficiency of 81% was achieved.

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OCIS codes: (160.3730) Lithium niobate; (190.4360) Nonlinear optics, devices; (230.7380) Waveguides, channeled

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References and links

1. A. M. Glass, "Photorefractive Effect," Opt. Eng. **17**, 470-479 (1978).
2. G. A. Magel, M. M. Fejer, and R. L. Byer, "Quasi-phase-matched second-harmonic generation of blue light in periodically poled $LiNbO_3$," Appl. Phys. Lett. **56,** 108-110 (1990).
3. Y. N. Korkishko, V. A. Fedorov, T. M. Morozova, F. Caccavale, F. Gonella, and F. Segato, "Reverse proton exchange for buried waveguides in $LiNbO_3$," J. Opt. Soc. Am. A **15**, 1838-1842 (1998).
4. M. L. Bortz, L. A. Eyres, and M. M. Fejer, "Depth profiling of the d_{33} nonlinear coefficient in annealed proton exchanged $LiNbO_3$ waveguides," App. Phys. Lett. **62**, 2012-2014 (1993).
5. M. H. Chou, I. Brener, M.M. Fejer, E. E. Chaban and S. B. Christman, "1.5-µm-Band Wavelength Conversion Based on Cascaded Second-Order Nonlinearity in $LiNbO_3$ Waveguides," IEEE Photon. Technol. Lett. **11**, 653-655 (1999).
6. P. J. Chandler, L. Zhang, and P. D. Townsend, "Double wave-guide in $LiNbO_3$ by ion-implantation," Appl. Phys. Lett. **55**, 1710-1712 (1989).
7. J. Amin, V.Pruneri, J. Webjörn, P. St. J. Russell, D.C. Hanna, J. S. Wilkinson, " Blue light generation in a periodically poled Ti: Lithium Niobate channel waveguide," Opt. Commun. **135**, 41-44 (1997).
8. G. Schreiber, H. Suche, Y. L. Lee, W. Grundkötter, V. Quiring, R. Ricken, W. Sohler, "Efficient Cascaded Difference Frequency Conversion in Periodically Poled Ti: Lithium Niobate Waveguides using Pulsed and CW Pumping," Appl. Phys. B **73**, 501-504 (2001).
9. W. M. Young, M. M. Fejer, M. J. F. Digonnet, A. F. Marshall, and R. S. Feigelson, "Fabrication, Characterization and Index Profile Modeling of High-Damage Resistance Zn-Diffused Waveguide in Congruent and MgO: Lithium Niobate," J. Lightwave Technol. **10**, 1238-1246 (1992).
10. Herreros and G. Lifante, "$LiNbO_3$ Optical Waveguides by Zn diffusion from Vapor Phase," Appl. Phys. Lett. **66,** 1449-1451 (1995).
11. R. C. Twu, C. C. Huang, and W. S. Wang, "Zn Indiffusion Waveguide Polarizer on Y-cut $LiNbO_3$ at 1.32-µm Wavelength," IEEE Photon. Technol. Lett. **12**, 161-163 (2000).
12. T. Suhara, T. Fujieda, M. Fujimura and H. Nishihara, "Fabrication Zn: Lithium Niobate Waveguides by Diffusing ZnO in Low Pressure Atmosphere," Jpn. J. Appl. Phys. **39,** L864-865 (2000).
13. R. Nevado, E. Cantelar, G. Lifante and F. Cusso, "Preservation of Periodically Poled Structures in Zn-Diffused Lithium Niobate Waveguides," Jpn. J. Appl. Phys. **39,** L488-L489 (2000).

#7284 - $15.00 USD Received 29 April 2005; revised 3 June 2005; accepted 10 June 2005

14. M. Fujimura, H. Ishizuki, T. Suhara and H. Nishihara, "Quasi-phasematched waveguide conversion in Zn-diffused $LiNbO_3$ waveguide," in Proceedings of Conference Lasers and Electro - Optics (CLEO/PR'01), ME1-5, Tech. Digest vol. I, pp. I96-97, Makuhari, July 15-19, (2001).
15. K. R. Parameswaran, J. R. Kurz, R. V. Roussev, M. M. Fejer, "Observation of 99% pump depletion in single-pass second-harmonic generation in a periodically poled lithium niobate waveguide," Opt. Lett. **27**, 43-45 (2002).
16. M. L. Bortz, S. J. Field, M. M. Fejer, D. W. Nam, R. G. Waarts, D. F. Welch, "Noncritical quasi-phase-matched second harmonic generation in an annealed proton-exchanged $LiNbO_3$ waveguide," IEEE J. Quantum. Electron. **30**, 2953-2960 (1994).
17. J. C. Campbell, "Coupling of fibers to Ti-diffused $LiNbO_3$ waveguides by butt-joining," Appl. Opt. **12**, 2037-2039 (1979)

Quasi-phase-matched wavelength conversion devices based on channel waveguides in periodically poled lithium niobate (PPLN) represent a means of achieving efficient compact laser sources at wavelengths not available in the traditional laser market. Potential applications of this technology lead towards specialised sources such as cw blue light generation for biomedical fluorescence microscopy and low-cost devices for telecommunications wavelength conversion. In recent years particular interest has been applied to the development of room temperature devices to eliminate the problems associated with photorefractive damage in this material [1,2]. A number of methods are currently employed for fabricating waveguides in PPLN, the most popular of which are annealed proton exchange (APE) [3,4,5], ion implantation [6], and titanium diffusion [7,8]. However, each of these well-developed techniques has some limits of applicability.

Annealed-proton-exchanged (APE) waveguides are formed in lithium niobate by an exchange of protons through a patterned mask with a heated bath of benzoic acid. As the temperatures required for this process is relatively low (350°C-400°C) [4], the waveguides are typically fabricated after the sample has been poled to provide a higher device yield. However, while APE can increase resistance to photorefractive damage, these waveguides only support extraordinary guided modes and often decrease the nonlinear coefficient of the material unless additional annealing steps are used [3].

Titanium-based waveguides are formed by depositing a metallic strip onto the surface of a lithium niobate substrate, which is then indiffused at temperatures around 1100°C [7]. The PPLN grating structure is not preserved under such high temperatures so poling must be performed after the waveguides are fabricated, where secondary effects such as lithium outdiffusion and surface poling can cause problems with domain uniformity [7,8] and often require the crystal to be re-polished. However, while the incorporation of titanium is known to increase photorefractive damage in PPLN, low-loss titanium-diffused waveguides that support both TE and TM modes and preserve nonlinearity to allow frequency doubling of 850nm have been demonstrated. [7]

A recently developed alternative to these techniques is that of zinc-indiffusion, an approach specifically developed to support both polarization modes and improve resistance to photorefractive damage in lithium niobate [9,10]. To date, the majority of zinc-based work has been applied towards low loss ($0.9dBcm^{-1}$) optical waveguides in unpoled $LiTaO_3$ and $LiNbO_3$ by zinc diffusion from the vapor phase [11,12]. This technique has been successfully applied to infrared electro-optic applications in y-cut substrates, [11] and also the fabrication of vapor-phase waveguides in y-cut Czochralski-grown PPLN where the existing periodic domain structure was preserved [13]. The main alternative to vapour phase diffusion is based on the thermal diffusion of a metallic zinc layer which is pre-deposited onto the crystal surface. While this route was successfully applied by Fujimura et al. [14] to create zinc waveguides in PPLN, it was determined that low-pressure diffusion was required to prevent unacceptable build-up of residue on the surface during the indiffusion stage and associated optical losses. However, in this paper we show that by carefully optimising the thickness of

#7284 - $15.00 USD
Received 29 April 2005; revised 3 June 2005; accepted 10 June 2005
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the deposited zinc layer it is possible to achieve high quality waveguides using a simplified thermal indiffusion process, without the additional complexity of low pressure processing.

To this end, this paper describes our technique for fabricating channel waveguides in z-cut PPLN by thermal indiffusion of a metallic zinc film. This approach allows us to combine the advantages of E-field poling with the relative simplicity and low processing temperature of thermally indiffused zinc from the metal phase, providing high fabrication yields. The subsequent waveguides support both TE and TM modes of propagation and enhance resistance to photorefractive damage. Here, the optimised diffusion conditions for single mode waveguides at 1550nm are presented and the nonlinearity of the waveguides investigated via generation of the second harmonic.

As a further demonstration of this technology, our waveguides have also been used to demonstrate high second harmonic conversion efficiency for light from a pulsed OPO source. PPLN waveguides formed by APE have previously been used to demonstrate 99% conversion efficiency [15]. This work used carefully tailored pulses produced by amplifying a narrow linewidth diode source in an EDFA chain to give 50ns pulses with a narrow linewidth allowing the use of a 6.45cm waveguide. This source had a peak power of around 20kW, and so allowed very high nonlinear drive. As discussed in Ref. [15], such high efficiency is much more difficult to achieve for a source with either Gaussian temporal or spatial profile due to the lower nonlinear drive in the rising and falling edges of the temporal pulse or the low power wings of the spatial pulse. In this paper we will show high conversion efficiency but with the use of lower peak power pulses in the picosecond regime, and with a much shorter waveguide.

Initial investigations into poling after channel formation were found to be problematic due to the presence of an electrically insulating lithium-outdiffused layer present on the +z face of the crystal, an effect similar to that found in titanium-diffused $LiNbO_3$. [7,8] The resulting PPLN gratings were poorly defined, and as such the following work was based on optimising low temperature thermal diffusion into E-field-poled substrates so avoiding distortion of the periodically inverted domain structure (Fig. 1).

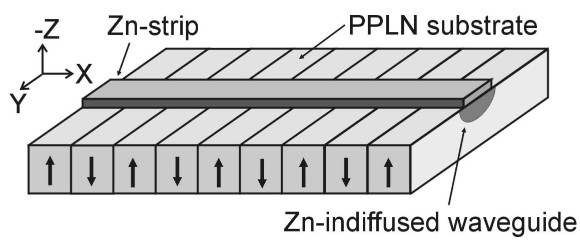

Fig. 1. A schematic representation of the zinc diffusion process in PPLN.

Production of the PPLN substrates used during this experiment began with 500µm-thick single domain z-cut lithium niobate crystals of ~15×30mm surface area. A photoresist pattern was deposited on the –z face of each sample by photolithography, and domain inversion was performed in the z-axis at room temperature by application of a single high-voltage pulse of ~11kV through liquid electrodes. In each substrate a set of gratings with periods ranging from 18.05µm to 18.60µm was fabricated, corresponding to the values required for frequency-doubling wavelengths of around 1550nm in the subsequent zinc-based waveguides.

After poling, a photolithographic pattern of open strips spaced 100µm apart and with various widths was applied to the existing gratings. As metallic zinc adheres poorly to the surface of $LiNbO_3$, [11] a 5nm-thick nickel film was deposited onto the surface of each patterned PPLN substrate, followed by a thicker zinc film. For the fabrication of single mode waveguides at 1550nm, several iterations of metal deposition were investigated and it was determined that the optimal deposited metallic zinc feature size is 5.6µm to 6.6µm wide with a layer thickness of 120nm. Thermal indiffusion of the zinc layer was performed in a covered platinum crucible in a high-temperature oven with a dry air atmosphere. Each substrate was heated at a rate of 6°C min^{-1} to a diffusion temperature of 930°C for 120 minutes, before allowing the sample to cool to room temperature, again at rate of 6°C min^{-1}. After waveguide fabrication, each device was diced and polished to a length of approximately 10mm. To verify preservation of the domain structure the gratings were revealed by etching in hydrofluoric acid, as shown in the photograph of Fig. 2.

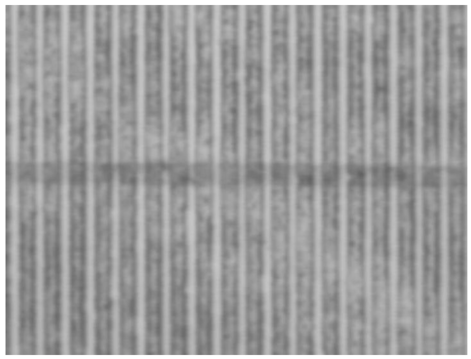

Fig. 2. A photograph of a 6μm wide zinc diffused waveguide (the dark horizontal stripe) in 10μm period PPLN after HF etching and the simulated mode profile of the SHG. As shown, the domain structure is preserved during the thermal indiffusion process.

The effective refractive index of the zinc indiffused waveguide was measured by prism coupling, giving a value of 2.2062 (TM00) for extraordinary polarization at 633nm wavelength. Based on this effective index, a simple rectangular waveguide model based on three step index sections was created to allow approximate second harmonic mode profiles to be simulated. The model coefficients were selected to match the experimental mode profiles and prism coupling data. Cutback was used to estimate an upper limit for the propagation loss in these waveguides of 0.8dBcm^{-1} at a wavelength of 1552.4nm. The cutback measurements were made using a single mode fibre launch to ensure reproducibility. The cutback approach is only of limited use in assessing low loss waveguides, but for the level of losses measured here, and the 2cm device length it provides a useful and robust way of rapidly quantifying the loss. Table 1 lists the propagation losses of waveguides formed under different conditions.

Table 1. The propagation loss of zinc indiffused waveguide

No.	Time (min)	Thickness of Zn (nm)	Diffusion Temp. (°C)	Width (μm)	Wavelength (nm)	Loss L_P (dB/cm)	Length (mm)
1	80	80	900	6.4	1552.4	1.2	20
2	80	120	930	6.4	1552.4	0.9	20
3	120	120	930	6.4	1552.4	0.85	20
4	120	150	930	6.4	1552.4	1.22	20
5	120	180	930	6.4	1552.4	1.3	20
6	120	200	930	6.4	1552.4	1.35	20

To test the nonlinear optical properties of the waveguides the second harmonic generation (SHG) characteristics of each grating was investigated using a single mode DFB laser diode with central wavelength of 1552.4nm and pigtailed polarization maintaining optical fiber. In each case the pump source was directly launched by butt-coupling the fiber to the end facet of

#7284 - $15.00 USD Received 29 April 2005; revised 3 June 2005; accepted 10 June 2005
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the waveguide, and the linear polarisation state of the laser was rotated at the fiber output so that it was parallel to the z axis of the device, allowing access to the material's largest nonlinear coefficient (d_{33}). The PPLN chip was mounted in a temperature controlled oven and transmitted light from the waveguide was collected using a 10× microscope objective. This objective was followed by an infrared filter that removed any pump light and the SHG power at 776.2nm was then measured on a power meter. It should be noted that for these experiments the end faces were polished but left uncoated, resulting in a 14% reflection loss at each surface.

As demonstrated in Fig. 3, temperature tuning of the PPLN chip allows selective wavelength conversion from the fundamental TM00 propagation mode of the pump laser to several distinct modes of propagation at 776.2nm. Here, the output power of the TM00, TM01, and TM02 SHG modes was individually measured with respect to temperature at the chosen grating period of 18.05µm. Similarly, the TM10, TM11, and TM02 SHG modes from a PPLN grating of 18.5µm period were also measured. Recorded dimensions of the 776.2nm SHG modes profiles are in qualitative agreement with our modelled mode profiles.

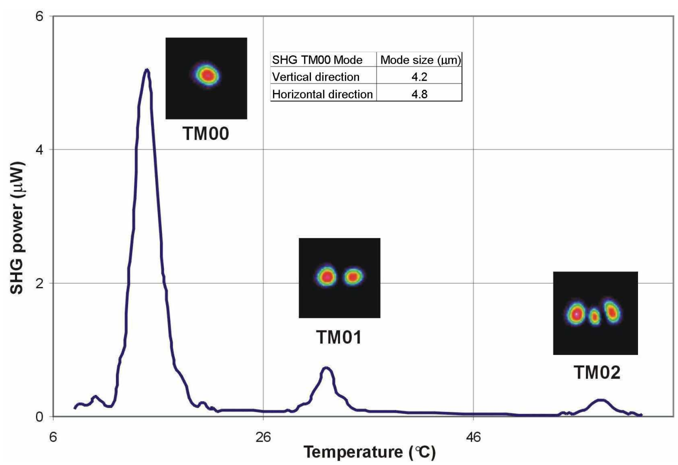

Fig. 3. A graph of SHG power versus QPM temperature for the first three supported modes of an 18.05µm period zinc-diffused PPLN waveguide.

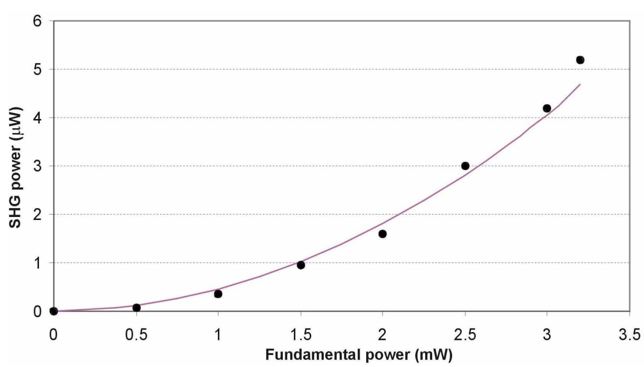

Fig. 4. A graph of SHG power versus pump power for an 18.05µm period zinc-diffused PPLN waveguide. The solid line represents the best quadratic fit.

Using the DFB laser diode, the maximum conversion efficiency measured in these devices was achieved by frequency doubling between the fundamental modes of the pump and SHG wavelengths in a 6.2µm wide zinc waveguide in an 18.05µm period PPLN grating at an operating temperature of 14.8°C. The graph of Fig. 4 shows the maximum external SHG power of 5.2μW, as measured for 3.2mW of internal pump power (calculated by measuring external output power and correcting for Fresnel reflections), corresponding to a maximum conversion efficiency of 59%$W^{-1}cm^{-2}$ in the 10mm-long waveguide. In comparison to prior techniques, this SHG conversion efficiency is similar to the 65%$W^{-1}cm^{-2}$ achieved in APE PPLN waveguides, [5] and much higher than the 9.4%$W^{-1}cm^{-2}$ achieved in titanium-indiffused waveguides. [8] As demonstrated by the graph of Fig. 3, the output power of the TM01, TM02, and higher-order modes is much lower due to the poor overlap with the fundamental mode of the pump source.

A value for the maximum theoretical SHG conversion efficiency in our waveguides was calculated based on a mathematical investigation of the overlap integral between the fundamental and second harmonic modes, as presented in Reference [16]. Based on our measured mode profiles, a Hermite-Gaussian fit as proposed by Campbell [17] was applied to the measured fundamental and second harmonic field distributions to represent normalised spatial mode profiles at each wavelength. From our experimental data the offset in peak power intensity between the fundamental and SHG fields was measured to be 1μm vertically (z-direction) and 0μm horizontally, such that the second harmonic was generated slightly offset to the fundamental mode. Subsequent analysis of the normalised modal overlap (between the Hermite-Gaussian fitted fundamental mode and the SHG mode) yields a predicted maximum SHG conversion efficiency of 177%$W^{-1}cm^{-2}$, a value larger than our measured result. This difference is attributed to the asymmetric nature of our real-life mode profiles with their larger offset between overlapping field intensities, and also the potential for local zinc-induced changes in the nonlinear coefficient. When operating for 1550nm doubling no evidence of photorefractive effect was seen.

To further investigate the waveguides under high peak power operation, we used a synchronously pumped optical parametric oscillator as a high peak power source at 1556nm running at 120MHz. Using this source with its higher peak power of 33.3W allows a much greater nonlinear drive. A shorter waveguide only 3.5mm long was fabricated to match the 1.2nm laser bandwidth, which is inherently much broader bandwidth than the cw DFB diode laser and has a near transform limited pulse lasting 5ps. Figure 5 shows the temperature tuning curve for this waveguide. Using the same definitions as used in Parameswaran [15] we measured 20mW of fundamental output away from phase matching, and 16.2mW of second harmonic at peak phase matching, which corresponds to a power conversion efficiency of 81%. Given the Gaussian temporal profile of the OPO output at 1556nm this represents an extremely high nonlinear conversion.

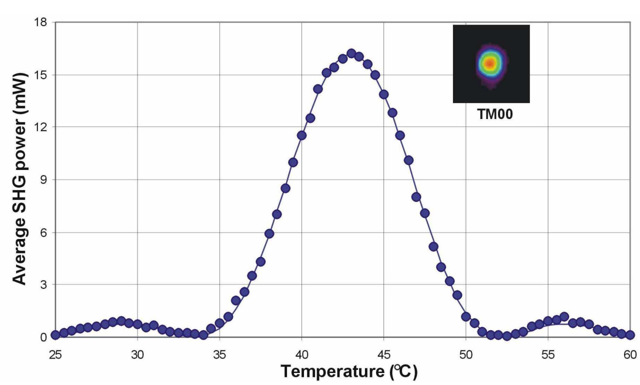

Fig. 5. SHG power vs. QPM temperature for PPLN waveguide (period=18.05μm) under high nonlinear drive conditions, the solid line corresponds to a sinc-square function

#7284 - $15.00 USD
Received 29 April 2005; revised 3 June 2005; accepted 10 June 2005
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In conclusion, we have demonstrated the first atmospheric diffusion process for the fabrication of channel waveguides in electric-field poled z-cut PPLN by the diffusion of a metallic zinc film in dry air. A high-yield process for single-mode 1550nm waveguides in pre-poled PPLN substrates has been described, and the periodically inverted domain structure demonstrated to survive the thermal diffusion processes. A SHG conversion efficiency of $59\%W^{-1}cm^{-2}$ was achieved in a 10mm-long waveguide and temperature tuning allowed investigation of individual modes of the second harmonic. Using a short pulse source and an appropriately short waveguide we achieved 81% second harmonic generation efficiency. Based on these encouraging results, shorter period devices for the generation of visible wavelengths at room temperature are currently being investigated.

Acknowledgments

This work was supported by the EPSRC, INTAS and NSF.

Received 29 April 2005; revised 3 June 2005; accepted 10 June 2005
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