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FIFTY-FIVE PERCENT CONVERSION EFFICIENCY TO GREEN IN BULK QUASI-PHASE-MATCHING LITHIUM NIOBATE

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Abstract

High voltage and liquid electrodes were used for periodic poling of lithium niobate. A sample with a period of 6.80 μm was used for first-order frequency doubling of 1064 nm Q-switched Nd:YAG light with an average power conversion of 55%, implying greater than 90% power conversion at the peak of the pulse. The effective nonlinear coefficient for both Q-switched and continuous-wave measurements was ~ 15 pm/V.

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The use of quasi-phase-matching media has a potential for high efficiency allied to great flexibility (one standard fabrication process for any wavelength within the transparency range, 0.4 μm to 4 μm in lithium niobate). For instance, Jundt et al have shown efficient generation of green light with a periodically grown lithium niobate crystal in a cavity [1].

As a further test of the performance of such materials, in particular of electric-field poled lithium niobate, we have investigated the capability for efficient single-pass frequency doubling of a Q-switched Nd:YAG laser. This has called for a short period of the domain grating (6.8 μm). We have also used the harmonic generation experiments to provide a measure of the effective nonlinear coefficient, and to test the damage behaviour. The very encouraging conclusion of these experiments is that the measured effective nonlinear coefficient, 15 pm/V, is approaching the theoretical value of 22 pm/V.

The phase-matching curve (SH power vs temperature) was in very close agreement with the theoretical curve for an ideal sample, demonstrating that the process involved the whole length of the 4 mm sample. Also, under the conditions of these experiments, where 55 mW of average internal fundamental power was converted to 30 mW of average internal second harmonic power, no evidence of the photorefractive effects appeared before we reached the irreversible damage threshold. The latter, at over 150 MW/cm^2, was the same as for standard bulk material.

The use of a strong electric field applied via liquid electrodes for periodic poling has been described in several earlier papers [2,3,4]. We have previously used this method to prepare samples for doubling of 1064 nm and used them for intracavity SHG in a Nd:YAG laser [5]. However, in that experiment the mark/space ratio of the photoresist mask pattern was not optimal. This had the result that if the high voltage was kept on long enough to initiate domain reversal over the full desired area, it actually caused the inverted domains in some regions to expand and fill in the gaps, so that these regions became totally inverted rather than periodically inverted. This resulted in a rather low effective nonlinear coefficient - 5pm/V compared to the 22 pm/V attainable.

The present sample was fabricated using a new mask with 1 μm wide electrode openings and 5.80 μm wide photoresist separations. This pattern allowed periodic poling over the full area without any filling in. The 0.2 mm thick sample was subjected to three pulses of 4.7 kV with a duration of 10 ms each.

By etching pieces of the sample that were cut off before polishing the end-faces, we determined that, as in previous experiments, there was a slight random variation in the positions of the domain walls [3].

Initially, the sample was characterized with a CW Nd:YAG laser. Fig.1 shows that this sample had the same phase-matching temperature, ~ 35°C, as the previous sample [5]. It also shows that the experimental trace closely follows the theoretical sinc^2 curve with a temperature-bandwidth of ~ 7 K. Following the treatment by Boyd and Kleinman [6], the second-harmonic power $P_{2\omega}$ for a loosely focused beam with Gaussian profile of waist spot size w_0 and crystal length l will be

$$P_{2\omega}=\frac{8\pi d_{eff}^2 P_\omega^2 l^2}{\lambda^2 \epsilon_0 c_0 n_\omega^2 n_{2\omega} w_0^2}\rho$$

In our case, with w_0 = 26 μm and l = 4 mm, an internal second-harmonic power of 50 μW was achieved with an internal pump power of 85 mW, which corresponds to an effective nonlinear coefficient of 14 pm/V. For this laser, having several longitudinal modes, the factor ρ which accounts for the mode structure was set to $\rho=1.8$.

The periodic crystal was also used for doubling light from a single frequency 2 kHz repetition rate Q-switched Nd:YAG laser [7]. Fig.2 shows the average conversion efficiency as function of average pump power. The pump power was varied with all other experimental parameters unchanged. At the higher power levels, the narrowing of the peak of the phase-matching curve was clearly evident [8]. The maximum output from the laser gave an average internal power of 55 mW of IR light, which was converted into an average internal power of 30 mW of green light.

In this experiment, the theoretical second-harmonic power was calculated by averaging the conversion efficiency in both space and time, assuming a Gaussian shape of the pulse. This gives the relation between conversion efficiency and pulse power, pulse duration etc. shown by Eckardt et al [8]. The calculations gave an estimated nonlinear coefficient of d_{eff} = 16 pm/V.

The peak intensity at the surface corresponding to the maximum conversion was 36 MW/cm^2. By tighter focusing of the beam, we found that permanent surface damage occurred at 160 MW/cm^2, i.e. 3.2 J/cm^2 for these 18.5 ns pulses.

Even at these ~ kilowatt powers of green light, no signs of photorefractive damage were seen up to the level at which permanent surface damage appeared. The M^2 value of the exit beam was measured for both fundamental and second harmonic as $M_F=1.0$ and $M_{SH}=1.2$, confirming the excellent quality of the second-harmonic beam.

The use of an electric field applied via patterned liquid electrodes has now reached the stage of being a reliable fabrication process, offering a highly nonlinear, very flexible optical media. This permits very high conversion efficiency in harmonic generation . In our case, the efficiency was above 90% at the peak of the pump pulse from a Q-switched Nd:YAG laser. The effective nonlinear coefficient d_{eff} of this crystal was measured to be ~ 15 pm/V, which is much larger than the coefficients available through birefringent phase-matching in most materials. The theoretical d_{eff} for a lithium niobate crystal with perfectly regular domain walls is 22 pm/V, and we attribute this reduction in our experimental value to some randomness in the domain-wall positions.

These experiments have confirmed that photorefractive effects have been greatly reduced, to the extent that they were not observed at all. The experiments also confirm that very high quality periodic gratings can be achieved for small grating periods.

Future work will investigate the possibility of extending the good results down to periods appropriate for doubling the 946 nm Nd:YAG line, and to see whether the high quality can be maintained when working with thicker samples, and hence higher voltages.

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Figures

1. Second harmonic power as function of crystal temperature. The points are experimental data and the full line is a theoretical trace.

2. Second harmonic output as function of average internal fundamental power. The full line is a theoretical trace for a sample with d_{eff} = 16 pm/V.

Fig.1

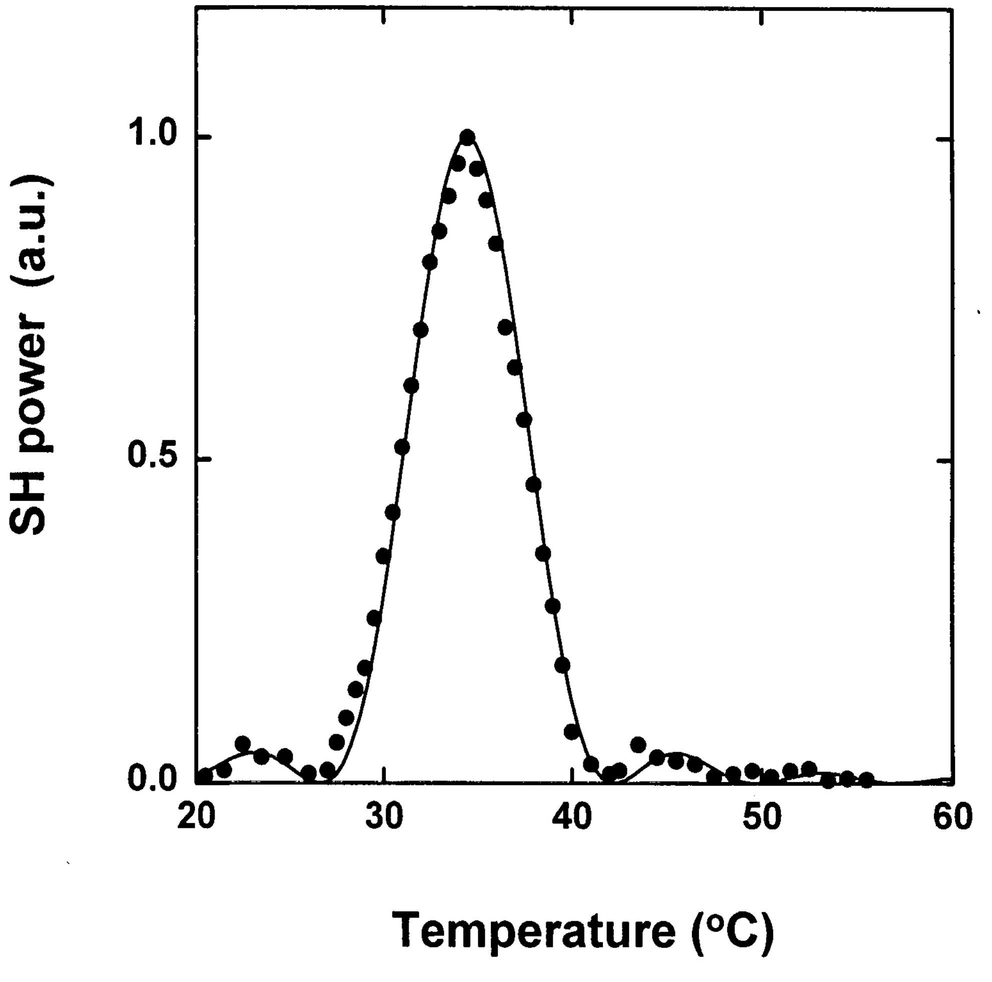
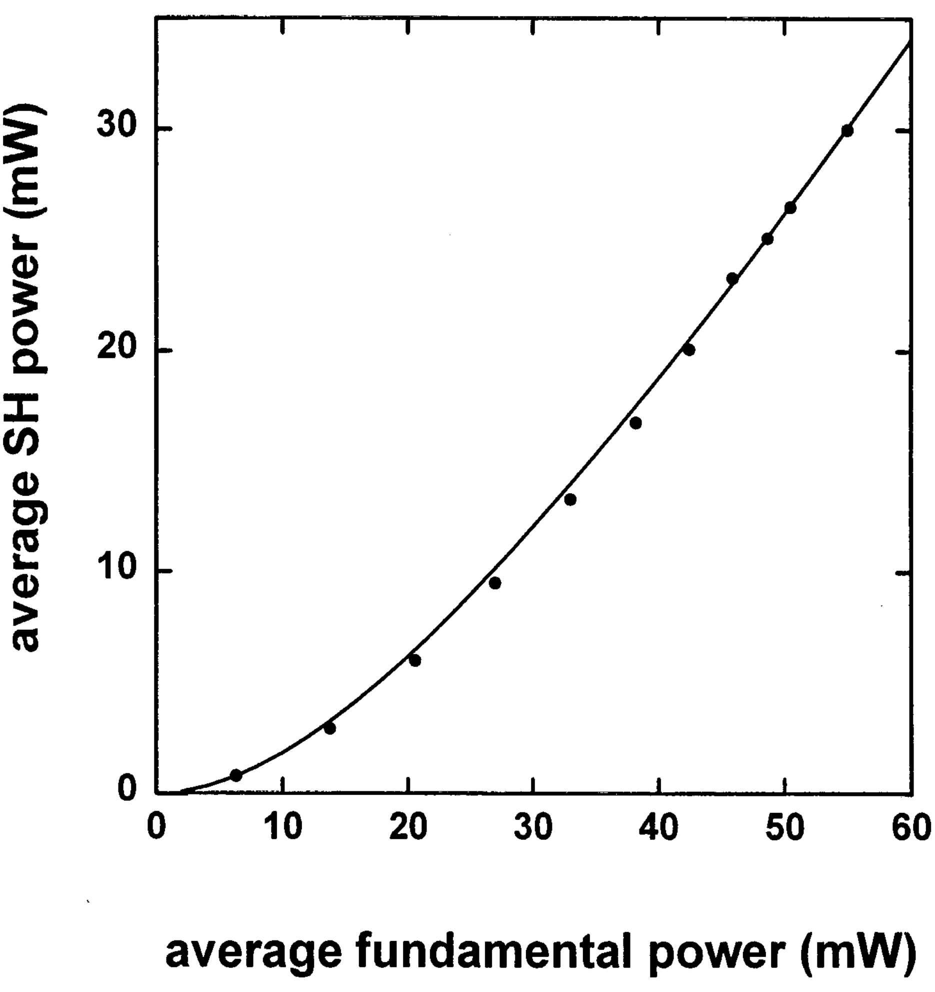


Fig.2



average SH power (mW)
30
20
10
0
0
10
20
30
40
50
60
average fundamental power (mW)