PRAMANA — journal of physics | © Indian Academy of Sciences | Vol. 75, No. 5
November 2010
pp. 935–940

101 W of average green beam from diode-side-pumped Nd:YAG/LBO-based system in a relay imaged cavity

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Abstract. Studies on intracavity frequency doubling of acousto-optically Q-switched Nd:YAG rod laser using 18 mm long type-II phase-matched LBO crystal in a relay-imaged cavity is reported. A single pump head comprised of Nd:YAG rod, diffusive reflectors and linear array laser diode bars is used. 101 W of average green power at a total diode pumping power of 700 W is obtained corresponding to 14.4% optical-to-optical conversion efficiency. The pulse repetition rate is 30 kHz with an individual pulse duration of 200 ns.

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

PACS Nos 42.55.Xi; 42.55.Rz; 42.60.Gd

1. Introduction

High average power green laser with high repetition rate is an attractive source for various applications such as high-speed processing of high reflectivity materials like silicon or metals, pumping of high power dye laser and Ti:sapphire laser etc. Intracavity frequency doubling of CW diode-pumped acousto-optic Q-switched Nd:YAG laser is an efficient way to generate high average power green beam with high efficiency and low instability. In the recent past many 100 W level intracavity-frequency-doubled green lasers have been reported but most of the systems employed two laser heads in various cavity configurations to achieve such high power [1–3]. But, use of two pump heads increases the complexity of the system as it requires precise alignment of the two pump heads, failing of which may lead to damage of the pump heads as well as distortion in the output beam profile. Further, both the pump heads should be identical in geometry for the compensation of pump power-induced thermal birefringence. These requirements impose a serious limitation on the development of a practical high-power green laser system for industrial use. In an earlier work we have demonstrated high average power green beam generation in an Nd:YAG/KTP-based system using a single pump head [4].

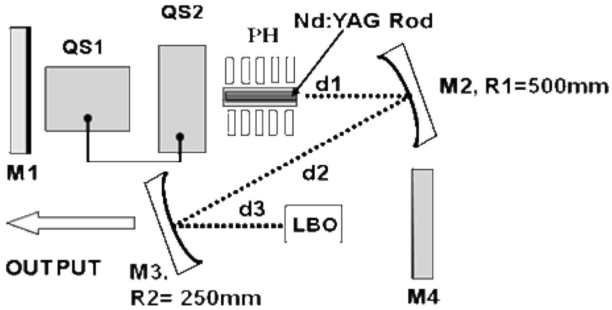

Figure 1. Schematic of experimental arrangement.

The output power, however, was limited to ∼75 W due to the gray track formation in the KTP crystal [5]. In contrast to KTP crystal, LBO has higher damage threshold and is free from gray track formation but has order of magnitude lower effective nonlinearity requiring a longer crystal.

In this paper we report our studies on intracavity frequency doubling of acousto-optically Q-switched Nd:YAG rod laser using 18 mm long type-II phase-matched LBO crystal in a relay-imaged cavity. A single pump head comprised of Nd:YAG rod, diffusive reflectors and linear array laser diode bars is used. 101 W of average green power at 532 nm at a total diode pumping power of 700 W is obtained corresponding to 14.4% optical-to-optical conversion efficiency. The pulse repetition rate is 30 kHz with an individual pulse duration of 200 ns.

2. Experimental set-up

The experimental arrangement is shown schematically in figure 1. The laser set-up is made of a pump head, acousto-optic modulators, LBO crystal and an Z-shaped resonator. The schematic of the pump head under diode-side pumping configuration is shown in figure 2. The pump head consists of an Nd:YAG rod, a flow tube, a diffusive reflector and 15 linear array laser diode bars. The Nd:YAG rod is of 4 mm in diameter, 100 mm long and 0.6 at.% Nd^{3+} doped with finely ground barrel surface. The rod is inserted within the flow tube through which the coolant water flows. The Nd:YAG rod and the flow tube is enclosed by diffusive reflectors with three narrow windows on it for coupling of the pump beam. The diode bars are grouped into three modules and placed carefully close to the windows on the diffuse reflector assembly for three-fold symmetric pumping of the laser rod. The effective pump length of the rod is about 55 mm. The Nd:YAG rod absorbs the pump beam on direct incidence as well as after multiple reflections from the diffusive reflector surface. It leads to efficient absorption and uniform distribution of the pump beam in the laser rod.

The Z-shaped cavity consists of a plane mirror M1 which is highly reflecting ($R > 99.8\%$) at the fundamental wavelength 1064 nm. The pump head and the LBO crystal are placed in the parallel arms of the Z-shaped cavity formed by the mirrors M1, M2 and M3, M4 respectively. The concave mirrors M2 and M3

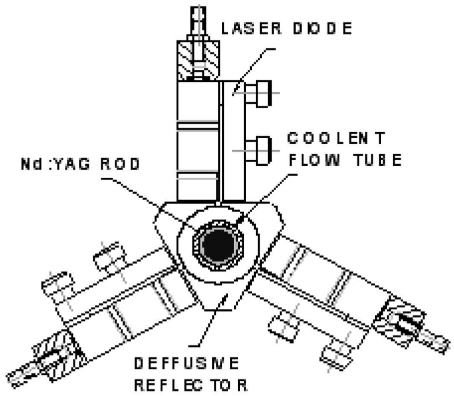

Figure 2. Schematic of the pump head assembly.

between the laser rod and the LBO crystal work as relay optics which images the laser rod aperture on the nonlinear crystal with a certain magnification. In diode-pumped solid-state lasers, the intracavity mode size varies dynamically with the pump power due to the thermal lensing effect. This may lead to very high power density and subsequent damage of the nonlinear crystal. In the relay-imaged cavity configuration the multimode spot size at the nonlinear crystal is clamped to the diameter of the Nd:YAG rod and will not collapse to tiny spot size even if the cavity becomes unstable because of the thermal lensing effect. Both the mirrors are kept at a folding angle of 10° to minimize the astigmatism. The radii of curvature $R1 = 50$ cm and $R2 = 25$ cm of mirrors M2 and M3 respectively determine the magnification ratio: $m = R2/R1$. Mirror M2 is highly reflecting ($R > 99.5\%$) at both 1064 and 532 nm wavelengths while mirror M3 is highly reflecting at 1064 nm and highly transmitting ($R < 2\%$) at 532 nm to get the output green beam. Mirrors M2 and M3 imaged the rod aperture on the nonlinear crystal with a magnification of 0.5. The distance between two curved mirror is kept at $d_2 = (R1 + R2)/2$ and distances d_1 and d_3 satisfy the relation $md_1 + d_3/m = d_2$ [6]. Mirror M4 is a plane mirror which is also highly reflecting at the fundamental wavelength 1064 nm as well as at the second harmonic wavelength at 532 nm. The laser is repetitively Q-switched with two acousto-optic modulators, oriented orthogonally to increase the hold-off capability [7] and operated synchronously at 30 kHz repetition rate. The LBO crystal ($4 \times 4 \times 18$ mm^3) for intracavity frequency doubling is AR-coated on both of its surfaces at 1064 nm and 532 nm to reduce the intracavity losses. The LBO crystal is cut for type-II critical phase matching at 1064 nm with $\theta = 21.1°$, $\phi = 90°$ in YZ principal plane at room temperature operation. The temperature of the LBO crystal is finely adjusted as the conversion efficiency is sensitive to fluctuation of temperature. The LBO crystal is wrapped with indium foil and installed in a water-cooled copper block. The temperature of the flowing water in copper block is maintained at 27 ± 0.5° with the help of a chiller unit.

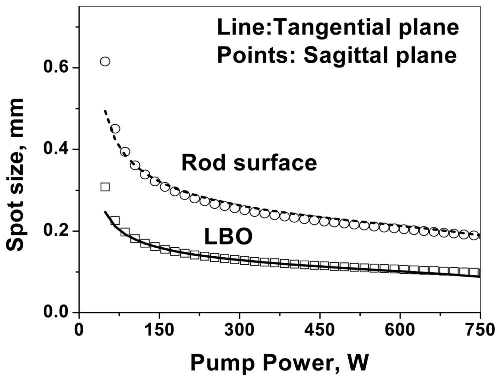

Figure 3. Calculated variation of fundamental mode size.

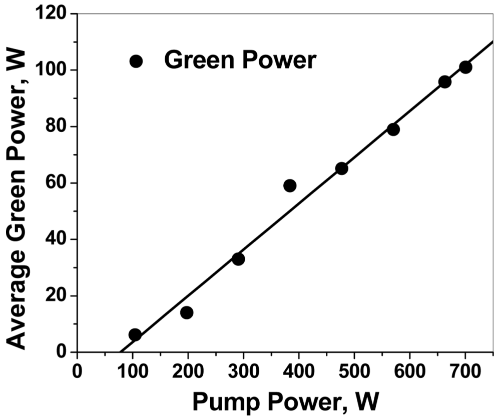

Figure 4. Green power vs. the pump power.

3. Experimental results and discussions

We calculated the variation of the fundamental mode radius at the laser rod and the LBO crystal as a function of diode pump power by ABCD matrix analysis of the cavity incorporating the measured variation of thermal lens focal length with the pump power. The results for these calculations for tangential and sagittal planes are shown in figure 3. It can be seen from figure 3 that the fundamental spot radius at the gain medium and at the LBO crystal decreases with the pump power due to the thermal lens. The spot radius at the LBO crystal, however, is always ∼0.5 times to that at the Nd:YAG rod due to the relay imaging. This implies that the multimode spot size at the LBO crystal will remain constant throughout the operating range of the pump power as the M^2 parameter of the fundamental beam is decided by the ratio of the aperture radius of the Nd:YAG rod and the fundamental spot radius at the aperture location [8]. It can also be seen that the output beam has a negligible astigmatism as the calculated spot radius for the sagittal and the tangential plane is nearly the same due

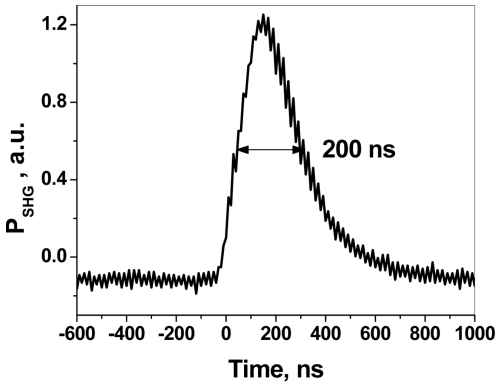

Figure 5. Recorded green pulse shape.

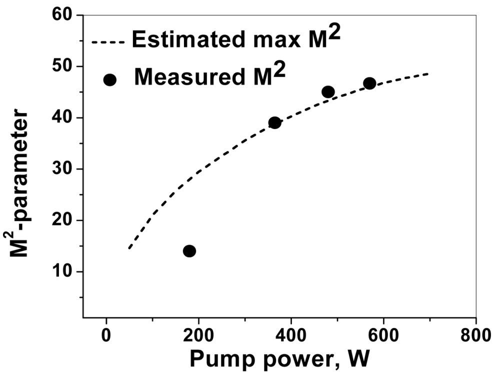

Figure 6. Calculated and measured M^2 parameters.

to the Z-shaped cavity construction. The laser was first operated at the fundamental wavelength at 1064 nm by removing the LBO crystal from the cavity and replacing the end mirror M4 with a plane output coupler mirror of 92% reflectivity. At a pump power of 664 W, the laser delivered 182.3 W CW output power at 1064 nm. In intracavity frequency doubled configuration the average green power increases linearly with the pump power with a slope of 16.3% as plotted in figure 4. A maximum average green output power of 101 W was obtained for an input pump power of ~700 W at a repetition rate of 30 kHz corresponding to 14.4% optical-to-optical conversion efficiency. We have not observed any damage of the nonlinear crystal, however the output green power is found to be sensitive on the temperature of the LBO crystal because of its narrow temperature acceptance bandwidth (~4°C). Figure 5 shows the recorded temporal profile of the green pulse. The minimum pulse width is measured to 200 ns (FWHM) at the maximum pumping power.

The output green profile is circular in shape due to the negligible astigmatism in the cavity. The M^2 parameter, however, is significantly high because of the side pumping configuration. In figure 6 we plot the measured variation of the

M^2 parameter as a function of the pump power along with the estimation of the maximum M^2 value from this cavity. The maximum M^2 value is estimated from the ratio of the radius of the Nd:YAG rod and the fundamental mode radius at the surface of the Nd:YAG rod facing the LBO crystal. As the fundamental spot radius decreases with the pump power as shown in figure 3, the M^2 parameter is expected to increase with the pump power as shown by the dashed line in figure 6. At the low pump power the measured M^2 parameter is found to be much smaller than its maximum possible value as the higher-order modes could not reach the threshold. But, at the higher pump power all the transverse modes are oscillating and the measured M^2 is found to be close to the maximum value. It is worth to mention here that the thermal aberration may further deteriorate the beam quality which is found to be negligible here.

4. Conclusion

In conclusion, by employing a single pump head with single crystal Nd:YAG laser rod in Z-shaped resonator we demonstrated high average power green beam generation by intracavity frequency doubling in type-II phase-matched LBO crystal. The laser was acousto-optically Q-switched at a repetition rate of 30 kHz. A maximum 101 W of average green power was obtained at ∼700 W of pump power with a slope efficiency of 16.3% and an optical-to-optical conversion efficiency of 14.4%.

Acknowledgements

The contributions of K Ranganathan and P Hedaoo, SSLD, RRCAT on mechanical design and fabrication of the pump head and crystal holders are gratefully acknowledged.

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