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Efficient and high-power green beam generation by frequency doubling of acousto-optic Q-switched diode-side pumped Nd:YAG rod laser in a coupled cavity

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Abstract. A 52-W green laser at 532 nm by extra-cavity second-harmonic generation in a coupled-cavity configuration is demonstrated. The fundamental laser is a diode-side-pumped acousto-optic (AO) Q-switched Nd:YAG rod laser producing 84 W of average power at 1064 nm at 8 kHz repetition rate. Type-II phase-matched polished KTP crystal is used as the nonlinear crystal for second-harmonic generation. The individual green pulse width is 50 ns and the fundamental to second harmonic conversion efficiency is 61.8%.

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

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1. Introduction

High-average-power green lasers are required for various applications in industry, research and even in entertainment. In some applications, particularly for pumping tunable lasers and optical parametric oscillators or amplifiers, a stable high-power short pulse green beam is desirable [1,2]. Intracavity frequency doubling using a KTP crystal of acousto-optic (AO) Q-switched Nd:YAG laser under diode laser pumping has proved to be an effective method in generating green laser beam at 532 nm with high average power and high efficiency [3]. But, intracavity frequency doubling suffers from power instabilities due to the thermal effects at the KTP crystal [4], Q-switching instabilities and long pulses due to the high finesse of the cavity. On the other hand, extra cavity frequency doubling is free from the complexities of intracavity frequency conversion process but requires multistage amplification of a high beam quality seed laser and sophisticated beam shaping for efficient frequency conversion [5]. Direct external frequency conversion of AO Q-switched diode-side-pumped dual Nd:YAG rod laser is reported in [6] using a two-stage KTP crystal architecture producing 30 W of average green power at 25 kHz repetition rate with

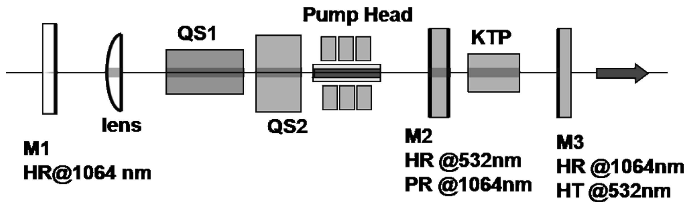

Figure 1. Schematic of the experimental set-up.

50 ns pulse duration, however the IR to green conversion efficiency was limited to 40% even with high-quality IR beam.

In this paper we report highly efficient frequency doubling of a compact AO Q-switched diode-side-pumped Nd:YAG rod laser involving a single pump head and a single KTP crystal in a coupled cavity configuration. 52 W of average green power at 8 kHz repetition rate are obtained with 50 ns pulse duration. The IR to green conversion efficiency is 61.8%. To the best of our knowledge these are the highest values obtained by frequency doubling of diode-side-pumped AO Q-switched Nd:YAG laser in a coupled cavity configuration.

2. Experimental set-up

The schematic of the laser arrangement is shown in figure 1. The laser consists of two cavities: the primary cavity for the fundamental laser beam and the secondary cavity for efficient second-harmonic generation. The fundamental laser resonator is constituted by the plane mirrors M1 and M2 with a geometrical separation of 31 cm. The back mirror M1 has a high reflection (HR) coating ($R > 99.8\%$) at the fundamental wavelength at 1064 nm and the front mirror M2 has a partial reflection (PR) coating ($R = 70\%$) at 1064 nm. A plano-convex lens of 50 mm focal length is placed near M1 to obtain a nearly collimated beam at M2 for efficient coupling with the secondary cavity. The exact position of the lens is decided by the ABCD matrix analysis of the resonator. The pump head is placed near M2 and consists of an Nd:YAG rod (Φ4 mm $\times$ 100 mm and 0.6 at.% Nd^{3+}-doped), a cooling flow tube, a diffusive optical reflector and nine linear array laser diode bars. The total power emitted by the diode bars is $\sim$420 W and here are arranged for three-fold symmetric pumping of the Nd:YAG rod. The laser is repetitively Q-switched at 8 kHz repetition rate with two acousto-optic modulators (placed between the pump head and the lens), with orthogonally oriented acoustic field directions to increase the hold-off capability.

For second-harmonic generation, we use type-II phase-matched KTP crystal (5 $\times$ 5 $\times$ 10 mm^3) press fitted in a water-cooled copper mount. The end faces of the KTP crystal are polished and no antireflection (AR) coating is applied for reliable operation as AR coatings are easily damaged at high powers [7]. The KTP crystal is placed inside the 5 cm long secondary cavity formed by the mirrors M2 and M3. The back surface of the mirror M2 is HR-coated at the second harmonic wavelength (532 nm) and is highly transmitting (HT, $R < 5\%$) at 1064 nm and acts as the back mirror for the second cavity. The front mirror, M3, is a plane mirror with

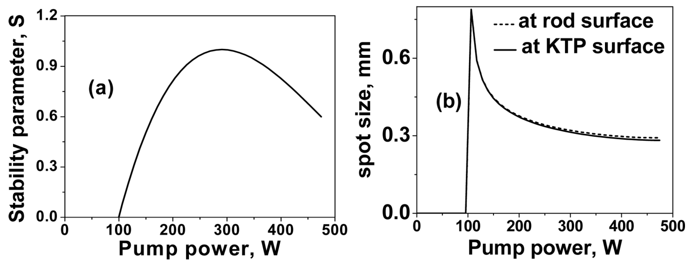

Figure 2. Calculated variation of the (**a**) stability and (**b**) spot sizes as a function of the pump power.

HR and HT coatings at 1064 nm and 532 nm respectively and provides the output coupling of the generated green beam.

For efficient coupling of the primary and the secondary cavity it is essential that the fundamental mode size should match closely in the two cavities throughout the operating range of the pump power. The stability of the resonator and hence the mode size, however, vary dynamically with the pump power due to thermal lensing in the Nd:YAG rod. The position of the lens in the primary cavity is crucial to counter the thermal lensing and is decided by the ABCD matrix analysis of the cavity incorporating the measured variation of the focal length of the thermal lens as a function of the pump power.

The stability parameter, S, is related to the trace of the net ABCD matrix of the cavity and is defined as $S = 1 - (A + D)^2/4$ [8]. S has a maximum value of unity and the cavity is stable if $S > 0$. In figure 2a the estimated variation of the cavity stability as a function of the pump power is plotted for the location of the lens at ~40 mm distance from the mirror M1. It can be seen from figure 2 that the cavity is unstable up to 100 W of the pump power and then it becomes stable throughout the operating range of the pump power. In figure 2b the estimated variation of the fundamental mode size at the Nd:YAG rod as well as at the KTP crystal is plotted as a function of the pump power. It can be seen that the beam size at the Nd:YAG and at the KTP crystal matches closely over the entire range of the pump power.

3. Experimental results and discussions

In the first stage the fundamental laser is characterized by removing the secondary cavity. Figure 3a shows the measured slope efficiency curves of the fundamental laser output at 1064 nm with 70% output coupling under CW and pulsed operation. The threshold pump power is ~125 W. The reason for the high threshold is that the cavity becomes stable only at a pump power more than 100 W as predicted in figure 2. More than 100 W of CW IR power at 1064 nm is obtained at 420 W of pump power. Under repetitive Q-switching 84 W of the average power at 8 kHz repetition rate is obtained. At a lower repetition rate multiple pulsing occurs particularly at the high pump power due to the large spot size at the Q-switches leading to slow switching.

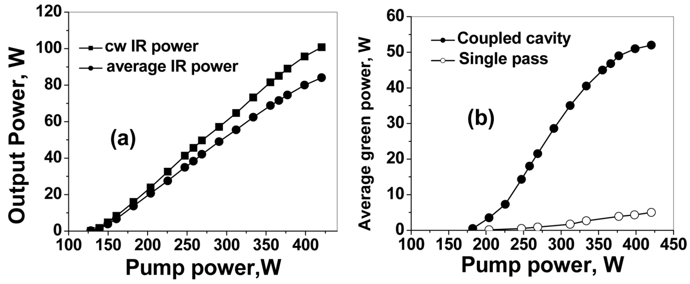

Figure 3. Measured slope efficiency curves (**a**) at 1064 nm and (**b**) at 532 nm.

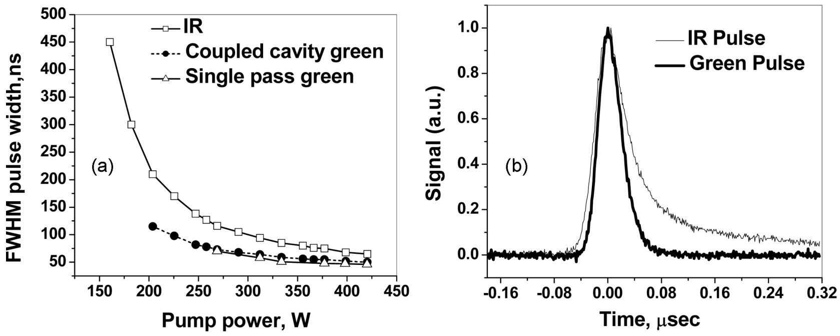

Figure 4. (**a**) Measured variation of pulse width with the pump power and (**b**) Q-switched pulse shape.

The performance of the extra cavity frequency doubling is shown in figure 3b. First we placed the KTP crystal after the mirror M2 and observed the green power under single-pass configuration. With an incident IR power of 84 W at 8 kHz repetition rate only 5 W of average green power at 532 nm is obtained by single-pass frequency doubling. But, the average green power is enhanced by more than ten times as the mirror M3 is placed after the KTP crystal to form the secondary cavity. The IR power in the secondary cavity is greatly enhanced leading to generation of high-power green beam due to the coupling with the primary cavity. An average green power of 52 W is obtained corresponding to 61.8% of the IR output from the fundamental laser. The optical-to-optical conversion efficiencies with respect to the CW IR power and the diode pump power are 52% and 12.3% respectively. In figure 4a the measured variation of the pulse width (FWHM) at the fundamental IR beam, green beam generated in the coupled cavity and green beam generated by single pass through KTP crystal are shown as a function of the pump power. At the maximum pump power of 420 W the IR pulse width is measured to be 65 ns. The single-pass green pulse duration at this pump power is measured to be 46 ns which is exactly $\sqrt{2}$ times of the fundamental pulse duration as expected from the nonlinear frequency conversion process. In the coupled cavity configuration the minimum pulse duration obtained is 50 ns which is slightly higher than the single-pass green. The Q-switched pulse shape at the fundamental and at the second-harmonic wavelength is shown in figure 4b. The green pulse has a rise time of 27 ns and a fall time of 75 ns. The green pulses from the coupled cavity are highly stable with less than ±3% timing and amplitude jitter. The green beam is circular in shape with a measured M^2-parameter of 27 which is the same as that of the fundamental laser beam.

To compare the performance with green beam generation in a conventional intracavity frequency doubling configuration, the coupler mirror M2 is replaced with a harmonic mirror (HR at 532 nm and HT at 1064 nm) so that the spot size at the KTP crystal remains the same as that of the coupled cavity configuration. An average green power of 48 W at 8 kHz repetition rate is obtained with 70 ns pulse duration at the maximum pumping power. The fall time of the intracavity generated green pulses is measured to be 125 ns which is 50 ns more than that from the coupled cavity. Further we observed intermittent power fluctuation due to the Q-switching instability. The results indicate that the performance of the coupled cavity configuration is superior to the intracavity frequency doubling.

4. Conclusion

In conclusion, we have for the first time employed the coupled cavity configuration to combine the advantages of the extracavity and intracavity frequency conversion processes and demonstrated more than 61% IR-to-green conversion efficiency using simple polished KTP crystal. Highly stable green pulses of 50 ns duration are obtained at 8 kHz repetition rate with 52 W of average power.

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