Highly-efficient second harmonic generation of green light from picosecond pulses in bulk quasi-phase-matched lithium niobate

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Abstract

1.3 W average power of green light was generated by quasi-phase-matched frequency doubling of a quasi-CW mode-locked Nd:YLF laser with 60% average conversion efficiency.

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Over the last few years quasi-phase-matching (QPM) has emerged as a reliable technique for efficient second-order nonlinear optical processes. QPM allows access to higher nonlinear coefficients and wider wavelength ranges compared to birefringent phase-matching. In lithium niobate (LN) QPM can be achieved by an appropriate periodic modulation of the sign of the nonlinear coefficient via periodic domain inversion, so that the phase-mismatch between interacting fields can be compensated. This nonlinear grating does not alter the linear properties of the material which are described by the dependence of the refractive index on the wavelength. Periodically poled LN (PPLN) has been demonstrated to give efficient operation for QPM frequency doubling [1,2] and QPM parametric oscillation [3,4] both in CW and Q-switched regimes. Recently 4.5 mW of average blue-light power with 13% conversion efficiency has been generated in a periodically domain-inverted $LiTaO_3$ waveguide by frequency doubling of ~20 ps pulses produced by a high-frequency superimposed laser diode [5].

When the nonlinear interaction involves pulses of a few picoseconds duration or less the linear dispersion of the material becomes important, since the temporal walk-off due to group-velocity mismatch (GVM) between interacting pulses having different frequencies can seriously limit the effective interaction length (l_{eff}). QPM is usually used in such a way that the largest component of the second-order nonlinear tensor can be exploited. In the case of PPLN this means that all the interacting waves should be extraordinary polarised, so that d_{33} (which has a value > 30 pm/V) can be accessed. Unfortunately for such a polarisation geometry the material is highly dispersive, e.g. in the case of frequency doubling of wavelengths around 1 μm, GVM is ~1 ps/mm. However, because of its high effective nonlinear coefficient d_{eff} ($=2/\pi * d_{33}$), PPLN can offer still a large product $d_{eff} * l_{eff}$ in the picosecond regime compared to other nonlinear materials.

Our experiments reported here have been aimed at confirming the suitability of PPLN for frequency doubling with picosecond pulses. Here we report on first-order QPM-frequency doubling of amplified picosecond pulses generated by an additive pulse mode-locked (APM) 1.047 μm Nd:YLF laser. The nonlinear material used in the experiment was a sample of PPLN, 3.2 mm long, suitable for frequency doubling of 2.6 ps pulses (l_{eff} ~ 2 mm). The periodic domain inversion, of pitch 6.4 μm, was obtained by applying high voltage pulses via liquid electrodes as described in refs. [1,2,4]. In these experiments we have scaled up the thickness of the sample from 0.2 mm to 0.3 mm and still find that it is possible to produce gratings of excellent quality.

Preliminary second harmonic (SH) measurements were carried out by using a CW diode-pumped Nd:YLF laser. The experimental temperature dependence of SH power on the crystal temperature (fig.1) agrees

well with the expected sinc^2 shape for a perfect grating 3.2 mm long. The estimated d_{eff} was ~ 15 pm/V. This reduced value compared to the theoretical limit of ~ 21 pm/V is probably mainly due to absence of periodic inversion in some regions of the sample as well as the duty cycle not being exactly 50/50, rather than due to random fluctuations in the position of the domain walls which would affect the shape of the phase-matching curve.

The APM configuration of the Nd:YLF laser gave transform-limited pulses at a repetition rate of 105 MHz. This CW mode-locked beam was pulse-sliced by an acousto-optic modulator and then the pulses were amplified in a diode-pumped bulk Nd:YLF amplifier used in a double pass configuration [6]. These amplified pulses of ~ 2.6 ps duration were frequency doubled in the PPLN sample.

At the QPM temperature of 73.5 °C, CW-mode-locked pulses of average power 650 mW (peak intensity ~ 110 MW/cm^2) were frequency doubled to ~ 275 mW of green with an average conversion efficiency of $\sim 43\%$. All the powers given here are internal values in the uncoated sample. Assuming a sech^2 shape, the SH pulse duration was estimated to be ~ 2.4 ps while the bandwidth of the corresponding frequency spectrum was ~ 175 GHz. The time-bandwidth product was thus ~ 0.42, indicating the presence of only a weak chirp.

The pulse train was then sliced before entering the amplifier, to produce an envelope of $\sim 10\mu$s duration and repetition rate of 2 kHz. Fig.2 shows the dependence of the average SH power within each 10 μs envelope on the corresponding average fundamental power. For an average fundamental power of 2.14 W (peak intensity ~ 360 MW/cm^2), the average SH power was 1.3 W, giving an average conversion efficiency $\sim 61\%$. Fig.3 shows the traces of the undepleted and depleted fundamental beam as well as of the SH beam.

At the highest conversion the measured M^2 beam quality factors for both SH and the exit fundamental beams were ~ 1.1 in both planes indicating that photorefractive damage was not significant even though the average green power within the envelope was > 1W and the peak intensities were > 300 MW/cm^2. The absence of any roll-off at higher powers in fig.2 is further evidence for the lack of photorefractive damage.

In addition the long term stability of the green output was tested over several hours and there was no sign of any degradation in terms of power and beam quality.

Thus we have confirmed that PPLN can be very effective nonlinear medium for picosecond pulses, with further prospects for power scaling from the values we have reported here.

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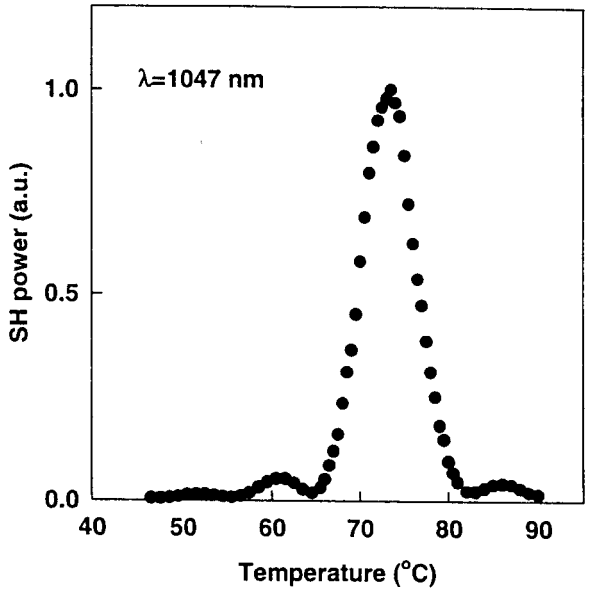

Fig.1 Dependence of generated second harmonic power on the temperature of the crystal.

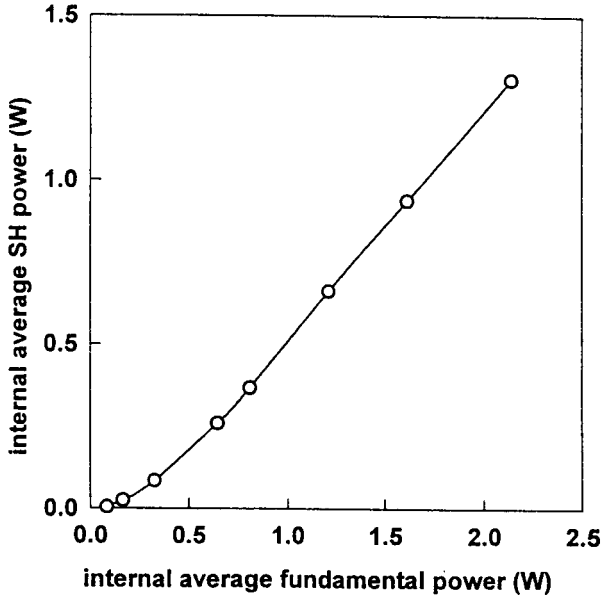

Fig.2 SH power as a function of the fundamental power in quasi-CW mode-locked regime. These powers are internal values in the uncoated crystal and average values over the 10 μs envelope.

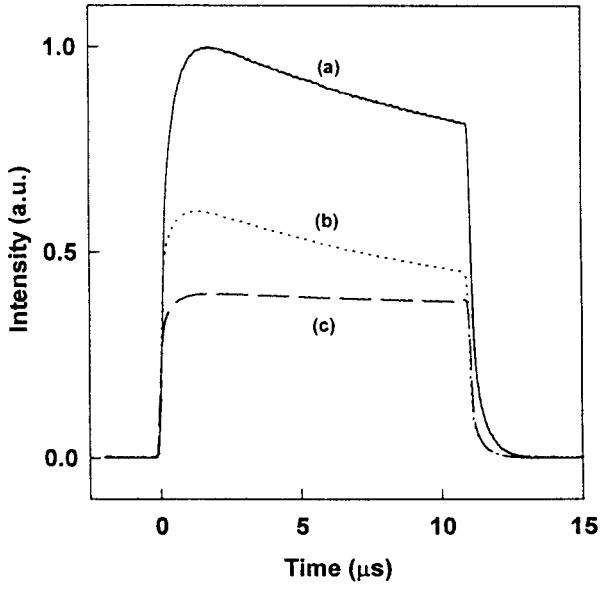

Fig.3 Temporal behaviour of: (a) undepleted pump, (b) second harmonic, (c) depleted pump.