University of Southampton

Optoelectronics Research Centre

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Southampton SO17 1BJ, UK. Telephone: +44 2380 593150 E-mail: light@orc.soton.ac.uk

High Power Diode-Bar-Pumped Intracavity-Frequency-Doubled Nd:YLF Ring Laser

P. J. Hardman, W. A. Clarkson and D. C. Hanna

Abstract

We report efficient cw operation of an intracavity-frequency-doubled Nd:YLF ring laser end-pumped by two beam-shaped 20W diode bars. A single-frequency, polarised output of 6.2W at 526.5nm (8.3W generated in the doubling crystal), was obtained in a TEM_{00} mode (M^2 < 1.2).

The use of diode-pumped solid-state lasers as sources of coherent high power visible light is an area which has attracted growing interest in recent years. This interest stems from the increased efficiencies available and the compact size compared to Ar^+ lasers. A further attractive feature of intracavity-doubled, single-frequency lasers, recently reported, [1] is that axial-mode-hopping is suppressed. Recent developments of diode-pumped, intracavity-frequency-doubled lasers have included; Nd:YAG [2][3] and Nd:YVO_4[4] lasers operating at 1.064µm and doubling to 532nm. A major problem with these lasers is that they exhibit strong thermal lensing which, furthermore, is highly aberrated. This places stringent requirements on the resonator design and complicates further power scaling. In this paper we describe a diode-pumped intracavity-frequency-doubled laser which uses an alternative material, not exhibiting these thermal problems to the same degree and hence has excellent prospects for further power scaling, i.e. Nd:YLF.

In Nd:YLF the pump-induced thermal lens is weak since there is a cancellation due to the opposite signs of the thermal lenses created by the change in refractive index with temperature (negative lens) and the convex bulging of the end-faces (positive lens). Another important advantage of Nd:YLF over Nd:YAG is the presence of natural birefringence which avoids the problem of thermally-induced stress-birefringence. The loss due to such stress-birefringence can impact significantly on the performance of intracavity-frequency-doubled lasers. A major limitation to the widespread acceptance of Nd:YLF has been its low thermally induced fracture limit, which is ~5 times lower than in Nd:YAG. With appropriate design of the pumping geometry this problem can be alleviated and we have recently demonstrated robust operation of a high-power Nd:YLF laser giving 11.1W of 1.053 µm output.[5] The fracture problems were overcome by detuning the pump wavelength and absorbing the pump over the combined length of two laser rods (each rod was ~8mm). A similar pump set-up is used in the laser described in this paper, although a single, longer rod was used (~15mm).

Fig. 1 shows the cavity arrangement for this laser. The basic design is a “bow-tie” ring resonator which provides a tight focus at the location of the frequency-doubling crystal and good mode-

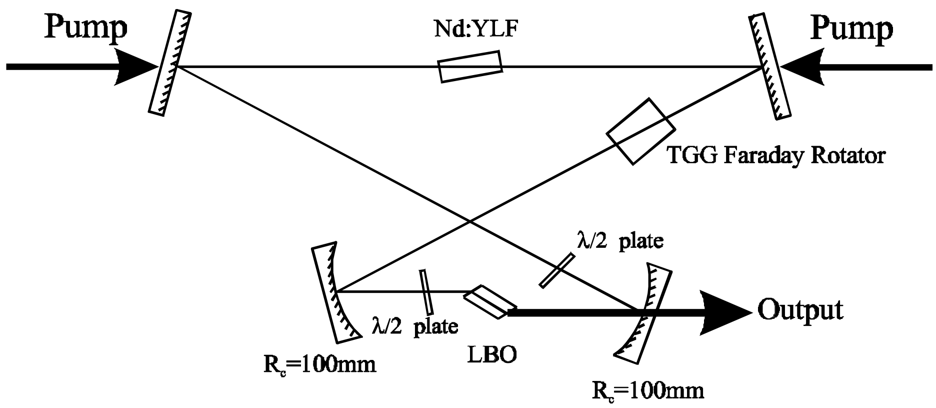

Fig. 1 Schematic Diagram of the Nd:YLF ring laser resonator, with TGG Faraday rotator and LBO frequency-doubling crystal.

matching with the pump in the Nd:YLF rod. The Nd:YLF rod is pumped from opposite ends by two beam-shaped diode bars and the laser is forced to operate unidirectionally by a Faraday rotator. A unidirectional ring resonator was used to enforce single-frequency operation and thus avoid the chaotic fluctuation behaviour commonly seen in multimode standing-wave resonators, colloquially known as the "green problem".[6]

The Nd:YLF rod was mounted such that the c-axis was parallel to the resonator plane (x-z). Since the pump was predominantly horizontally polarised, this crystal orientation ensured that the pump observed the stronger absorption polarisation. In order to obtain operation on the 1.053μm transition, which observes the weaker thermal lens, the laser polarisation through the crystal needed to be vertical to the resonator plane. After leaving the crystal, the laser light polarisation observed a ~6° rotation due to the Faraday rotator and was rotated to horizontally polarised light by a half-wave plate before entering the Brewster-angled frequency-doubling crystal. Another half-wave plate was needed in order to rotate the horizontally polarised light back to vertical polarisation. Sufficient loss difference was provided by the reduced gain observed by the other lasing direction due to the extra loss incurred from the Brewster surface.

In contrast to the previous laser setup, [5] thermally-induced fracture was avoided by using a low Nd-doped rod (0.5 at. %) with the diode temperature tuned onto the absorption peak at λ=792 nm. For the same laser gain this approach offers a reduced risk of fracture compared with our previous method, since in the temperature detuned scheme, with a high doped rod, there can often be strong absorption in the wings of the diode pumping, even though the average absorption is weak. The diode pump beam was predominantly horizontally polarised and ~91% of the beam was absorbed (implying an average absorption length of ~6mm). Some pump light of vertical polarisation was unabsorbed, due to the weaker absorption for this polarisation. However, pumping at 797nm, for which both polarisations have more similar absorption coefficients should give slightly more efficient pumping.

The use of the two-mirror beam shaper to reconfigure the output from the diode bar was an important feature since optimum beam quality was needed to ensure that the pump remained collimated throughout the length of the crystal. The principle of operation of the two mirror beam shaper is described in detail in Ref. [7]. The pump focussing optics were configured in order to obtain a waist radius of ~300μm with similar M^2-values in orthogonal planes. This relatively large spot-size was chosen in order to reduce thermal effects and enable a long collimated region within the rod. The actual values achieved were waist radii of 300μm x 280μm in orthogonal planes with M^2 values of ~ 130 and ~80 respectively, for diode bar A and waist radii of 310μm x 315μm with respective M^2 values of ~70 and ~80, for diode bar B. With the pump beam parameters a confocal

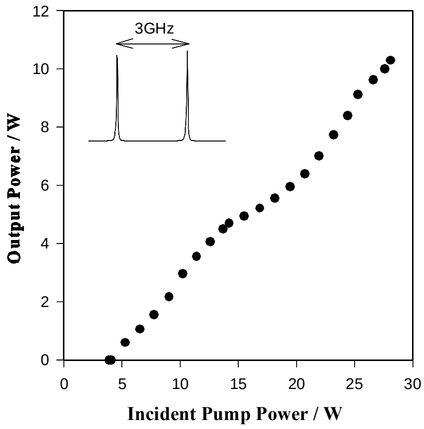

Fig. 2 Output power versus incident pump power with T = 10 % output coupler. At full pump power 95% of output is at 1.053µm. *Insert* : Scanning Fabry-Perot trace, for the 1.053µm leakage, at full pump power. This confirms single-frequency operation.

parameter of ~12 mm within the rod is achieved. The pump power was measured using a Coherent LM-45 power meter with an accuracy of ±2%.The maximum pump power incident upon the crystal was 14.2W for diode bar A and 13.9W for diode bar B.

The laser was operated on the lower gain 1.053µm transition because this transition has a weaker thermal lens than the higher gain 1.047µm transition. The thermal lens focal length, for the 1.053µm polarisation, was measured as ~700mm perpendicular to the c-axis and ~ 2000mm parallel to the c-axis. This weak lensing allowed use of a simple cavity design which did not require compensation for the thermal lens. The two curved mirrors (R_c=100mm), see fig. 1, produced a waist in the Brewster-angled frequency-doubling crystal of ~60µm radius. The cavity dimensions were; ~180mm between plane mirrors; ~170mm between the plane and the curved mirrors; ~115mm between the curved mirrors. The angled incidence on the curved mirror (~ 14°) was chosen to compensate for the astigmatism created by the Brewster-angled crystal. It was essential to ensure that all the intracavity components had low loss since for efficient frequency conversion the non-linear loss must dominate. All AR coatings had <0.2% reflection loss and the total round-trip cavity loss was measured, via the so called Findley-Clay method, as being ~2%. A Faraday rotator was chosen to provide unidirectional operation since a large loss difference was required i.e. large enough to maintain unidirectional operation even with the presence of significant non-linear loss due to frequency conversion. The Faraday medium was a 6mm long Terbium Gallium Garnet (TGG) crystal which produced ~ 6° rotation at 1.053µm. It was found that robust unidirectional operation could be achieved at all pump powers. Lithium Triborate (LBO) was chosen as the frequency-doubling crystal, its nonlinearity being sufficient for efficient frequency conversion at the anticipated intracavity fundamental powers. The crystal was operated at a temperature of 162.6 °C in order to achieve type 1 non-critical phase matching. LBO has other advantages for high power operation, namely a high damage threshold, a large angular acceptance and type-I phase matching, so that the IR beam retains the same polarisation after propagation through the crystal.

Initially the laser was adjusted to optimise the fundamental output using a 10% output coupler in place of the right-hand curved mirror, see fig. 1. Fig. 2 shows the corresponding total output power as a function of incident pump power, the highest total output power being 10.3W of which ~9.7W was at 1.053µm and ~0.6W at 526.5nm. This was with an incident pump power of

28.1W (25.6W absorbed). The average slope efficiency (output power against incident pump power) is ~ 40%. The slope efficiency showed no sign of roll-off, thus indicating scope for further power-scaling. The first part of plot was with one diode only, its increasing gradient is caused by the diode progressively temperature tuning to the optimum pump wavelength. The second part of the plot, where the second diode is pumped progressively harder, represents the same behaviour. Even without a frequency selective device, such as a birefringent filter, [4] the laser was robustly single frequency, throughout the pump power range, as confirmed by a Fabry-Perot interferometer. A typical scanning Fabry-Perot trace, taken at the full pump power, is shown in the insert of fig. 2, free from any sign of adjacent modes at ~ 0.5 Ghz spacing. The compensation of the astigmatism was successful, resulting in less than ~10% difference between the x and y-planes for the output beam. The beam quality was measured using a Coherent Modemaster, which gave $M_{x,y}^2 < 1.1$, throughout the pump power range. Also, over this range, the pump spot size varied by less than 15%, clearly demonstrating the weak nature of the thermal lens. Previously a fundamental output power of 11.1W was obtained in a simple folded resonator[5] without a doubling crystal. The output power of 10.3W from this ring resonator, which has more mirrors and many additional intra-cavity components, is a testiment to the lower losses of these various components, and confirms the efficiency of this pump scheme with the 0.5 at.% doped rod.

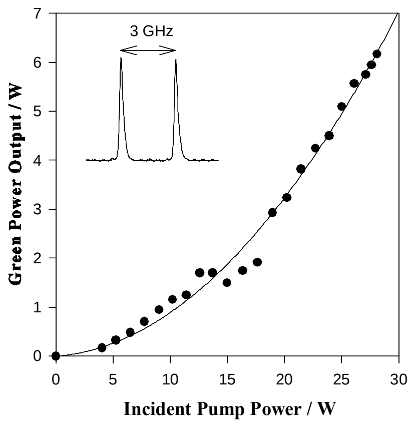

Fig. 3 Output power versus incident pump power at 526.5nm. *Insert* : Scanning Fabry-Perot trace, for the 1.053µm leakage, at full pump power. This confirms single-frequency operation.

To maximise the output at 526.5nm, we replaced the 10% output coupler with a mirror having high reflectivity at 1.053µm and ~91% transmission at 526.5nm. With the laser optimised for operation when pumped by one diode the maximum power achieved was 2.7W. This corresponds to 3.6W generated within the crystal, since 18 % was lost at the Brewster-angled exit face of the LBO and 9% was lost through imperfect transmission of the output mirror. Fig. 3 shows the output power as a function of incident pump power with both diodes. The highest output power achieved was 6.2W (corresponding to 8.3W generated). This curve shows no sign of roll-over i.e. to less than linear growth at highest powers. This confirms that lensing is not causing problems and suggests that further power scaling, which would be expected to show a linear dependence on pump power at these higher power levels, should be possible. The beam quality factor of the 526.5nm output was measured with a Merchantek beam profiler, since this unit operated at 526.5nm, and it was found that $M_{x,y}^2<1.2$ throughout the pump power range. Again the beam size altered by < 15% and the amplitude stability of the laser was excellent with peak to peak fluctuations of ≤ ±0.5% throughout the pump power range. The insert in fig. 3 gives a scanning Fabry-Perot trace at full pump power. Even without a frequency selective element single-frequency operation was robust up to ~5W of output power. Above 5W operation more frequencies would occur, however it is expected that robust single-frequency operation should be restored by using a frequency selective element, such as a birefringent filter[4]. Despite the tendency to multi-frequency operation, above 5W of output power, the amplitude stability of the laser remained excellent, i.e. ≤ ±0.5%.

In summary, we have verified that Nd:YLF offers the distinct advantage of weak lensing over Nd:YVO_4 and the additional advantage of natural birefringence over Nd:YAG for high power operation of diode-pumped lasers. Its main perceived problem has been stress-fracture at high-power levels. However using a low doped crystal and a well collimated pump beam we have obtained > 10W of single-frequency output with a 10% output coupler (~9.7W at 1.053µm and ~0.6W at 526.5). With a high reflector, for 1.053µm, 6.2W of polarised output (8.3W generated inside the LBO), at 526.5nm, was obtained. This output had excellent beam quality ($M_{x,y}^2$ <1.2) and amplitude stability (≤ ±0.5%) throughout the pump power range. A small variation in beam size confirmed the weak nature of the thermal lens in Nd:YLF. There is clearly scope for further power scaling of this laser since no decrease of the slope efficiency was observed. Future work will include optimising the pump absorption and coupling more diode bars into the system.

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