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Thermal birefringence-compensated linear intracavity frequency doubled Nd:YAG rod laser with 73 ns pulse duration and 160 W green output power

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Abstract. In a thermally birefringence-compensated linear cavity configuration, ∼160 W of average green power by intracavity frequency doubling of AO Q-switched Nd:YAG/LBO-based laser is demonstrated. The corresponding optical to optical conversion efficiency is estimated to be ∼12.7%. The pulse repetition rate is 20 kHz with the individual pulse duration of 73 ns. The beam quality parameter is measured to be 18.

Keywords. Nd:YAG laser; diode-side-pumped; thermal lens Q-switched; linear cavity; intracavity second harmonic generation.

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1. Introduction

High average power green laser beam with high repetition rate, short pulse duration and reasonably good beam quality is an attractive source for various industrial and scientific applications. One of the important applications of such lasers is to pump high power Ti:sapphire or dye laser-based tunable oscillator and amplifier systems. For efficient pumping of these systems, high average power green laser beam with high repetition rate [1], high pulse energy (5–10 mJ) [2], high peak power (∼100 kW) [2] and M^2 parameter less than 30 [3] is required. Intracavity frequency doubling of repetitively Q-switched high power diode-pumped Nd:YAG rod laser operating at ∼1 μm wavelength has proven to be an effective method in generating high average power green beam with high efficiency, good beam quality and low instability. However, it is difficult to obtain high average power as well as short pulse duration from intracavity frequency doubled systems primarily due to the high finesse of the resonator required for efficient frequency conversion [4]. Though considerable efforts have been made in the recent past to reduce the pulse duration from the intracavity frequency doubled Nd:YAG laser, the average power was limited to less than or around 100 W [5–7].

In this paper we report the development of a high average power green laser system to meet the requirements for the above-mentioned applications. We have demonstrated 160 W of average green power from a thermal birefringence-compensated linear intracavity frequency doubled Nd:YAG laser with ∼12.7% pump to green conversion efficiency. The laser is repetitively Q-switched at 20 kHz repetition rate. The pulse energy, pulse duration, peak power and beam quality parameter are measured to be 8 mJ, 73 ns, 110 kW and 18 respectively at the maximum operating pump power.

2. Experimental set-up

The laser arrangement is shown schematically in figure 1. The laser consists of two pump heads (PH1 and PH2) to couple the diode laser beam to the Nd:YAG rod, a nonlinear crystal for intracavity frequency doubling, two acousto-optic modulators (QS1 and QS2) for repetitive Q-switching, a 90° quartz rotator and a linear resonator. Two laser head modules have the same geometry and each laser head consists of a Nd:YAG rod (diameter: 4 mm; length: 100 mm, orientation: [1 1 1]) with 0.6 at% Nd^{3+} doping concentration, a cooling sleeve, a diffusive optical reflector and three diode array modules. The crystal rod has a fine ground barrel to minimize the optical loss caused by the gallery modes that occur within the round crystal surface. The rod is surrounded by an antireflection-coated cooling sleeve and placed at the centre of the three-slit symmetric cylindrical diffusive optical cavity. The diffusive optical cavity distributes the pump beam uniformly through the crystal rod, and minimizes the thermally related optical loss. The pump beam from the linear diode arrays was coupled to the laser rod through three slits (1.5 mm width) of the diffusive optical cavity in three-fold symmetry. The total pumping power from the laser diodes used in these two laser heads was ∼1.5 kW at the maximum operating current used in this set-up. The distance between two pump heads for thermally stable resonator was optimized on the basis of prior simulation results and was kept 190 mm. A 90° polarization rotator made of crystalline quartz was placed between two identical pumps for compensating the thermally-induced birefringence in the laser rods. Two water-cooled apertures A1 and A2 of 3.8 mm diameter were placed close to the outer faces of both the laser rods to avoid their damage.

For second harmonic generation (SHG), we used an 18 mm long LBO crystal cut for type-II phase matching at room temperature. The LBO crystal was placed in a press-fitted copper block mount which was maintained at 20°C using a chiller unit. For repetitive

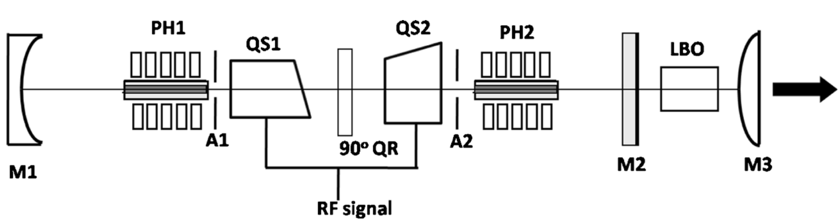

Figure 1. Schematic of the experimental set-up.

Q-switching we used two orthogonally oriented AO modulators (carrier frequency = 24 MHz) to increase the hold-off capability and placed between both the pump heads as shown in figure 1. The laser resonator was a concave–convex linear cavity designed to obtain both a large mode area at the gain medium and tight spot size at the LBO crystal for efficient second harmonic generation. The rear mirror M1 was a plano-concave (radius of curvature = 2 m) with high reflection coating at the fundamental wavelength at 1064 nm ($R > 99.7\%$) and second harmonic wavelength 532 nm ($R > 99.5\%$). Mirror M2 is a plane harmonic mirror with antireflection coating at 1064 nm ($R < 0.2\%$) and high reflection at 532 nm ($R > 99.5\%$) in order to retro-reflect the backward generated green beam. The output mirror M3 was a plano-convex mirror with high reflection coating at the fundamental wavelength ($R > 99.7\%$) and high transmission coating ($T > 95\%$) at the SHG wavelength to couple out the green beam. The pump head was placed between the two mirrors M1 and M2 and the LBO crystal was kept between the mirrors M2 and M3. The total physical length of the resonator was kept as ~71.5 cm.

3. Results and discussion

The variation of the resonator stability and fundamental mode radius at the laser rod and the LBO crystal as a function of diode pump power was estimated using ABCD matrix analysis of the resonator incorporating the measured variation of thermal lens focal length with pump power for both the pump heads. Figure 2a represents the change in the resonator stability as a function of distance d_1 (distance between mirror M1 and PH1) at different levels of operating pump power. The optimum value of distance d_1 was found to be 190 mm for pumping up to higher power level (~600 W). In figure 2b the estimated variation of TEM_{00} mode radius at the Nd:YAG rods in both the pump heads and that at the LBO crystal are shown as a function of the pump power. It can be seen that the mode

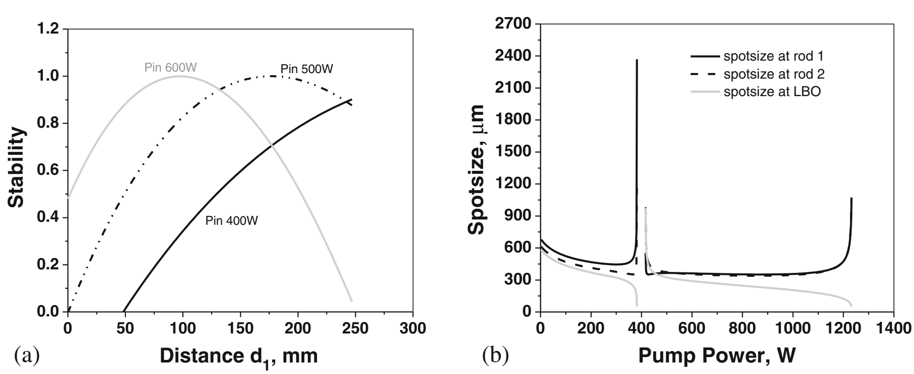

Figure 2. (**a**) Variation of resonator stability as a function of distance d_1 and (**b**) estimated variation of the TEM_{00} spot size as a function of pump power for $d_1 = 190$ mm.

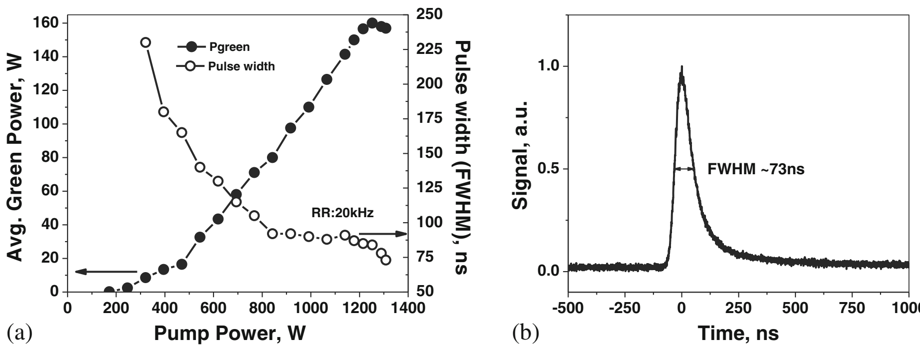

Figure 3. (**a**) Slope efficiency curve for the green laser and (**b**) recorded green laser pulse shape.

radii (∼450 μm) at both the laser rods are nearly equal and independent of the pump power above ∼430 W. This ensures that the overlap efficiency of the pump beam and cavity mode would not vary dynamically over this range of the pump power and should lead to a linear slope efficiency curve. On the other hand, the TEM_{00} mode radius at the LBO crystal reduces with the pump power. Thus, the cavity has a moderate ratio of spot sizes at the gain medium and nonlinear crystal which is essential for efficient second harmonic conversion. Further, the thermal stress-induced birefringence in one pumped laser rod is compensated in another pumped rod using a 90° quartz rotator between them.

The performance of the laser in intracavity frequency doubled configuration is shown in figure 3a. The solid circles represent the average green power at 20 kHz and the open circles are the corresponding full-width at half-maximum (FWHM) of the green pulse as a function of the total pump power. The threshold pump power was measured to be ∼190 W. As the pump power was increased beyond 200 W, the average green power increased linearly with the pump power. A maximum average power of 160 W at 532 nm was obtained at 1.25 kW of pump power with 20 kHz of repetition rate. The pump to green conversion efficiency was measured to be ∼12.7%. On further increasing of pump power, the output power starts to roll off as the cavity becomes unstable due to strong thermal effects. At the maximum output power, the green pulse duration (FWHM) was measured to be ∼73 ns. A typical green pulse shape is shown in figure 3b. The beam quality parameter was measured to be 18 at the maximum output power.

4. Conclusions

We have demonstrated stable 160 W of average green power with 12.7% optical to optical conversion efficiency from a thermal birefringence-compensated linear intracavity frequency doubled Nd:YAG/LBO-based laser. The laser was Q-switched by two AO modulators at 20 kHz repetition rate. The green pulse duration (FWHM) and M^2-parameter were measured to be 73 ns and 18 respectively.

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