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Second-Harmonic Generation in a Direct-Bonded Periodically-Poled-LiNbO$_3$ Buried Waveguide

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ABSTRACT

We report the fabrication of a 12-μm-thick periodically poled $LiNbO_3$ planar waveguide, buried in $LiTaO_3$ by direct bonding of precision polished surfaces. Frequency doubling of the 1064 nm output of a cw diode-pumped Nd:YAG laser was performed in a 5.5-mm-long device using a 6.50-μm-period grating at an elevated temperature of 174 °C. The resultant green second harmonic output exhibited fundamental-spatial-mode characteristics at a 4.3 % W^{-1} conversion efficiency.

Periodically poled lithium niobate (PPLN) combines the important characteristics of a large non-linear coefficient and non-critical phase-matching capabilities for any wavelength in its transmission range, which makes it an attractive material for nonlinear frequency conversion[1]. The combination of these material characteristics with the optical confinement offered by a waveguide geometry provides a promising route to the realisation of various compact nonlinear devices based on harmonic[2] or parametric[3] generation.

The two most common methods for fabricating waveguides in $LiNbO_3$, which also work for PPLN, are annealed proton exchange[4] and Ti indiffusion[5]. These processes modify the crystal near the surface in order to create regions of higher refractive index for optical confinement. In contrast, direct bonding (DB)[6] is a fabrication technique that uses the Van der Waals forces present when two atomically flat bodies approach each other to combine layers of different materials to form waveguiding boundaries. Such a bond can be formed irrespective of the lattice constants and orientation of the materials concerned and involves no deleterious modification[7] of the crystalline microstructure of either material. By contacting surfaces this way, DB preserves the bulk characteristics of each bonded material.

Some recent experiments investigating the bonding characteristics of PPLN have been directed towards fabricating thick multi-layered stacks[8] of the material for a large physical aperture, and thus high power applications. By contrast, our experiments have been aimed at creating a thin waveguide layer of PPLN, and exploiting optical confinement to allow efficient SHG even at low pump powers. Our initial attempts have been directed at planar waveguide devices. Fabrication of such a device can be achieved by bonding PPLN onto a suitable substrate before precision polishing down to waveguide dimensions, a method which has already been demonstrated in the production of $LiNbO_3$ planar waveguides[7,9] for electro-optic applications. One of the primary attractions offered by this technique is that during the fabrication process, in contrast with proton exchange[4] and Ti indiffusion[5] methods, the nonlinearity and domain characteristics of the PPLN structure should remain entirely unchanged from the bulk material. A further attraction of the DB method is the extra flexibility available when designing devices, offering the possibility, for example, of combinations of multiple layers with different material properties. Such structures have previously been explored in the fabrication of silicon semiconductors (see 10 and other papers on DB in the same journal issue), and garnet and glass waveguides for use in lasers[11], although much scope remains for DB multi-layered optical devices. To this end, this paper describes the fabrication of a symmetrical PPLN waveguide, buried in $LiTaO_3$ by DB and precision polishing methods, and the SHG characteristics exhibited by the domain inverted structure.

Production of the PPLN grating began with a 0.5-mm-thick single domain z-cut $LiNbO_3$ sample of ~ 15×15 mm^2 surface area. A photoresist pattern was created on the -z face of the crystal by photolithography, and domain inversion in the z-axis was performed at room temperature by the application of a single high voltage pulse of ~11 kV through liquid electrodes. This resulted in three 5.5-mm-long PPLN gratings, positioned in the center of the $LiNbO_3$ sample at 1 mm intervals. Grating periods of; 6.58, 6.50, and 6.38 μm were created, the first two of which are suitable for frequency doubling of a Nd:YAG laser operating at 1064 nm. $LiTaO_3$ was chosen as a suitable material for both the substrate and cladding layers as it has a lower refractive index and also combines thermal characteristics that are a good match for $LiNbO_3$, an essential pre-requisite when annealing bonds at high temperatures. The $LiTaO_3$ substrate used was 0.5-mm-thick and shaped relative to the PPLN sample to provide a bonding area of $\sim 12\times10$ mm^2 between the two optically flat surfaces. Once cleaned, a mixture of H_2O_2-NH_4OH-H_2O (1:1:6) was applied to both materials, followed by several minutes of rinsing in de-ionized water, in order to render their surfaces hydrophilic[9]. Contacting of the PPLN and $LiTaO_3$ layers was performed at room temperature with both samples aligned along the same crystalline orientation. A heat treatment up to 120 °C immediately followed crystal contact to induce the pyroelectric effect[8] at the DB interface. The resultant electrostatic attraction forced any excess air or liquid from between the two surfaces, whilst bringing them close enough to encourage the formation of hydrogen bonds[12]. This effect was demonstrated by the elimination of most of the contact fringes at the crystal interface. Annealing of the bonded sample at 320 °C for 6 hours provided a bond strength sufficient for further machining, and the PPLN region was then lapped down to obtain a waveguiding layer of 12-μm-thickness. A further DB cladding layer of $LiTaO_3$ was then added with the same procedure as above. The final DB structure included bonded interfaces of $\sim 12\times10$ mm^2 above and below the PPLN core, although evidence of small unbonded regions at the edges of the sample were detected by the presence of optical fringes. The unwanted material surrounding the gratings was later removed using dicing equipment and the waveguide end-faces were then polished to a parallel optical finish. Dimensions of the resulting buried PPLN planar struture are given schematically in Figure 1.

An upper limit for the value of the propagation loss of the waveguide structure was found by measuring the transmission of a 1064 nm laser beam when end-launched into the waveguide. It was noted that the transmission changed between the PPLN and $LiNbO_3$ (not periodically poled) sections of the waveguide and the launch condition was therefore optimised individually for each of these regions. Maximum transmissions of 81 % were found at the edges of the PPLN grating (where best SHG occured) and throughout the uniform $LiNbO_3$ sections, whilst 65 % transmission was obtained at the center of the PPLN grating. Thus, over the 5.5-mm-length of the grating, an upper-limit to the propagation loss in each section is found to be 1.7 dB cm^{-1} for the PPLN edges and $LiNbO_3$ regions, and 3.4 dB cm^{-1} for the center of the PPLN grating. In fact these transmission figures also include launch losses so the propagation losses are likely to be much lower. Indeed, DB waveguides in garnets and glasses for laser applications have shown losses of ~ 0.5 dB cm^{-1} and less[11].

To test the nonlinear properties of the buried PPLN structure the SHG characteristics of the 6.50 μm grating were investigated. This grating, which occupied the middle section of the PPLN waveguide, was chosen for investigation as its phase-matching temperature (for 1064 nm doubling) of 174.1 °C supressed the photorefractive effect. The 1064 nm pump source was a cw diode-pumped Nd:YAG laser operating with multi-axial modes. The linear polarisation state was rotated with a half-wave plate to be parallel with the z-axis of the PPLN in order to access the material's largest nonlinear coefficient (d_{33}). Focussing of the pump radiation for launching into the waveguide was performed using a combination of microscope objective and cylindrical lenses, as shown in Figure 2. The initially circular pump beam was passed through a ×2.4 cylindrical-lens telescope to expand in the guided direction before being focussed onto the PPLN grating by a ×10 microscope objective. Such a combination of optics was chosen to provide good launch efficiency whilst helping to reduce divergence in the horizontal unguided plane. This resulted in a pump source with a line focus and measured spot sizes of 4±1 μm in the guided direction and 11±1 μm in the non-guided direction. It should be noted that focussing to a waist in the non-guided plane at the input face is not the optimum condition for maximum SHG efficiency[13] and was chosen here for the sake of simplicity. Also, for this initial demonstration both the input and output end-faces of the waveguide were polished but left uncoated, leading to 14 % reflection losses at each face.

A second ×10 microscope objective was used to collect the transmitted light from the waveguide. This was followed by an infra-red filter to remove any pump light and the second harmonic power was then measured on a power meter. For 204 mW of launched pump power ($\lambda = 1064$ nm), a second-harmonic (SH) power of 1.8 mW ($\lambda = 532$ nm) was generated internal to the crystal. Figure 3 shows a plot of the square root of the SH power versus launched pump power, confirming the expected quadratic dependence.

In the absence of a detailed analysis for SHG in this mixed guided / unguided geometry, we have made a comparison of the observed efficiency with a calculation of the SH power expected from a similar length of bulk PPLN with optimised focussing in the centre of the grating[13]. Assuming a non-linear coefficient of 16 pm V^{-1} (a value consistent with results in bulk experiments using similarly produced PPLN gratings) an optimised SH output power of 1.3 mW is predicted for the bulk material - a lower result than the 1.8 mW obtained from the direct-bonded waveguide. This comparison demonstrates that even with non-optimum focussing, the short crystal length, and only one guided dimension, the buried PPLN device shows an improved SHG efficiency of almost 40 % over the bulk material.

Modal characterisation of the output from the PPLN waveguide was performed using a video camera and PC-based evaluation software. It was observed that both the remaining 1064 nm light and the generated SH radiation from the PPLN grating were in the fundamental spatial mode, despite the fact that a 12-μm-thick waveguide with such a large index difference ($\Delta n_e \approx 1$ %) could be expected to support a number of modes. Indeed, only by using a deliberately poor launch was it possible to excite anything other than the fundamental mode at 1064 nm. At the same time it was noted that the 1064 nm throughput from the $LiNbO_3$ region within the same buried structure was multi-spatial-mode in nature. This clear difference in the mode properties, combined with the different transmissions described earlier, suggests that the index profile of the PPLN grating is different from that of the uniform $LiNbO_3$ region. The reason for these unexpected but potentially useful properties has not yet been defined, although they are possibly linked to strain-induced changes in refractive index which we have noted in other DB experiments. It is hoped that this effect can be exploited to provide a simple route to creating channel waveguides in a DB structure.

In conclusion, we have reported the successful fabrication via direct bonding of a 12 μm-thick, 5.5-mm-long, symmetrical PPLN waveguide buried in $LiTaO_3$. Using the 6.50-μm-period PPLN grating at an elevated temperature of 174 °C, we have demonstrated efficient quasi-phase-matched frequency doubling of the 1064 nm line of a cw diode-pumped Nd:YAG laser. For 204 mW of fundamental pump power, nearly 2 mW of green power was generated at an output wavelength of 532 nm. This result, obtained with non-optimum focussing conditions, provides a SHG output of almost 40 % greater than the theoretical expectation for a similar length of bulk material. The waveguiding properties were shown to be different in the PPLN and uniform $LiNbO_3$ regions of the sample, with the PPLN grating showing a surprisingly robust single-spatial-mode behaviour. These results suggest that the production of longer buried waveguides, potentially incorporating channel structures, could lead to highly-efficient nonlinear devices. The ability to work with thin samples may allow shorter periods to be fabricated effectively, thus extending second harmonic generation to shorter blue wavelengths[14]. More generally, the DB technique offers promise in providing extra degrees of design freedom for nonlinear waveguiding devices.

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FIGURE CAPTIONS

FIG. 1. Schematic end-face diagram of the buried PPLN waveguide.

FIG. 2. Experimental arrangement for SHG in the buried PPLN waveguide (side view).

FIG. 3. Dependence of the square root of the generated SH (532 nm) power on the fundamental infrared (1064 nm) power. Powers are internal to the PPLN.

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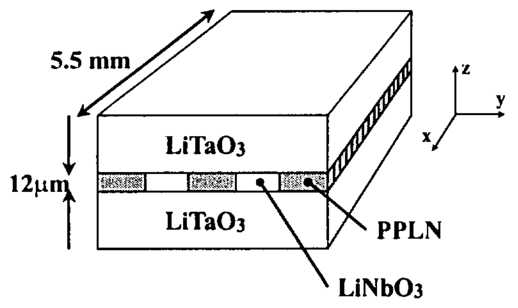
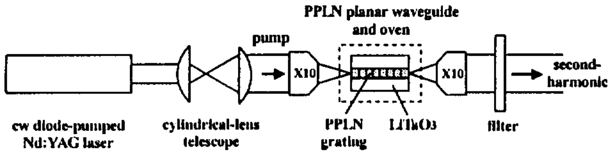
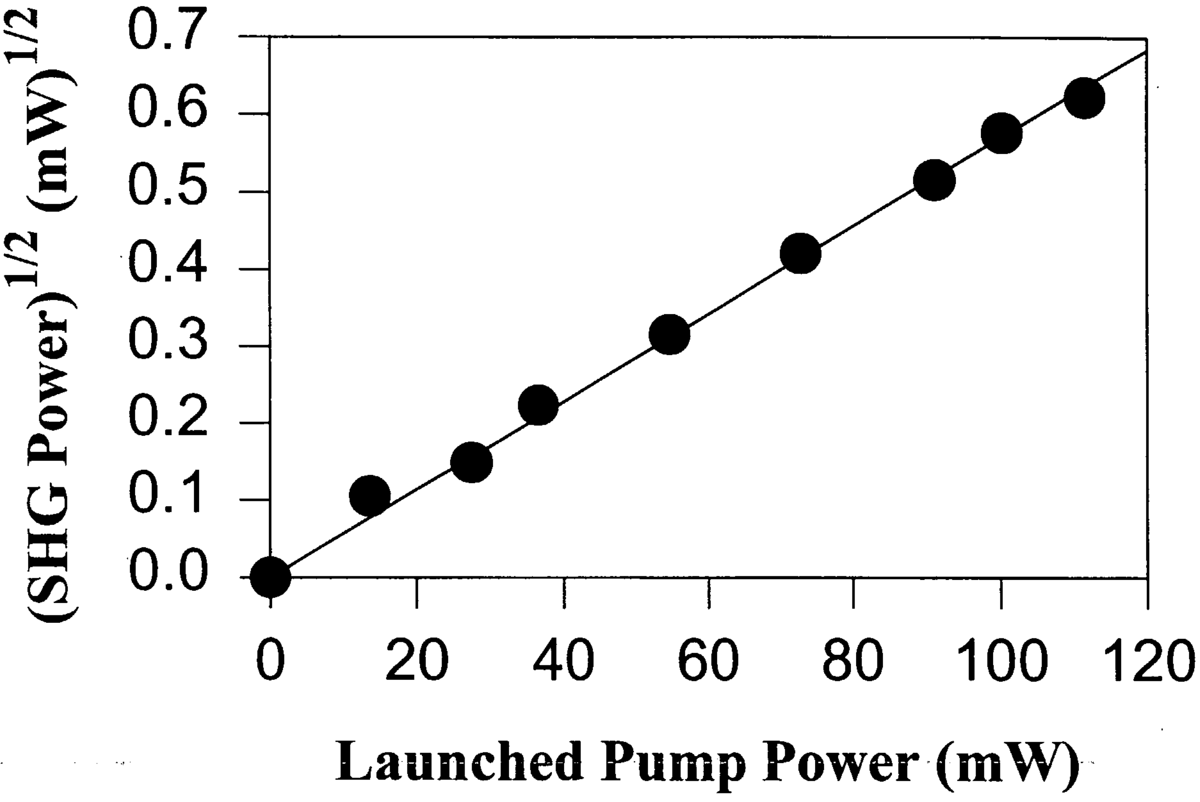

5.5 mm
12μm
LiTaO$_3$
LiTaO$_3$
PPLN
LiNbO$_3$
z
y
x


PPLN planar waveguide and oven
pump
X10
X10
second-harmonic
cw diode-pumped Nd:YAG laser
cylindrical-lens telescope
PPLN grating
$LiTaO_3$
filter


(SHG Power)^1/2 (mW)^1/2
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0
20
40
60
80
100
120
Launched Pump Power (mW)