BLUE LIGHT GENERATION IN A PERIODICALLY POLED Ti:LiNbO$_3$ CHANNEL WAVEGUIDE

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Abstract: We report the first realisation of periodic domain inversion by electric-field poling in Ti:LiNbO$_3$ waveguides, for quasi-phase-matching (QPM) applications. Using a tunable Ti:Al$_2$O$_3$ laser we demonstrate guided blue light generation in a third-order QPM interaction.

I. INTRODUCTION

Second harmonic generation (SHG) by quasi-phasematching (QPM) in $LiNbO_3$, via periodic modulation of the non-linear coefficient, provides an attractive route for the realisation of blue and green light sources with several mW of output power. Electric-field poling has recently been used extensively for periodic domain reversal in ferroelectric materials, and hence modulation of the nonlinear coefficient which follows the sign of the spontaneous polarisation. This technique allows the use of the large d_{33} coefficient and provides deep, laminar domain structures with high potential conversion efficiencies. Several devices have been demonstrated using this technique for QPM-SHG from IR wavelengths to the visible, both in bulk geometries [1,2], and in waveguide structures[3,4]. However, as with most other waveguide QPM-SHG devices demonstrated thus far[5], the waveguides in Refs[3,4] were fabricated using the annealed proton exchange technique. The only demonstration of periodic domain inversion for QPM-SHG in a $Ti:LiNbO_3$ waveguide to date has been that by Webjörn *et al*[6], using a periodically segmented waveguide. The domain inversion in this case was achieved through outdiffusion between the patterned Ti segments. However, the conversion efficiency obtained in this experiment was 0.1%/W.cm^2, much smaller than that predicted by theory, possibly due to the domains being too shallow to allow a good overlap with the optical modes. Extension of electric-field poling to Ti-indiffused waveguides would circumvent this problem by providing deep domains, hence allowing better interaction with the guided modes. Electric-field poled $Ti:LiNbO_3$ waveguides would also provide additional design options over those available with proton-exchanged waveguides, such as allowing the use of both the extraordinary and ordinary waves for frequency conversion, and offering opportunities for active guides doped with rare-earths. In this paper we demonstrate, for the first time to our knowledge, blue light generation by QPM in an electric-field poled Ti:LiNbO$_3$ channel waveguide.

II. FABRICATION

A 0.2mm thick piece of Z-cut LiNbO$_3$ was used for the fabrication of the waveguide device. Channel waveguides, ranging in width from 3μm to 16μm in 1μm steps, were defined in a photoresist mask on the -Z face, with the guides oriented parallel to the X-axis. A 95nm layer of Ti was deposited on the surface and, following lift-off, diffused into the substrate at 1005°C over a period of 9 hours. Following this, 50μm of material was polished off the +Z face in order to remove a thin domain-inverted layer caused by outdiffusion of Li$_2$O during the high-temperature waveguide fabrication process. Next, a photoresist pattern with a period of 9μm and a duty cycle of 33% (3μm linewidth) was prepared on the -Z face of the sample, oriented perpendicular to the waveguides. This period was chosen as suitable for third-order QPM frequency-doubling to the blue from an IR wavelength of approximately 850nm. The poling was achieved by applying 4 pulses of ~3kV and ~300ms duration via liquid electrodes, as described previously[1]. Figure 1 shows the -Z face of a small part of the sample, etched in a mixture of HF and HNO$_3$. The photograph shows a 10μm wide waveguide, with evidence of non-uniformity of the grating, including random fluctuations in the domain wall positions within the waveguide. Furthermore, the final grating structure obtained in the waveguides had, on average over the complete interaction length, a duty cycle between 60% and 80%. The occurence of this non-optimal mark/space ratio requires further investigation to allow accurate control of device parameters. The waveguide endfaces were then polished, yielding 5mm long guides, periodically poled along the entire length.

III. OPTICAL CHARACTERISATION

A tunable Ti:Al_2O_3 laser was used for the characterisation of SHG from the waveguides. In this initial study we investigated blue light generation from a 6μm wide guide. Fig. 2 shows the third order SH output, which emerged entirely from the waveguide, as a function of the fundamental wavelength. The fundamental light beam in this case was polarised along the *z*-direction, ie TM polarised, producing an interaction with the d_{33} coefficient. As shown in the figure, conversion was achieved from the TM_{00} mode at the fundamental frequency to the TM_{00} and TM_{10} modes at the SH frequency. It was noticed that, for the same input power, the conversion efficiency to the second order harmonic mode was higher than that to the first order. We believe this to be due to a nonuniformity in the grating across the waveguide over a substantial part of the device length, as revealed through close inspection of the device, so that the second order mode interacts with the fundamental over a QPM structure which has a duty cycle closer to that required for optimum conversion efficiency in third order QPM. Moreover, there may be a reduced nonlinearity near the surface, due to the diffusion process, and variations in the index profile along the length of the waveguide, which would have a strong detrimental effect on the coupling to the TM_{00} mode. The effect of index variations is also evident in the difference in shape of the phase matching curves for the first and second order mode interactions. The phase matching curve for the $TM^{\omega}_{00} \rightarrow TM^{2\omega}_{00}$ interaction is centred at ~845nm, in good agreement with the calculated wavelength using dispersion relations for Ti:$LiNbO_3$ waveguides[7]. The curve however shows a FWHM bandwidth of ~0.25nm, twice that calculated from theory. This could be caused either by the irregular grating period or the above mentioned variation in effective index along the guide, due to inhomogeneities in the waveguide[8,9]. Fig. 3 shows the measured blue power in the fundamental mode of the harmonic frequency as a function of the coupled fundamental power at ~845nm, the line in the figure being the best quadratic fit to the experimental points. The maximum power obtained in the blue was 7.9μW for a coupled power of 45mW, giving a conversion efficiency of 1.6%/W.cm^2. The conversion efficiency in this non-optimised demonstration device is more than one order of magnitude lower than that expected from theory. This, as mentioned above, is believed to be due to the grating mark/space ratio not being ideal, non-perfect axial and transverse uniformity of the grating, non-optimised overlap between the interacting modes and inhomogeneities in the effective index.

The experimental points in Fig. 3 do not exactly follow a quadratic dependence, indicating the presence of photorefractive damage. Although periodic poling has been observed to increase the photorefractive damage threshold of $LiNbO_3$[1], Goldberg *et al* have recently observed damage effects at room temperature in their SHG experiments[2]. These were attributed largely to a non-ideal grating structure, which would also apply to our waveguide. At coupled fundamental powers greater than 45mW, the photorefractive damage was even more evident, with the blue output radiation spreading along the Z-axis. No attempt was made, in this initial experiment, to heat the sample and thereby anneal the damage. However,it is expected that it may be possible to reduce the photorefractive damage in periodically poled $Ti:LiNbO_3$ waveguides by moving to a period smaller than the mode size in the waveguide and ensuring that the domain structures are continuous and well defined. Using a period smaller than the mode size would enable a better compensation of the accumulated charges at the top and bottom of the beam profile[10]. These charges have opposite signs in adjacent domains as the photogalvanic current, which produces this charge transport across the beam, follows the direction of the Z-axis. The resulting transverse electric field component, and therefore the induced refractive index change via the electro-optic effect, would thus be reduced.

Finally, the polarisation of the input mode at the fundamental wavelength was rotated by 90°, so that the guides were excited in the TE polarisation, and an interaction was made with the d_{31} coefficient. The phase matching curve for the $TE^{\omega}_{00} \rightarrow TM^{2\omega}_{10}$ interaction, centred at 876nm, is shown in Fig. 4. The theoretically predicted wavelength for conversion to the first order SH mode is ~884nm, which was outside the tuning range of our laser. The experiment however demonstrates the versatility of poled Ti:LiNbO$_3$ waveguides in terms of accessibility to different wavelengths using the same waveguide. Moreover, using the ordinary polarisation for a given order of QPM-SHG for a given blue wavelength would require a longer period of domain reversal than needed for the extraordinary polarisation, alleviating some of the problems encountered in fabricating short periods. Frequency conversion using the d_{31} coefficient is less efficient ($d_{31} \sim 0.17 d_{33}$) but may be important for interactions which involve very short pulses[11], as the group velocity mismatch between interacting fields at different frequencies is reduced in this polarisation scheme, due to the lower dispersion. This makes the effective pulse interaction length longer, thus maintaining a good $d_{eff} \cdot l_{eff}$ product. Possibilities for RE-doped waveguide lasers in LiNbO$_3$ can also be extended, as the lasing signal in these waveguides may be in the ordinary(σ) polarisation.

IV. CONCLUSIONS

We have demonstrated, for the first time to our knowledge, periodic poling in a Ti:LiNbO$_3$ channel waveguide using electric-field techniques, and generated blue light via third order QPM. Further work is in progress to optimise the domain uniformity and modal overlaps within the waveguide, and achieve control over the resulting mark/space ratio. With these optimisations, and in particular by using a first order QPM interaction, significant increases in conversion efficiencies are expected. Moreover, we have recently demonstrated periodic poling in a Nd-diffused $LiNbO_3$ substrate[12] and also in a Tm-diffused $Ti:LiNbO_3$ waveguide[13], and intend to combine RE-diffusion and poling in Ti-indiffused waveguides for intra-cavity frequency doubling within a waveguide laser.

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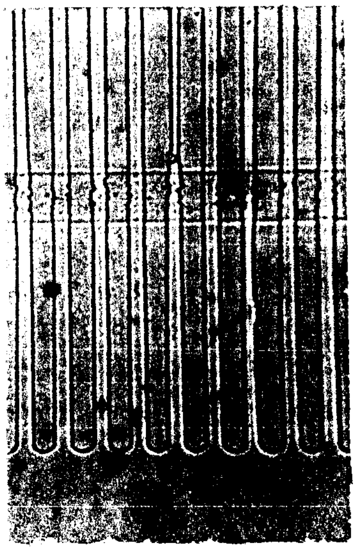
Figure Captions:

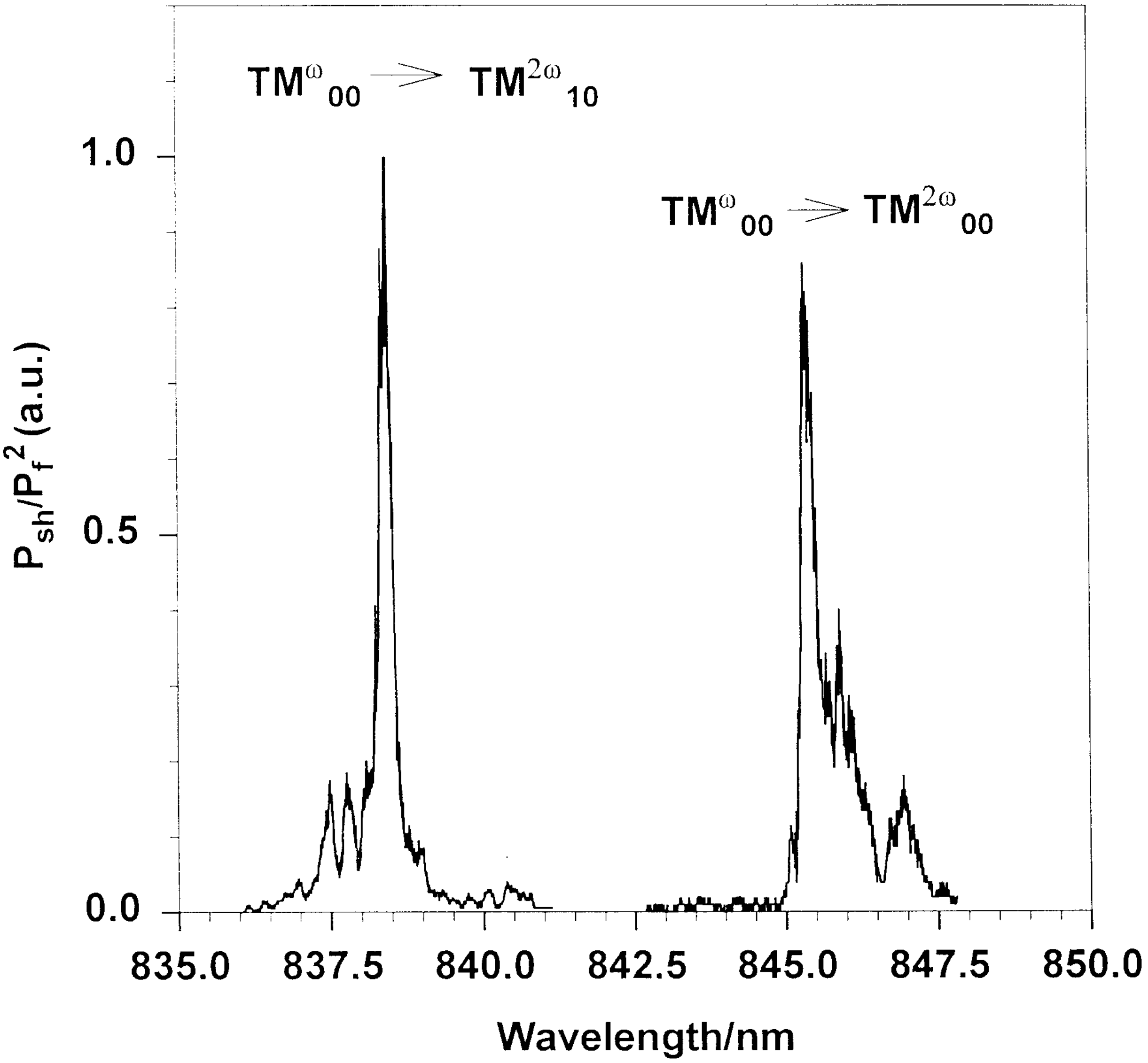
Fig 1. Etched -Z face of a section of the sample, showing a 10μm wide waveguide along the X-axis. The non-uniform domains within the waveguide are clearly visible.

Fig 2. Guided second harmonic generated power normalised to the launched pump power, as a function of the fundamental wavelength. The phase matching wavelength in the bulk was found to be ~834nm.

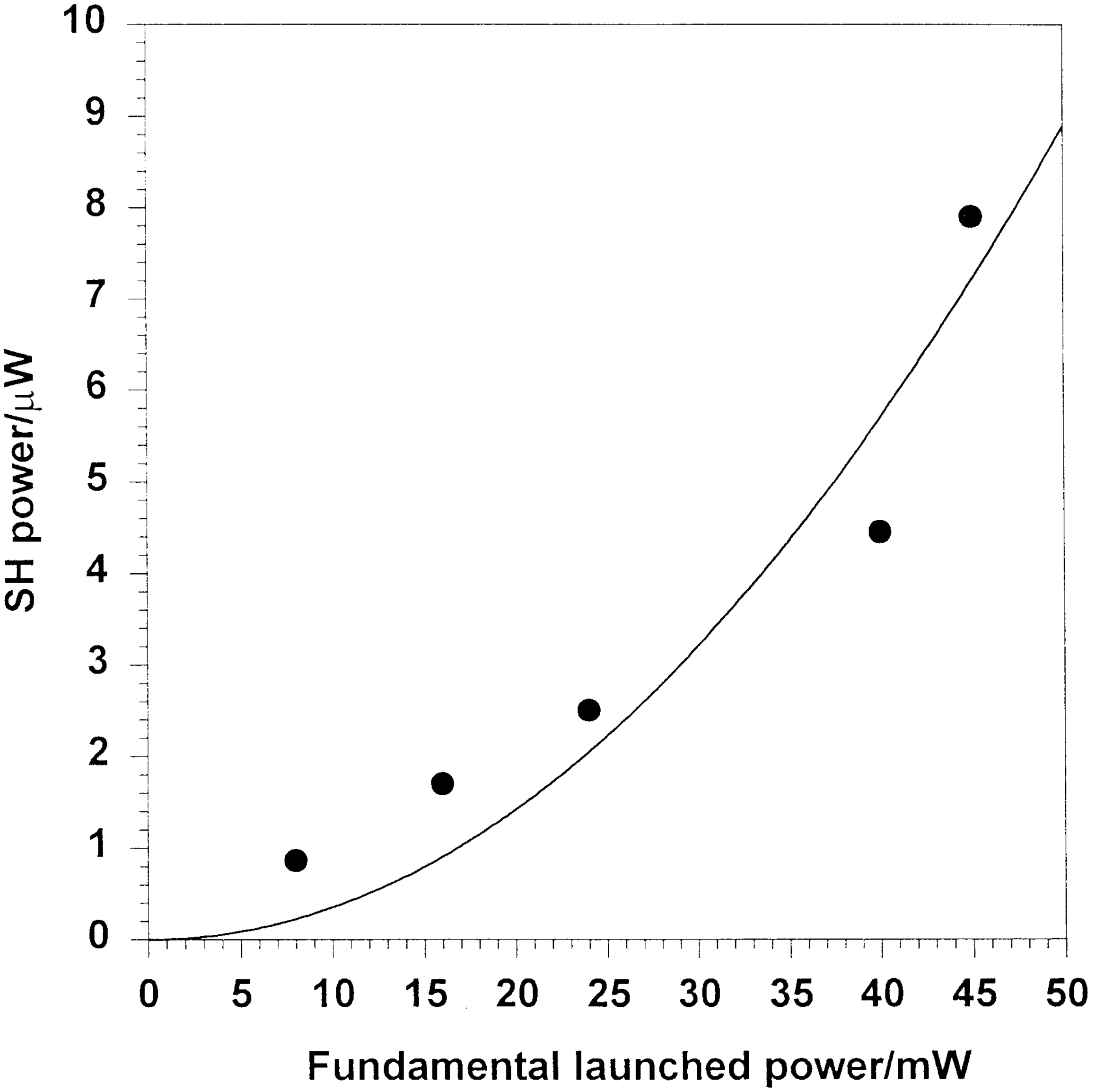
Fig 3. Second harmonic generated power as a function of the launched pump power. Note that the SHG power is that detected in the fundamental SHG mode at ~422.5nm. The solid line is the best quadratic fit to the measured data points.

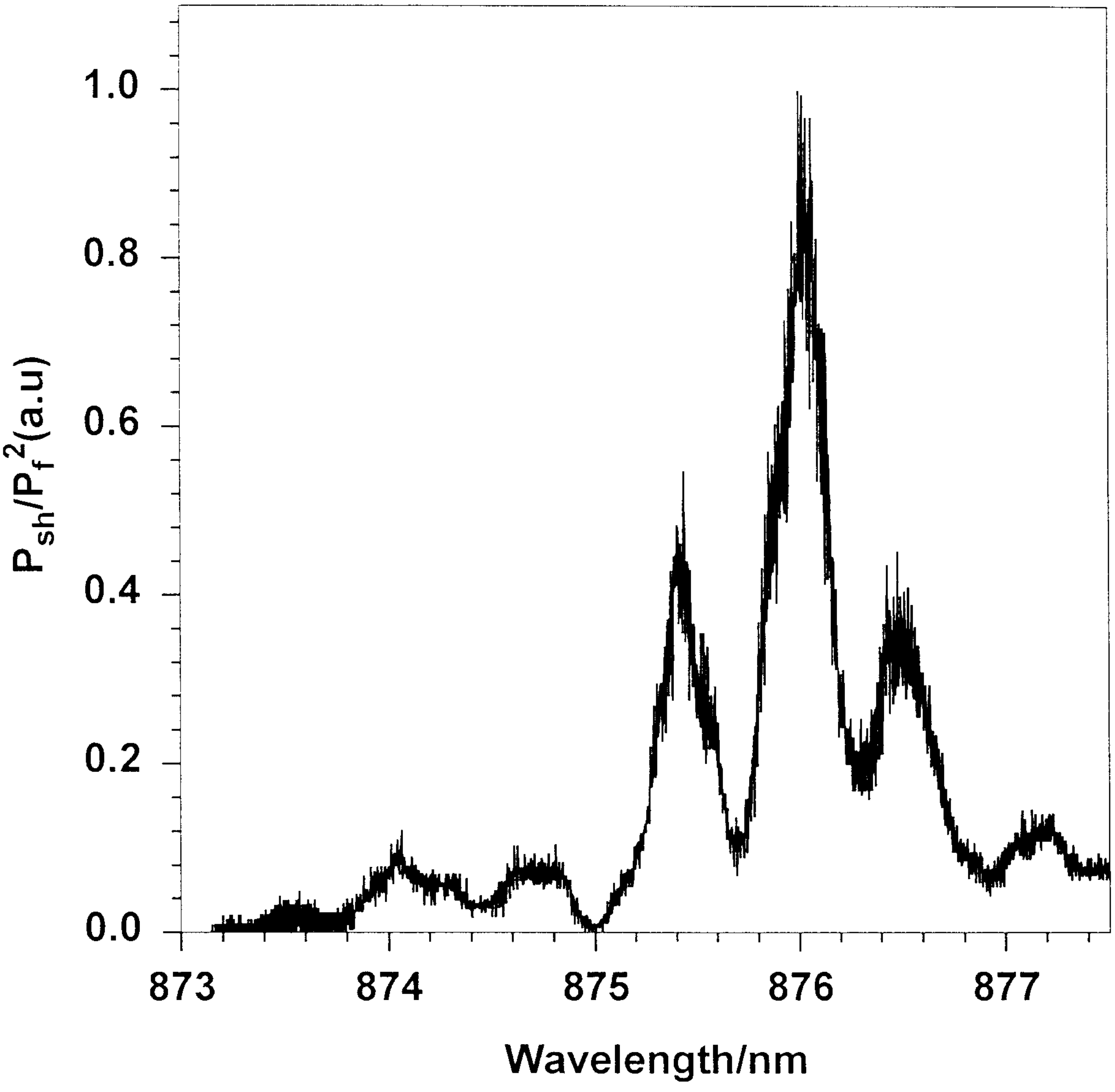
Fig. 4 Phase matching curve for the interaction of the fundamental mode in the TE polarisation to the second order mode of the second harmonic in the TM polarisation ($TE^{\omega}_{00} \rightarrow TM^{2\omega}_{10}$).





$TM^{\omega}_{00} \rightarrow TM^{2\omega}_{10}$
$TM^{\omega}_{00} \rightarrow TM^{2\omega}_{00}$
P_{sh}/P_f^2 (a.u.)
1.0
0.5
0.0
835.0
837.5
840.0
842.5
845.0
847.5
850.0
Wavelength/nm


SH power/μW
0
1
2
3
4
5
6
7
8
9
10
0
5
10
15
20
25
30
35
40
45
50
Fundamental launched power/mW



P_{sh}/P_f^2(a.u)
0.0
0.2
0.4
0.6
0.8
1.0
873
874
875
876
877
Wavelength/nm