3061

Guided-Wave Second Harmonic Generation in Hexagonally Poled RPE:LiNbO$_3$

K. Gallo, C. Codemard, C.B.E. Gawith, N.G. Broderick, P.G.R. Smith, J. Nilsson and D.J. Richardson
Optoelectronics Research Centre, University of Southampton, SO17 1BJ, United Kingdom, kag@orc.soton.ac.uk

Buried waveguides fabricated by reverse proton exchange (RPE) have recently allowed the demonstration of the highest Second Harmonic Generation (SHG) efficiency reported to date in 1D Periodically poled LiNbO$_3$ (PPLN) [1] and appear extremely promising for practical applications of $\chi^{(2)}$ nonlinearities. In this communication, we report on efficient SHG at telecom wavelengths in an optimised buried waveguide made by RPE in 2D Hexagonally poled LiNbO$_3$ (HexLN). We demonstrate an RPE:HexLN device (the integrated version of the configuration of Ref.[2]) allowing the simultaneous generation of a pair of guided SH waves by means of two concurrent $TM_0(\omega)+TM_0(\omega)\rightarrow TM_0(2\omega)$ processes, quasi-phase-matched by different reciprocal lattice vectors of the HexLN pattern. A full characterisation of the angular and spectral SHG response of the RPE:HexLN device provides us also with additional information on the linear properties of the buried waveguide, difficult to determine via conventional linear measurements.

Fabrication - We fabricated the HexLN crystal (period $\Lambda = 16.4\mu m$) by conventional electric field poling. A detail of the 18mm-long and 8mm-wide domain pattern is shown in Fig.1. The HexLN was proton exchanged in benzoic acid at 170°C to a depth of 1.39μm, then annealed to produce a waveguide with a 1/e depth $d_a = 2.78$ μm and an index increase $\Delta n = 0.086$ (measured at 633 nm). Finally, the slab was reverse proton exchanged for 28 hours in a LiNO$_3$:NaNO$_3$:KNO$_3$ melt at 320°.

Experiments - To characterise the SHG response of the HexLN slab we employed an all-fibre source, consisting of a directly modulated tunable laser, amplified in an EDFA whose output was time-gated by an AOM (few ns pulses, rep-rates: 1–100 kHz) and finally amplified by an Er-Yb stage. The infrared (λ_ω = 1530 –1570 nm) pulses were free-space coupled into the slab waveguide via a cylindrical lens (f = 20 cm) and a 10x objective (acting in a telescope configuration to provide a weaker focusing in the lateral dimension). The waveguide was single-mode (TM$_0$) at the fundamental (FF) wavelength. We first studied the SHG configuration sketched in Fig.1*a*, in which two symmetric SH TM$_0$ waves are generated via G_{10} and G_{-10} by a FF mode propagating along a symmetry axis (*x*) of the HexLN pattern. Fig.1 shows the external SH average power as a function of the FF input for this case. The dots are the experimental data, while the solid line is the result of numerical simulations (including the effects of: propagation losses, FF pulse shape and coupling efficiencies). The fit yields an intrinsic efficiency $\eta_{nor} = 0.2\%/Wcm^2$ (corresponding to our experimental input beam waist w=203μm), one order of magnitude higher than previous results [3] and close to the theoretical value (1% /Wcm^2, for a perfect HexLN and no diffraction in the lateral dimension). We also analysed the response of the HexLN device for the non-symmetric case, in which the two SHG processes, quasi-phase-matched by G_{10} and G_{-10}, respectively, occur at two distinct wavelengths. By measuring the SHG wavelength tuning curves for different FF input angles, we could trace the variation of the phase-matching wavelengths for both SHG processes (fig.2). Through numerical fits on these data (solid lines in fig.2) we could also evaluate the refractive index profile of the RPE waveguide (estimated RPE depth $x_0 = 3.4$ μm).

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[2] N.G. Broderick, G.W. Ross, H.L. Offerhaus, D.J. Richardson, D.C. Hanna, *Phys. Rev. Lett.* **84**, 4345 (2000).
[3] K. Gallo, R.T. Bratfalean, A.C. Peacock, N.G. Broderick, C.B.E. Gawith, L. Ming, P.G.R. Smith, D.J. Richardson, *Electron. Lett.* **39**, 75 (2003).

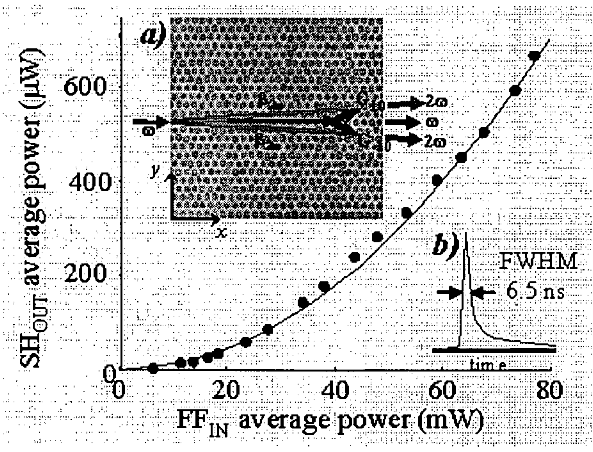

Fig. 1: *SH output versus FF input average powers (T=84.7°C, λ_{FF} = 1550.1 nm, rep-rate = 65 kHz). a) image of the HexLN pattern together with a sketch of the geometry for the symmetric SHG case; b) shape of the FF pulses.*

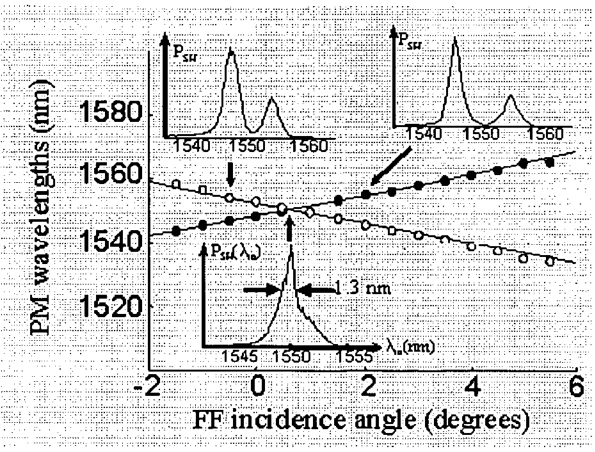

Fig. 2: *Measured phase-matching wavelengths for SHG via G_{10}(o) and G_{-10} (•) as a function of the FF input angle. Solid lines: simulations for a slab buried at a depth of 3.4μm. The plots show some measured SHG tuning curves.*