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HeXLN: A 2-Dimensional nonlinear photonic crystal

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Abstract

The fabrication of a two dimensional hexagonally poled lithium niobate (HeXLN) crystal is reported. 2nd harmonic conversion efficiencies > 60% were measured with picosecond pulses. The 2nd harmonic light is phase matched by multiple reciprocal lattice vectors, resulting in multiple coherent beams being generated.

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In one dimension, the concept of quasi-phase matching nonlinear processes by periodically changing the sign of the nonlinearity is well known. The advantages of materials such as periodically poled lithium niobate (PPLN) lies in their engineerability – nonlinear processes over a wide wavelength range can be phase-matched by writing the appropriate nonlinear grating. In these crystals nonlinear processes are efficient when the momentum (phase) mismatch between the interacting waves equals one of the reciprocal lattice vectors (RLV) of the 1-D periodic crystal. Clearly this can only occur in either the co- or counter-propagating direction. Furthermore, for a strictly periodic lattice quasi-phase matching can only occur over a narrow wavelength range since the RLVs are discrete and periodically spaced in momentum space. In order to obtain broader bandwidths densely spaced RLVs are needed. Recently broadband phase-matching was obtained by using a Fibonacci lattice[1]. Fibonacci lattices are an example of 1-D quasi-crystals[2] and as such have a dense spectrum in momentum space. Fibonacci lattices can be thought of as being the 1-D projection of a regular 2-D crystal.

Recently the idea of quasi-phase matching was extended to two-dimensions and the notion of a 2-D "nonlinear photonic crystal" was introduced[3]. In such a 2-D photonic crystal the nonlinear susceptibility changes periodically across the plane while the linear refractive index is constant. Such crystals would have many advantages over a 1-D periodically poled crystal, such as being angle rather than temperature tuned and being able to phase-match multiple wavelengths simultaneously. We report here what is to the best of our knowledge both the first example of hexagonally poled lithium niobate (HeXLN) and the first 2-D nonlinear photonic crystal to be fabricated.

A thin layer of photoresist was first deposited onto the -z face of a 0.3mm thick, z-cut wafer, of $LiNbO_3$, and then photolithographically patterned with the hexagonal array. The x-y orientation of the hexagonal structure was carefully aligned to coincide with the crystal's natural preferred domain wall orientation : $LiNbO_3$ itself has a hexagonal atomic symmetry and shows a tendency for domain walls to form parallel to the y-axis and at +/-60 . Poling was accomplished by applying an electric field via liquid electrodes on the +/- z faces. The short period of the hexagonal array was 18.05 μm, designed for quasi-phase-matched frequency-doubling of 1536nm at a temperature of 160 C. After poling, the sample was lightly etched in acid to reveal the domain profile. The hexagonal pattern was found to be uniform across the sample dimensions of 14 × 7mm (x-y). Fig. 1 shows a magnified section of the HeXLN sample showing clearly the hexagonal honeycomb structure. Each hexagon is a region of domain inverted material - the total inverted area comprises 25% of the overall sample area. Lastly we polished two opposite sides of the HeXLN crystal allowing a propagation length of 14mm through the crystal.

To investigate the properties of the HeXLN crystal we proceeded as follows. The HeXLN crystal was placed in an oven and mounted on a rotational stage which could be rotated by ±10 degrees while still allowing the light to enter. It was pumped by 4ps, 200kW pulses obtained from a high power all-fibre chirped pulse amplification system[4] operating at 20kHz. The output from the CPA system was focussed onto the HeXLN crystal using a 12cm focal length lens. At low input powers the output was as shown in Fig. 2 and consisted of multiple output beams of different colours emerging from the crystal at different angles. In particular two 2nd harmonic beams emerged from the crystal at identical angles of $1.1^\circ \pm 0.1^\circ$ degrees from the remaining fundamental which was, as expected, undeflected by the crystal. Then at slightly wider angles were two green beams (third harmonic of the pump) and at an even wider angle was a blue beam (the fourth harmonic). There was also a third green beam copropagating with the fundamental. As the input power increased the 2nd harmonic spots remained in the same positions while the green light appeared to be emitted over an almost continuous range of angles rather than the discrete angles observed at low powers.

The two 2nd harmonic beams can be understood by referring to the reciprocal lattice (RL) of a hexagonal lattice. The RL of a 2-D hexagonal lattice is another hexagonal lattice[5] only rotated by $\pi/2$. Fig. 2 shows the first Brillouin zone for our crystal. Due to our setup the pump beam propagated along the ΓK direction while the closest reciprocal lattice vectors (RLV) are in the ΓM directions and it is these RLVs that account for the 2nd harmonic light[3]. Using Eq. (6) of Berger[3] the angle between the fundamental and 2nd harmonic should be 1.07° degrees which agrees well with our measured values. The shortest RLV in the direction of propagation is $\sqrt{3}$ longer and this RLV accounts for the sum frequency generation between the fundamental and the 2nd harmonic. If the crystal were to be rotated by 30 degrees then the propagation angle would be along the ΓM direction and hence we would expect to see efficient 2nd harmonic generation in the co-propagation direction (however at present this is not possible due to the geometry of the oven and the size of the HeXLN crystal).

After filtering out the other wavelengths the 2nd harmonic (from both beams) was directed onto a power meter and the efficiency and temperature tuning characteristics were measured. These results are shown in Fig. 3. Note that the maximum external conversion efficiency is greater than 60% and this is constant over a wide range of input powers. Taking into account the Fresnel reflections from the front and rear faces of the crystal this implies a maximum internal conversion efficiency of 82% - ~ 40% in each beam. Note that, due to nonlinearity in the CPA system the pump bandwidth increased as the pump power increased limiting the conversion efficiency at higher powers. In addition, as the 2nd harmonic power increases the amount of back conversion increases which limits the efficiency as is seen in Fig. 3(c).

In the 1-D case the temperature tuning curve of a length of periodically poled material is expected to have a $sinc(T)$ shape and to be quite narrow - 4.66° degrees for a 1-D PPLN crystal with the same length and period as the HeXLN crystal used here. However, as can be from Fig. 3(b), the temperature tuning curve is much broader with a FWHM of ~ 25° degrees and it exhibits considerable structure. To obtain the temperature tuning curve we collected the 2nd harmonic light from all angles and focussed it onto a silicon head detector. We believe that the increased bandwidth is is due to the multiple reciprocal lattice vectors that are available for quasi-phase matching with each RLV producing a beam in a slightly different direction. Thus the graph in Fig. 3(b) should be considered as the sum of multiple $sinc(T)$ shaped curves. Due to the limitations of the oven we were not able to raise the temperature about 205° degrees and hence could not completely measure the tail of the temperature tuning curve. At temperatures below 120° degrees the conversion efficiency is limited by photorefractive effects. Note that temperature tuning is equivalent to wavelength tuning of the pump pulse and hence it should be possible to obtain efficient phase-matching over a wide wavelength range at a fixed temperature as suggested by the efficient conversion of the broadband pump pulses.

Lastly we measured at the spectra of the light produced however due to space constraints only the fundamental is shown in Fig. 3(c). Fig. 3(c) shows the spectrum near 1533nm for horizontally (solid line) and vertically (dashed) polarised input light. As the phase matching only works for the vertically polarised light the horizontally polarised spectrum is identical to that of the input beam and when compared with the other trace (dashed line) shows the effect of pump depletion and of back-conversion. Note that for the vertically polarised light the amount of back-converted light is almost equal to the residue pump which is as expected given the large conversion efficiency. Fig. 3(c) shows ~ 8dB (85%) of pump depletion which agrees well with the measured value for the internal efficiency calculated using the average power.

In conclusion we have fabricated what we believe to be the first example of a two dimensional nonlinear photonic crystal in Lithium Niobate. Due to the hexagonal structure of the crystal quasi-phase matching is obtained for multiple directions of propagation with conversion efficiencies > 70%. Such HeXLN crystals could find many applications in optics where simultaneous conversion of multiple wavelengths is required. Alternatively a HeXLN crystal could be used as an efficient monolithic optical parametric oscillator. In the near future we will measure the angular dependence of the HeXLN crystal as well as the correlation properties of the two 2nd harmonic beams.

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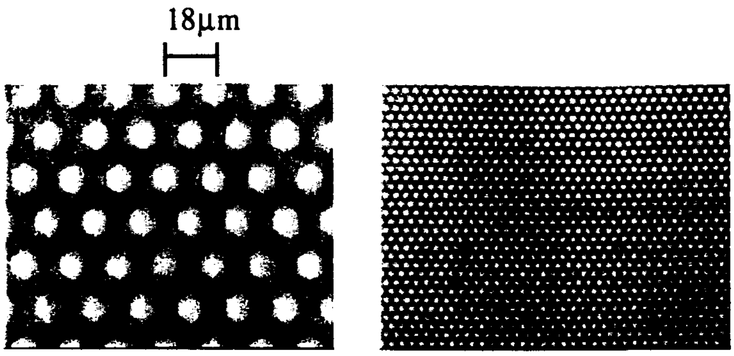

Figure 1: Pictures of the HeXLN crystal on both the large and small scales. The large scales pictures shows the excellent uniformity over the crystal while the fine detail can be seen in the small scale.

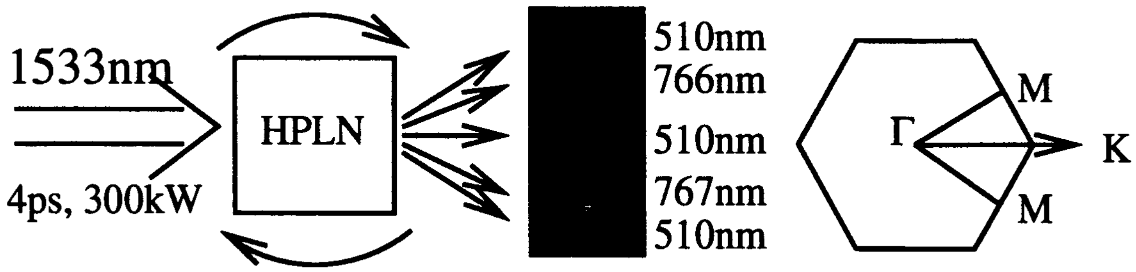

Figure 2: Schematic of the experimental setup, the output beam pattern and a diagram of the first Brillouin zone. For our geometry the pump propagates along the ΓM direction while phase-matching is achieved by RLV in the ΓK directions.

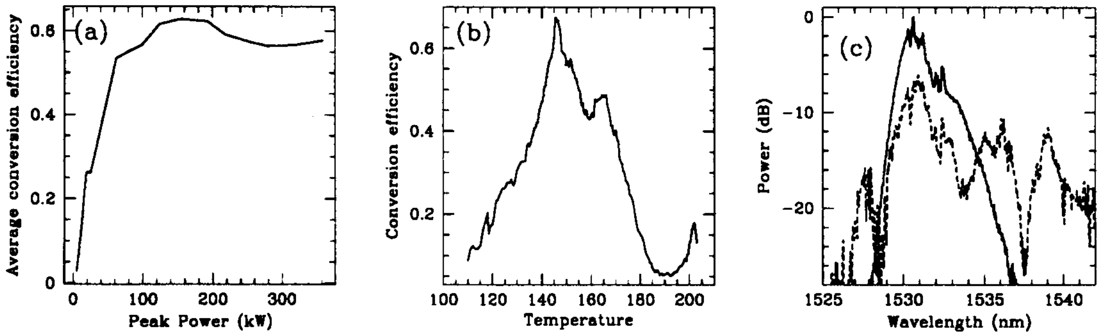

Figure 3: Efficiency and temperature tuning of the HeXLN crystal. Note that the maximum efficiency is > 60% and is limited by pulse walk-off and down conversion. The temperature tuning curve is much broader than a comparable 1-D PPLN crystal and posses multiple features due to the large number of reciprocal lattice vectors available. The last graph shows the pump for both horizontally (solid line) and vertically (dashed line) polarised inputs. Note that the effect of pump depletion and back conversion can be clearly seen.