Generation of high-power blue light in periodically-poled $LiNbO_3$ (PPLN)

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Abstract

We report the generation of 450mW average blue (473nm) power by frequency-doubling of a diode-pumped 946nm Nd:YAG laser. Pulsed operation at high repetition rate (~ 160 kHz) was achieved by driving the relaxation oscillations of the laser. A 40% conversion efficiency to the second harmonic is obtained in a single-pass, extra-cavity, first-order, quasi phase-matched process using periodically-poled lithium niobate (period 4.5µm, thickness 0.5mm and length 15mm) at 140°C. The resulting high-power, blue beam is circular in profile and near-diffraction-limited, indicating that photorefractive effects do not appear to limit device performance.

With the continuing interest in the development of compact coherent blue light sources, nonlinear frequency conversion remains an attractive route. In particular, frequency doubling of the 946nm line of Nd:YAG offers a possible route to the generation of high average power in the blue (473nm) using all-solid-state technology. For example lithium iodate ($LiIO_3$), has been used as an intracavity frequency-doubler to give a cw output at 473nm from a diode-pumped Nd:YAG laser[1]. The technique of quasi-phase-matching, using periodically-poled lithium niobate (PPLN) offers an attractive alternative to $LiIO_3$, providing exact noncritical phase-matching, thus allowing tighter focussing, so that ultimately one can anticipate high conversion efficiency for the simple arrangement of single-pass extracavity frequency doubling. An earlier result with such an arrangement, using PPLN led to the generation of 49mW of 473nm light from a 6mm long sample[2].

It was noted in that work, that there was much scope for improvement. Here we describe how, with various improvements introduced, we have now achieved nearly an order of magnitude increase in average blue power, to 450mW, (although in this case using high repetition rate pulses rather than cw), with a performance that indicates that significant further power scaling should be possible. A particular aim of this work was to examine whether photorefractive damage, which is more problematic at shorter wavelengths, could in fact be kept to a minimal level, so that good beam quality could be maintained even at the higher average powers. This has been confirmed.

It is known that the periodically-poled structure can lead to significant reduction of the photorefractive effect[3,4]. Elevated temperatures also help. For the PPLN crystal used in these experiments a period of 4.5µm was chosen, so that first order quasi-phase-matching occurred at a temperature of 140°C. This is to be compared with the phase-match temperature of 68.5°C for the 4.6µm period used in ref.2 where a significant degree of photorefractive beam distortion (second harmonic beam quality factor of M^2 ~3) was becoming apparent at the 49mW blue power level. Electric field poling[5,6] was used to create the domain

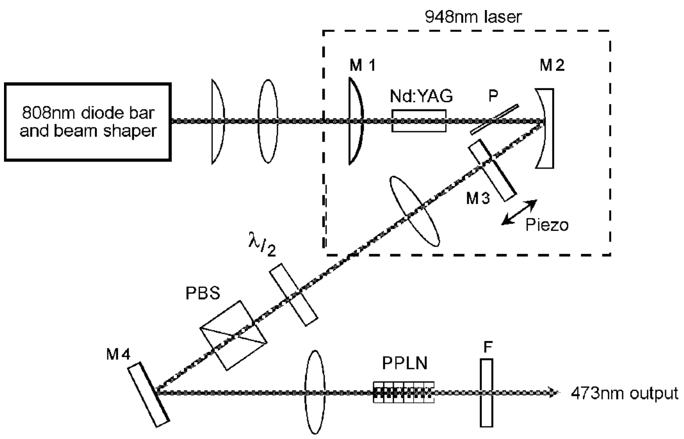

Fig. 1 The experimental arrangement for high power blue light generation. M1, M2, mirrors with radii of curvature of 100mm and 25mm respectively; M3, M4, plane mirrors. L1 and L2 are lenses with focal lengths 150mm and 50mm respectively. P is a polarising slide, λ/2 a half-wave plate, PBS a polarising beam splitter and F an IR filter. The Nd:YAG rod was 3mm long and 2mm in diameter with a Nd concentration of 1.1%.

grating. Preparation of the PPLN involved first photolithographically patterning the grating structure in photoresist on the -z face of a z-cut, 0.5mm thick, single domain crystal sample, followed by the application of a single high-voltage pulse (of ~11kV) along the z axis via liquid electrodes, at room temperature. The resulting PPLN structure was 15mm long, (c.f. 6mm in ref.2). Besides the length advantage, the 0.5mm thickness made the crystal much easier to use than the 0.2mm in ref.2.

The fundamental 946nm radiation for frequency-doubling was provided by a Nd:YAG laser, operating in a quasi-three level regime on the $^4F_{3/2}$ - $^4I_{9/2}$ transition, and end-pumped by a single beam-shaped diode-bar[7]. This transition requires intense pumping for efficient operation, and at the high average power level required for these investigations, there is strong thermally-induced lensing in the rod accompanied by significant spherical aberration. Under such conditions care is needed in the choice of resonator[8] to achieve the required good beam quality in a single polarisation at powers in excess of 1 Watt. With the resonator shown in fig. 1, with 14.2W of pump beam focussed to a 165µm spot-size ($1/e^2$ intensity radius) in the rod, and a convex mirror M_1 to partially compensate the thermal lensing, we were able to obtain a power of 1.5W at 946nm in a linearly polarised mode with a measured beam quality factor $M^2 = 1.1$. This beam

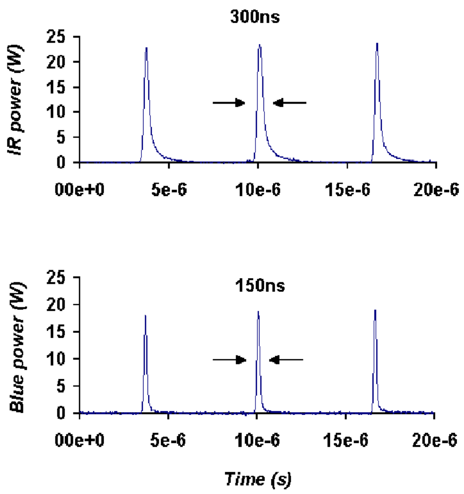

Fig. 2 The input infrared 946nm pulses (upper graph) and the corresponding generated blue 473nm pulses (lower graph) measured using a fast photodiode and sampling scope.

was focussed using lens L_2, into the PPLN sample to a spot-size of radius 30µm. Both the input and output faces of the PPLN sample were polished but left uncoated, with the faces deliberately angled

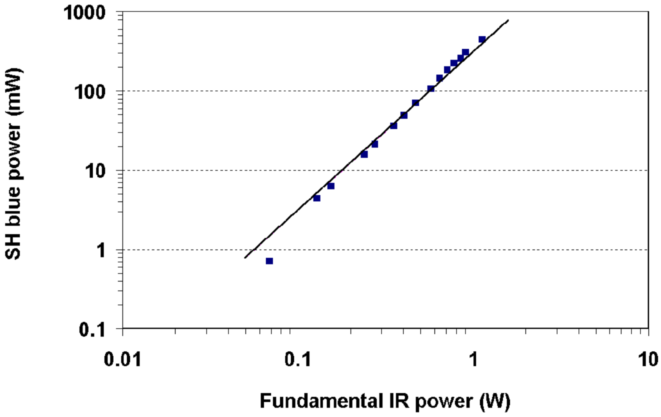

Fig. 3 Graph showing the dependence of the generated second harmonic (473nm) average power on the fundamental infrared (946nm) average power. Powers are internal to the PPLN. The solid line indicates a quadratic dependence.

slightly relative to each other to avoid any resonance effects. The sample was mounted in an oven, capable of up to 200°C operation and stable to within 0.1°C.

With the mean fundamental power available, in order to reach as high a mean SH power as possible, and thus be able to examine the degree of beam degradation due to photorefractive damage, the laser was deliberately operated in a pulsed fashion, via driven relaxation oscillation. This was achieved by the combination of optical feedback from the input face of the PPLN, with a piezoelectrically driven modulation of the axial position of the output coupler, M_3. The resulting train of regular pulses, of duration ~300ns, had a repetition rate of 160kHz, corresponding to the relaxation oscillation frequency of the laser. The average fundamental power incident on the PPLN was 1.32W, corresponding to 1.13W inside the PPLN. The upper graph in fig.2 shows this pulsing behaviour for the fundamental, the vertical power scale having been calculated from known average power, pulse shape and repetition rate.

The generated second harmonic is shown in the lower graph in fig.2. With the averaged 1.13W of (internal) fundamental power, an average of 450mW (internal) power was generated at the second harmonic. As expected, the second harmonic pulses were shortened (see fig.2) to

~150ns. Fig. 3 shows a plot of second harmonic power versus fundamental power, revealing a dependence close to the expected quadratic behaviour and showing little sign of roll-off at the highest power level. This, together with the observation that the SH beam had a clean circular profile, with measured M^2 values of $M_x^2 = M_y^2 = 1.25$, suggest that at these power and intensity levels, and at this temperature of operation (measured to be 141.6°C), there is little degradation in performance from photorefractive effects.

The PPLN sample was further characterised with the Nd:YAG laser operating in the cw mode. Using a loosely focussed beam, so as to satisfy the plane wave approximation, the SH temperature bandwidth was measured to be 1.2°C, from which an effective grating length, L_{eff},of 12mm is inferred. The difference between L_{eff} and the actual physical length of the grating, 15mm, arises from some non-uniformities in the grating, where periods are missed or regions are over-poled. Despite these imperfections the sample shows a respectably large d_{eff}. A value for d_{eff} was calculated from the experimental results obtained for cw operation, with 1.13W of internal fundamental power, focussed to a 30µm spot-size, generating 81mW of internal SH power. Under these conditions the Boyd-Kleinmann focussing factor[9,2] h = 0.9 and the factor   [see ref.2] accounting for SH enhancement due to multimode operation (4 modes) of the laser, was taken as   = 1.7. From these data it is calculated that the d_{eff} averaged over the 15mm length is $10pmV^{-1}$, or correspondingly $12pmV^{-1}$ over the effective length of 12mm.

In conclusion, we report the successful fabrication of fine-period bulk PPLN of thickness 0.5mm, length 15mm and grating period 4.5µm. Using the PPLN operating at around 140°C we have demonstrated efficient first-order, quasi phase-matched frequency-doubling of the 946nm line of a diode-pumped Nd:YAG laser. Driven relaxation oscillations allowed the laser to be operated in a high repetition-rate pulsed mode and under these conditions 450mW of average blue (473nm) power was generated, corresponding to a conversion efficiency of 40% from the infrared, in a single-pass, extra-cavity configuration. The high-power blue beam was circular in profile and near-diffraction-limited, indicating that photorefractive effects do not appear to impose a severe limitation to device performance. Thus compared with earlier results[2], by using an elevated phase-match temperature to reduce photorefractive effects, the beam quality has now been significantly improved, while at the same time the mean SH power has increased by nearly an order of magnitude. The results demonstrate the high-power handling capability of PPLN at this wavelength and suggest that, with further optimisations, of the 946nm laser and with provision of anti-reflection coatings on the PPLN, blue powers exceeding 1W should be readily achievable. The greater thickness of the PPLN sample would in fact permit multiwatt SH power once techniques have been perfected for maintaining high brightness operation of the Nd:YAG laser at multiwatt levels.

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