Highly-efficient first-order quasi-phase-matched frequency doubling to blue of a cw diode-pumped 946 nm Nd:YAG laser

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The generation of blue-light via frequency doubling has attracted growing interest over recent years, owing to its potential use in high density optical storage and in medicine. Traditionally, frequency doubling of infra-red lasers has been accomplished with nonlinear crystals which rely on birefringent phase-matching. This dependence on birefringent phase-matching has greatly restricted the range of suitable nonlinear materials as well as the range of wavelengths that can be efficiently doubled. The net result has been that cw frequency doubling efficiencies in single-pass configurations have tended to be rather low.

More recently, there has been increasing interest in the use of quasi-phase-matched nonlinear crystals. Quasi-phase-matching (QPM) has several advantages over birefringent phase-matching, including access to higher nonlinear coefficients and non-critical interaction geometries for any wavelength in the transparency range of the crystal. QPM can be achieved by an appropriate periodic modulation of the nonlinear coefficient [1]. Nonlinear gratings fabricated in crystals such as $KTiOPO_4$ (KTP) [2], $LiTaO_3$ [3] and $LiNbO_3$ [4,5] have been used for blue light generation via frequency doubling both in bulk and waveguide geometries. So far, however, cw blue power from QPM materials has been limited to only few mW in bulk [3] and ~20 mW [4] in waveguide geometries.

In this paper we report single-pass highly efficient cw blue light generation by first-order QPM-SHG in lithium niobate of a high power diode-pumped Nd:YAG laser which oscillates at 946 nm. The results indicate a d_{eff} of ~19 pm/V.

The lithium niobate sample, used in our experiment, had a thickness of 200 μm and a length of 6 mm, and was periodically poled by applying a high voltage pulse, of ~4.5 kV and ~300 ms duration, via liquid electrodes as described in refs. [5]-[8]. The period of domain reversal required was rather short (4.6 μm), so careful attention was paid to the significant spreading of the inverted domains during the poling process in order to obtain a domain reversal period with mark-to-space ratio close to the optimum at 50:50.

The fundamental source used in our frequency doubling experiment was a diode-pumped Nd:YAG laser oscillating on the quasi-three-level transition $^4F_{3/2}$ - $^4I_{9/2}$ at 946 nm. This laser was end-pumped by a beam-shaped 20 W cw diode bar [9] and produced a polarised output of 1.5 W at 946 nm with beam quality factor $M^2 \leq 1.5$. The output from this laser was collimated and then focused into the uncoated PPLN sample with a $1/e^2$ waist spot diameter of 58 μm.

Fig.1 shows the SH power as a function of crystal temperature. The curve follows the expected sinc^2

shape and the bandwidth FWHM of ~3 °C is seen to be in good agreement with the theoretical prediction shown in fig.1.

Fig.2 shows that the dependence of the generated blue power on the fundamental power is close to the expected quadratic behaviour and shows no sign of roll-off at higher power.

Following the Boyd and Kleinmann treatment [10] we have estimated that the nonlinear coefficient d_{eff} is ~19 pm/V and thus is close to the theoretical limit of 21 pm/V expected for an ideal first order QPM grating in PPLN. In arriving at this estimate we have taken account of the multimode nature of the fundamental source (i.e. several longitudinal modes were oscillating and the beam was not perfectly diffraction-limited).

The highest conversion efficiency we have achieved was for a fundamental beam with a slightly smaller spot size in the PPLN sample, of $1/e^2$ diameter 38 μm. In this case an internal SH power of 49 mW was generated for an internal fundamental power of 1.07 W, corresponding to a fundamental intensity at beam centre of ~190 kW/cm^2. This result corresponds to a conversion efficiency of ~4.6% and a corresponding normalised conversion efficiency of ~7.1 %/(W*cm). To the best of our knowledge this is the highest value reported for blue light generation in bulk periodically poled materials.

At the maximum conversion efficiency we measured the M^2 beam quality factor of the SH beam to be ~3. The origin of this degradation in beam quality relative to the fundamental has not yet been conclusively identified. Some contributions may be due to imperfect polishing of the end faces of the sample, as well as the onset of photorefractive damage. This is the subject of continuing further investigation.

We believe that there are good prospects for further increasing the cw blue output power by fabricating longer gratings and by scaling the power of the 946 nm Nd:YAG laser.

References

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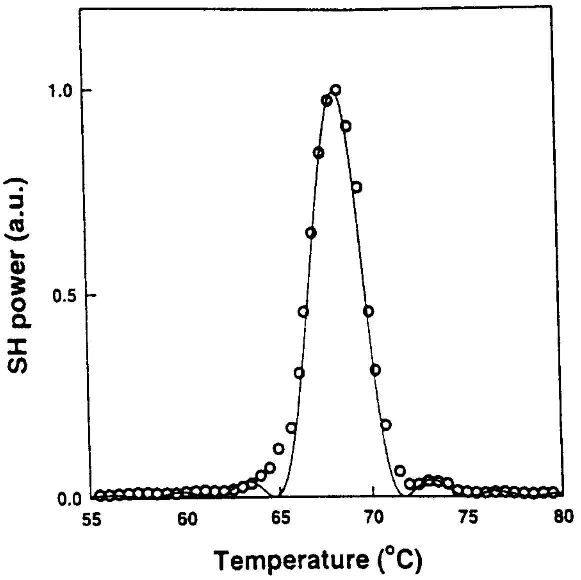

Figure 1 Temperature dependence of generated second harmonic power on the temperature of the crystal. The continuous line is the result of a computation for a pair of grating of the same length.

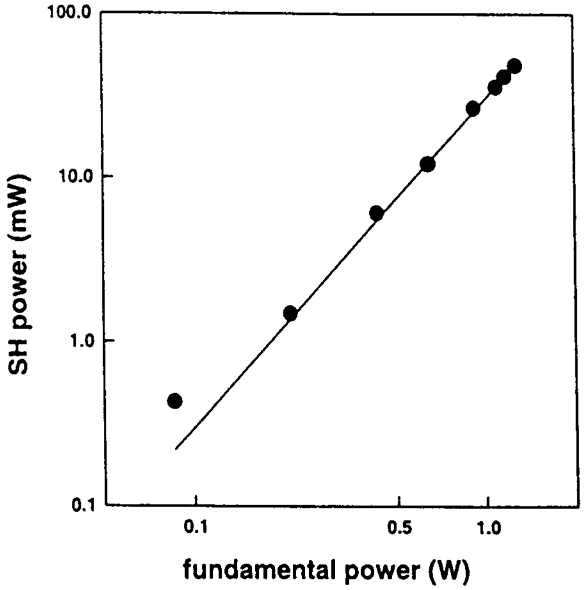

Figure 2 SH power as a function of the fundamental power. The powers relate to internal values for the uncoated sample. The continuous line is the best quadratic fit.