QUASIPHASE-MATCHED SECOND HARMONIC GENERATION OF BLUE LIGHT IN ELECTRICALLY PERIODICALLY-POLED LITHIUM TANTALATE WAVEGUIDES

Indexing terms: Harmonic generation, Waveguides, Light sources

Blue light was generated at room temperature by quasiphase-matched second harmonic generation in planar and channel lithium tantalate (LiTaO$_3$) annealed proton exchange waveguides using the d_{33} nonlinear coefficient. Alternating ferroelectric domains for third order quasiphase matching were created by poling the substrates with a periodic electric field.

Introduction: The demand for sources of coherent blue light with milliwatt output powers has stimulated much research activity in guided-wave devices for second harmonic generation (SHG). Waveguides can maintain high optical intensities over considerable interaction lengths, resulting in high SHG efficiencies.[1]

LiTaO$_3$, an isomorph of LiNbO$_3$, is a positive uniaxial crystal that is produced in large quantity for surface acoustic wave (SAW) devices. It is reported to be 30 times more resistant to photorefractive damage than LiNbO$_3$,[2] and has relatively large nonlinear coefficients ($d_{33}(\text{LiTaO}_3) = 26\,\text{pm/V} \simeq 0{\cdot}75 d_{33}(\text{LiNbO}_3)$).[3] The crystal, however, lacks enough birefringence to phase match SHG of visible radiation.

To address the inability of materials to phase match birefringently, quasiphase-matching (QPM) has been used for SHG of visible radiation in LiNbO$_3$,[4,5] polymer,[6] KTiOPO$_4$,[7] and most recently, LiTaO$_3$ waveguides.[8–11] Quasiphase matching can be accomplished through the reversal of the sign of the nonlinear coefficient at odd multiples of the coherence length.[12] As in LiNbO$_3$, the relative signs of the nonlinear coefficients in LiTaO$_3$ are linked to the orientation of the ferroelectric spontaneous polarisation, and can thus be patterned by control of the spatial distribution of ferroelectric domains. Periodically-poled LiTaO$_3$ has been fabricated in bulk form using Czochralski growth,[13] and in wafer form using patterned proton exchange followed by an anneal,[9–11,14] and periodic electric poling fields.[8,15]* This Letter reports blue light generated by quasiphase-matched SHG in electrically periodically-poled LiTaO$_3$ planar and channel waveguides.

Fabrication: To pole the surface of a substrate, a spatially periodic electric field was applied with interdigital electrodes while heating the LiTaO$_3$ sample to just below the Curie temperature, T_C, ~610°C. A poling period of 14 μm was chosen to accomplish third order QPM of SHG of 450 nm radiation, working from a Sellmeier equation fitted to the bulk refractive index data for LiTaO$_3$.[16]† Interdigital electrodes were fabricated on the +Z face of a Z-cut, SAW-grade LiTaO$_3$ wafer[18] using liftoff lithography. Each interdigital electrode was made up of 3·5 μm wide fingers, parallel to the Y axis, spaced every 14 μm, and consisting of a 200 nm thick Au layer with a 5 nm thick Ti adhesion layer. The patterned region extended 1 mm in the X direction and 2 mm in the Y direction. For poling, the sample was heated to 600°C and a voltage of about 1·4 V was applied between the electrodes for a 10 min period as the sample was cooled by approximately 5 K. During this time the poling current decreased from about 8 μA/finger to 3·5 μA/finger. After poling, the Au electrodes were removed in an iodine solution. The surface corrugation on the Z face caused by the electrodes during the poling process was measured with a surface profilometer to be about 20 nm. Fig. 1*a* shows a Y face of a sample poled below T_C that was polished and then etched in HF to reveal the periodic ferroelectric domain structure. Deeper domains can be obtained by applying the poling fields at temperatures above T_C, as shown in Fig. 1*b*, but the surface corrugation arising from the electrodes is more significant.

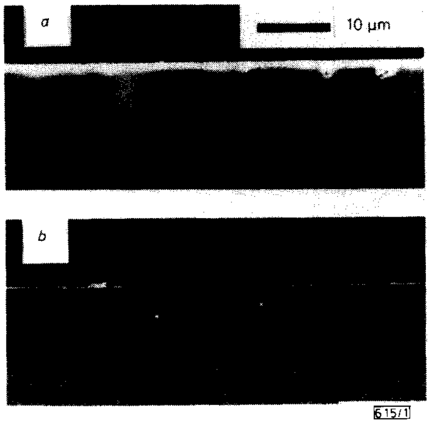

Fig. 1 *Scanning electron micrographs of cross-sections of periodically reversed domains in LiTaO$_3$ produced by electrical poling*

$\text{TM}_0^{\omega} \rightarrow \text{TM}_0^{2\omega}$
a ~600°C (below T_C)
b ~650°C (above T_C)

After poling the substrates, we fabricated planar and channel waveguide samples using the annealed proton exchange process.[19] The planar sample was exchanged in pure benzoic acid at 200°C for 4 h and then annealed in a flowing oxygen atmosphere at 333°C for 5 h. The mask for the channel waveguides was formed by first sputtering 200 nm of SiO$_2$ onto the poled surface of the sample. Channels parallel to the X axis with widths in the range 3–10 μm were then formed in the SiO$_2$ film by photolithography and wet etching. The sample was exchanged in pure benzoic acid at 200°C for 4 h. Following the exchange, the SiO$_2$ mask was etched away and the sample was annealed in a flowing oxygen atmosphere at 333°C for 10 h.

Experiments: For the SHG experiments, a CW tunable Ti : Al$_2$O$_3$ laser was used as the source for the fundamental radiation at $\lambda \simeq 0{\cdot}9\,\mu$m. In both planar and channel waveguide samples the waveguides supported one mode at the fundamental wavelength and two depth modes at the harmonic wavelength. All the observed infra-red and blue modes were TM-polarised, consistent with the guiding properties of APE waveguides and nonlinear optical interactions using the d_{33} nonlinear coefficient. To measure the wavelength tuning bandwidths, lock-in detection was used to measure the harmonic power and a wavemeter was used to measure the wavelength of the Ti : Al$_2$O$_3$ laser.

In the experiments with the planar device, rutile prisms were used for input and output coupling. A lens with a focal length of 10 cm was placed before the input prism to provide focusing in the plane of the waveguide. Frequency doubling into both the TM$_0$ and TM$_1$ blue modes was observed, where the TM$_1$ interaction had the higher efficiency. With 20·8 mW of power at 905 nm measured at the output, we observed the generation of 7·5 nW of 453 nm radiation in the TM$_1$ mode. Fig. 2*a* displays the measured wavelength tuning curve for doubling into the TM$_0$ mode. The width of the tuning curve for the TM$_1$ mode was identical.

For characterisation of the channel sample, input and output coupling was achieved with microscope objectives. Channels with a width of 10 μm were found to have the highest conversion efficiency. Frequency doubling into the TM$_{00}$ and TM$_{10}$ blue modes occurred, where the TM$_{00}$ interaction had the higher efficiency. Fig. 2*b* displays the measured wavelength tuning curve for doubling into both modes. With 41 mW of CW power at 916 nm measured at the output, we observed the generation of 1·3 μW of 458 mm radiation.

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* Periodic electric poling has been used in fibres: KASHYAP, R.: 'Phase-matched second harmonic generation in periodically poled optical fibres', *Appl. Phys. Lett.*, 1991, **58**, (12), pp. 1233–1235

† The data were fitted to a Sellmeier equation of the form $n^2 = a_1 + a_2/(\lambda^2 - a_3^2) - a_4 \lambda^2$, where, for n_e, $a_1 = 4{\cdot}529$, $a_2 = 0{\cdot}084$, $a_3 = 0{\cdot}203$, and $a_4 = 0{\cdot}0238$, and for n_0, $a_1 = 4{\cdot}512$, $a_2 = 0{\cdot}085$, $a_3 = 0{\cdot}199$, and $a_4 = 0{\cdot}0239$.

Discussion: Using the bulk index data for $LiTaO_3$, the theoretical wavelength tuning bandwidth for frequency doubling of 0·9 μm radiation is calculated to be 1·2 nm . mm. Thus the measured wavelength tuning curves for the planar and channel devices shown in Fig. 2 imply effective interaction lengths of 1 mm, in agreement with the 1 mm long gratings used in the devices. Together with the measured powers presented above, the 1 mm interaction length results in normalised conversion efficiencies of about 0·2%/W . cm^2 for the planar device and 8%/W . cm^2 for the channel device.

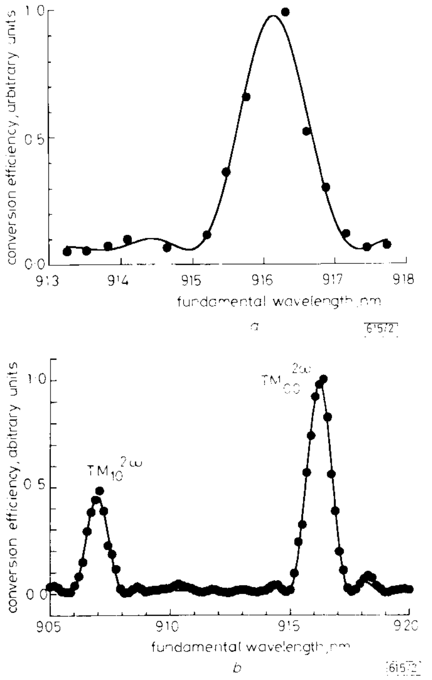

Fig. 2 *Measured SHG conversion efficiency as function of fundamental wavelength, with fitted* $sinc^2$ *curves, for periodically-poled* $LiTaO_3$

a Planar waveguides
b Channel waveguides
where length of QPM grating is 1 mm

To estimate the expected conversion efficiency of our channel device we evaluated overlap integrals using the measured near field profiles of the infra-red and blue modes of the 10 μm wide waveguide. For the TM_{00} modes in the infra-red and blue, the waveguide had an effective area of about 50 μm^2, resulting in a predicted efficiency of 22%/W . cm^2. We suspect the discrepancy between the measured and calculated normalised conversion efficiencies results from a reduction in the nonlinear coefficient due to the proton exchange waveguide process. In $LiNbO_3$, the value of d_{33} has been estimated to be 40–60% of its bulk value after proton exchange.[20–22] Post-exchange annealing has been reported to restore the nonlinear coefficient to its bulk value.[21,22] We believe a similar situation exists for $LiTaO_3$ because we observed no SHG in unannealed guides, and that our annealed waveguides were not annealed enough to recover the full nonlinear coefficient.

Conclusion: In conclusion, we have demonstrated room temperature, quasiphase-matched second harmonic generation of blue radiation in $LiTaO_3$ waveguides that were periodically-poled by the application of a periodic electric field near the Curie temperature. In both planar and channel waveguides the interaction length implied by the width of the wavelength tuning curve was in agreement with the periodically-poled length of 1 mm. A maximum of 1·3 μW of blue light was generated in the TM_{00} mode in the channel sample for a fundamental input power of 41 mW, resulting in a normalised conversion efficiency of 8%/W . cm^2.

Although we have discussed poling of Z-cut substrates in this Letter, electrical periodic-poling of X-cut $LiTaO_3$ is attractive because an APE waveguide in X-cut material is TE-guiding, making it easier to couple to TE-polarised diode lasers. Extending the current work to electrical poling of X-cut wafers should be straightforward, as electrical poling for periodic domains has been investigated on rotated Y-cut wafers for SAW applications.[15] Poling of $LiTaO_3$ by proton exchange and annealing, however, has so far been demonstrated only on Z-cut substrates.

Future work will focus on optimising the APE parameters. Proper annealing should recover the nonlinear coefficient and result in experimental efficiencies closer to the theoretical values. A 1 cm long waveguide with an efficiency or 20%/W . cm^2 would produce 1 mW of blue light for about 70 mW of input infra-red radiation. Optimising the channel waveguide process for widths smaller than the 10 μm width investigated here will increase the modal confinement and further increase the efficiency.

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COMMENT

CRYPTANALYSIS OF PUBLIC KEY DISTRIBUTION SYSTEMS BASED ON DICKSON POLYNOMIALS

This comment is in response to an earlier letter by Da-Xing Li[1] in which it is claimed that 'public-key distribution systems based on Dickson polynomials are insecure no matter how the system parameters are chosen and no matter how the Dickson polynomials are calculated'. The claim is based on an attack which can be executed in no more than the square of the time taken by the legal users. The attack is however flawed.

The key result is proposition 4 which states that the cost T of evaluating the Dickson polynomial $g_k(a, x)$ is at least k. As a consequence, given a, x_0, P_{ab} such that $g_k(a, x_0) = P_{ab}$, the cost of the exhaustive search for k: $g_i(a, x_0) \overset{?}{=} P_{ab}$, $i = 1, 2, \ldots$, is bounded by $k \,.\, T \leq T^2$. This is polynomial in the cost of the legal user (who must compute $g_k(a, x_0)$) and is therefore feasible. Therefore, a wiretapper who has obtained the 'user-keys' P_{ab}, P_{ba}, can also compute the 'common-key' $g_k(a, P_{ba})$.

The flaw in this argument is that ordinary arithmetic is used instead of modular arithmetic (it is hard to comprehend a cryptographic implementation with ordinary arithmetic). Indeed if the modulus is n then the cost of computing $g_k(a, x_0)$ is only[2] $O(\log_2 k)$, so that the cost of the exhaustive search is $O(k \log_2 k)$. The attack is therefore infeasible when k is superpolynomial in the length of n.

In general, when the parameters of a Dickson-based cryptosystem are chosen appropriately, the security of the system is similar to that of the RSA or the DH system.[2–5]

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REPLY

The attack and all the conclusions in Reference 1 are only directed against the Dickson polynomial distribution system suggested by Yang Yi-xian in Reference 2, in which the Dickson polynomial is on integer ring Z; it is neither on residue class ring $Z/(n)$ as in Reference 3 nor on finite field F_q as in Reference 4. Similarly, the arguments about the choice of system paremeters and the calculations of Dickson polynomial are restricted to integer ring Z. Hence, the counter example of Burmester goes beyond the bounds of Reference 1. Whether Dickson polynomial public-key distribution systems on $Z/(n)$ and F_q are secure is a well known open problem, as mentioned in the comment of Burmester.

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COMMENT

REALISATION OF SWITCHED CAPACITOR DELAY LINES AND HILBERT TRANSFORMERS

Reference 1 describes the realisation of switched-capacitor delay lines and Hilbert transformers based on switched-capacitor sample-delay-hold (SDH) buffers presented in Reference 2. The double-sampling implementation of the SDH buffer is used as delay element and the single-sampling version as reflection circuit. The latter fact seems not to have been recognised by the author of Reference 1, describing the reflection circuit as a modification of the delay element.

Care has to be taken in double-sampling circuits not to unbalance the charge flows in both circuit paths. Parasitic capacitances should be excluded from the common signal path, because the biphase clock pattern allows no additional reset phase to eliminate their effects on the transfer function.