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Generation of 11.5 W coherent red-light by intra-cavity frequency-doubling of a side-pumped Nd:YAG laser in a 4-cm LBO

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Abstract

We report the generation of high-power, quasi-continuous wave red-light up to 11.5 W in a 4-cm LiB_3O_5 crystal with intracavity frequency-doubling of two compact and simple side-pumped Nd:YAG laser modules under a repetition rate of 3.5 kHz. The beam quality of M^2 value is 15 ± 3 in both directions. The short-term stability of the red-light source is better than 1% at an output of 9 W. Other characteristics of the red-light laser were also experimentally studied and presented.

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Keywords: Red light; Nd:YAG red light; Nd:YAG laser; Intracavity frequency-doubling; Diode-pumped laser

1. Introduction

With its all-solid-state concept, diode-pumped solid-state red laser is an attractive source for large image projection systems, laser therapy and pumping source for tunable lasers such as Cr:LiSAF. The all-solid-state concept assumes additional importance in areas which put a premium on ruggedness, size, efficiency and reliability [1–5]. Although, the power available from red laser diodes has increased and various types of beam-shaping techniques are under investigation, the

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outputs of these diodes still remain relatively low and the beam quality of the diodes is generally much poorer compared with solid-state lasers.

Optical parametric converters potentially represent the most flexible and tunable solution, but they are often too complicated for routine operation [6,7]. Frequency-doubling of a 1.3-μm all solid laser is an efficient way to obtain the high-brightness red radiation [1–5,8]. In 1999, Lee et al. [5] reported that a red laser radiation of 6.1-W was yielded by frequency-doubling by a side-pumped Nd:YAG laser using a KTP crystal as the nonlinear medium. More recently, Agnesi et al. [8] reported the generation of red light of 2.4-W by frequency-doubling of $Nd:GdVO_4$ laser in a LiB_3O_5(LBO) crystal. However, the highest output powers published so far were limited to watt-level.

In this paper, we narrate the generation of 11.5-W of quasi-continuous wave (Q-CW) red beam by the intracavity frequency-doubling of a side-pumped Nd:YAG laser operating at 1.3 μm in a 4-cm LBO. The short-term stability of the red-light source is better than 1% at 9 W and it is still about 10% at the maximum output of 11.5 W. The beam quality of M^2 value at the maximum output is 15 ± 3 in both directions and it can be improved to 5 ± 1 at a lower output of 5-W. To the best of our knowledge, the red laser reported in this paper has the highest output power among the all-solid-state Q-CW red lasers ever reported.

2. Experimental setup

The laser system in our experimental study contains two diode-pumped Nd:YAG laser-modules in a linear cavity designed to oscillate at 1.3 μm. The Nd:YAG rod in each module has a diameter of 3 and 80 mm in length. The YAG is doped with 1% of Nd^{3+}. The system is Q-switched and operated at a repetition rate of 3.5 kHz. A 4-cm long LBO crystal is used as the nonlinear medium for intracavity frequency-doubling.

The experimental arrangement of the system is illustrated in Fig. 1. The plane–plane resonator was composed of two flat mirrors: the mirror 1 (M1) was coated for high reflection at 1319 and 659.4 nm, while the mirror 2 (M2) is an output couple for 659.4 nm, with high transmission at 659.4 nm and high reflection for 1319 nm. In order to suppress oscillation at 1064 nm, the coatings of M1 and M2 also have the transmission greater than 60% at 1064 nm. The high transmission at 1064 nm for the mirrors is necessary since the gain of the oscillation line at 1064 nm is much higher

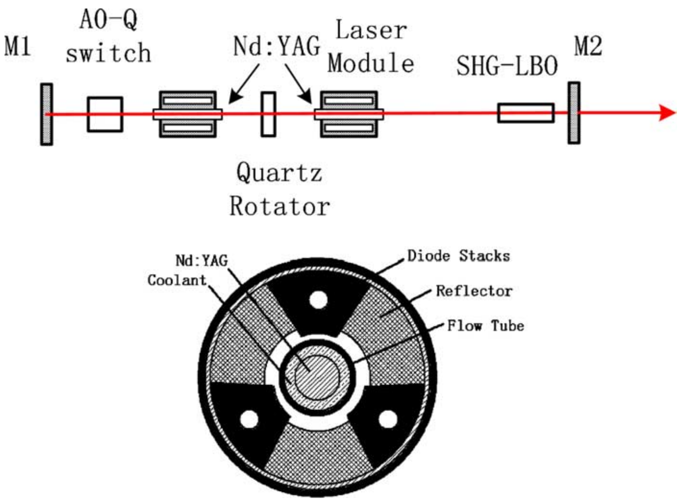

Fig. 1. The schematic drawings of the experimental arrangement: M1, M2, plane cavity mirror; AO-Q switch, acousto-optic Q switch.

than that at 1319 nm. The highly wavelength-selective dielectric coatings suppress the laser oscillation at the strongest transition at 1064 nm and provide optimum conditions at 1319 nm. Each face of the elements in the cavity was coated for high transmission at 659.4 and 1319 nm to minimize insertion losses. In order to compensate the thermal birefringence, a quartz 90° polarization rotator at 1319 nm was inserted between the two identical laser modules [9]. With this technique, the radial and tangential components of the polarizations are exchanged between two identical laser rods to achieve equal phase retardation in the cross-section along the entire Nd:YAG rods. An acousto-optic modulator with high diffraction loss at 1319 nm was used for Q-switching.

The lower part of Fig. 1 shows the schematic cross-section of the pumping laser module. It consists of three modules arranged in a threefold symmetry around the laser rod. Four 1-cm-long linear laser diodes are arranged on each module, in which the cooling water flows parallel to the laser diodes. To match the Nd:YAG absorption band near 808.5 nm, we carefully selected the 12 laser diodes at a given drive current and a given cooling temperature to obtain the lowest spectral dispersion in the laser modules. The maximum output power of each laser diode is 20 W at the maximum input current of 25 A. The Nd:YAG rod is surrounded by a flow tube and a circular reflector. The choose of Nd:YAG as the laser medium is due to the fact that it is favorable for laser operation and its relative strong transition at 1.3 μm. Pump lights from the diodes are coupled into the Nd:YAG rod directly. O-Rings of $\phi = 3$ mm were used to seal the cooling water for the crystal. From the design standpoint, this desirable arrangements is by far the most compact and simplest approach to couple the radiation emitted from the laser diodes into the Nd:YAG rod.

A LBO crystal used as the nonlinear crystal for intracavity frequency doubling in this experiment, was cut for type-II noncritical phase matching second harmonic generation (SHG) ($\theta = 0, \phi = 0$). The size of the LBO is $4 \times 4 \times 40$ mm^3 and it is provided by Fujian Castech Crystals Inc. of China. The LBO is well-suited for high-power SHG with long-term reliability owing to its high damage threshold and low absorption at both the fundamental and second harmonic outputs of the Nd:YAG laser at 1.3 μm. The crystal is placed in an oven, whose temperature was maintained by a temperature controller to a precision of ±0.1 °C. The LBO crystal is set close to the output coupler, where the beam waist is located based on the design of the cavity, to take the advantage of the strongest power density of the fundamental beam.

3. Results and discussion

Fig. 2 shows the calculated pump energy distribution inside the Nd:YAG laser rod obtained from a ray trace analysis which takes into account the spectral and spatial properties of the laser diodes and the absorption spectrum of the laser material [10]. The absorption coefficient α used in our calculation is 4 cm^{-1}. As can be seen in Fig. 2, the pump energy distribution at the center of the laser rod is nearly a Gaussian distribution. This profile also represents the radial gain profile. Such a pump energy distribution matched with the oscillation beam profile helps to increase the gain extraction in the medium [11].

Experimentally, we measured the output power of the red light as a function of the pump power of the diodes. Fig. 3 shows the SHG output power versus the pump power at 808 nm under the repetition rate of 3.5 kHz. The red-light output started

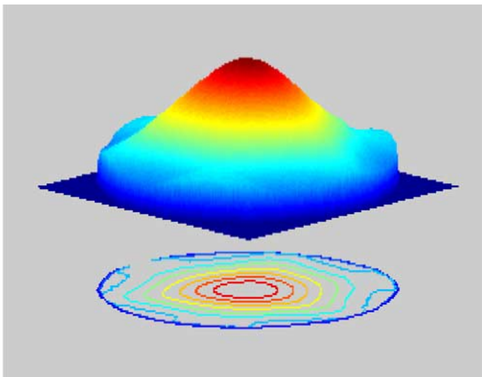

Fig. 2. Pump energy distribution within Nd:YAG rod. The pump energy distribution value is normalized in the upper figure. Each line represents a 12.5% change in intensity in the lower figure.

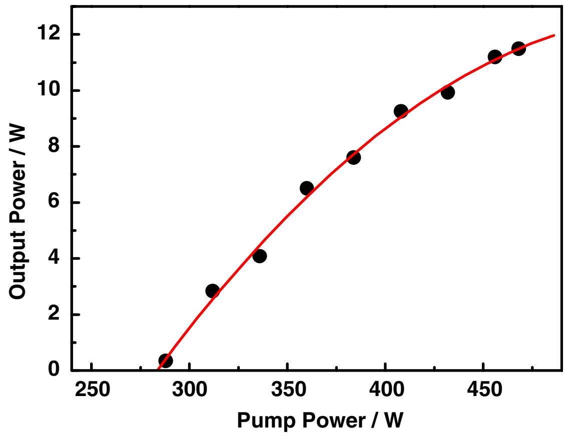

Fig. 3. The output power of red light at 659.5 nm versus pump power.

at a pumping power around 280 W. It increases rapidly as the pumping power of the diode laser increases and becomes saturated at 480 W, where the maximum red output power is 11.5 W.

Two wavelengths can be obtained around 1.3-μm in the output of a Nd:YAG laser. One is the R_2–X_1 transition at 1319 nm and the other is the R_2–X_3 transition at 1338 nm [5]. Under normal operation conditions, the 1319 nm transition can oscillate more easily than the 1338 nm line [10]. We analyzed the spectrum of the red beam under maximum output power and it is displayed in Fig. 4. The radiation at 659.4 nm in Fig. 4 was generated by frequency doubling of 1319 nm, while the output at 664 nm can be attributed to the

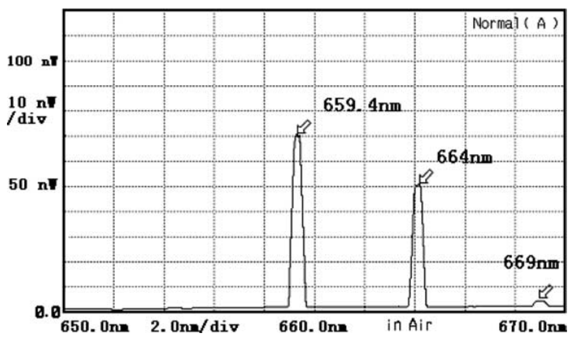

Fig. 4. The spectrum of the red beam under highest output power. Under lower pump power, the lights at 664 and 669 nm are ignorable than the one at 659.4 nm.

sum-frequency between 1319 and 1338 nm. The 669-nm radiation generated by frequency doubling of 1338 nm was always negligible all the time at the current pump power level in our experiments. It indicates that the Nd:YAG laser may oscillate on the two transitions at the same time under high pump power, and the laser at 1319 nm is stronger than the one at 1338 nm in the cavity. Obviously, the coexistence of the two wavelengths is a problem for the generation of high efficiency frequency doubling to get high power red light. First, the existence of 1338 nm radiation, consuming the energy stored in the Nd:YAG material, reduces the peak power density of 1319 nm radiation in the cavity accordingly, which is disadvantageous for high efficiency frequency doubling of the stronger transition at 1319 nm; Second, the sum-frequency between 1319 and 1338 nm consumes a larger portion of the energy oscillated at 1319 nm in the cavity. Therefore, the coexistence of the two transitions, generating the coexistence of the red radiation generated by frequency doubling and sum-frequency, holds back the efficient increase of total red output power at the high pump power level; Third, the mode competition between two transitions around 1.3-μm in the cavity makes the output unstable. The first two disadvantages can be easily seen from the Fig. 3 that under higher pumping condition the output is not increased as linearly as expected.

Experimentally, we also studied the fundamental output of the laser. It was found that at lower pump power, the transition at 1338 nm is always negligible compared with the strong transition at 1319 nm. Only when the pumping power is above 350 W in the condition of our experiment, one can start to see the transition at 1338 nm. It was found that once the transition at 1338 nm becomes significant, it affects the output power of the red light as discussed. In order to confirm this point, we investigated the relationship between the stability of the output power and the output spectrum by measuring the relative ratio of the 664–659.4 nm at various output level corresponding to different pump level. The time trace of the output power at the output power level of 9 W is shown in Fig. 5. The fluctuation of the red beam output power was better than 1.0% in the given 20 min. Under

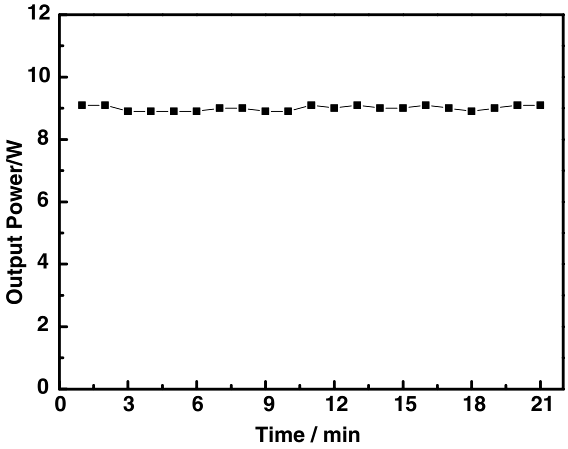

Fig. 5. Stability of the red output power at output power of 9 W. At the maximum output power of 11.5 W, the stability is about 10%.

this condition, the frequency component at 664 nm is negligible in the output spectrum. With the increase of the pump power, the increasing output power is unstable, and the radiation component at 664 nm is bigger. At the maximum output power, the instability is about 10% and the radiation component at 664 nm, as can be seen from Fig. 4, becomes comparable with that at 659.4 nm.

The coexistence of two transitions around 1.3-μm can be solved by inserting a mode-selector in the cavity. In order to improve the optical efficiency, further investigations are under the way aiming at eliminating the other frequency component in the cavity. A higher output is expected. The dual-wavelength that exists in the output laser, making no difference for the applications by using the intensity of laser, is an adverse fact for the applications by using the coherence of laser. It could be very useful in some special application fields, for example large image projection systems.

Other characteristics of the red-light laser were also experimentally studied. The temporal profile of the output red beam is shown in Fig. 6. The pulse width is about 180±20 ns at the maximum output power.

Beam quality is very important for many applications. The beam quality factor M^2 becomes poorer as the pump power increases. At maximum output of 11.5 W, the M^2 value is 15±3 in both

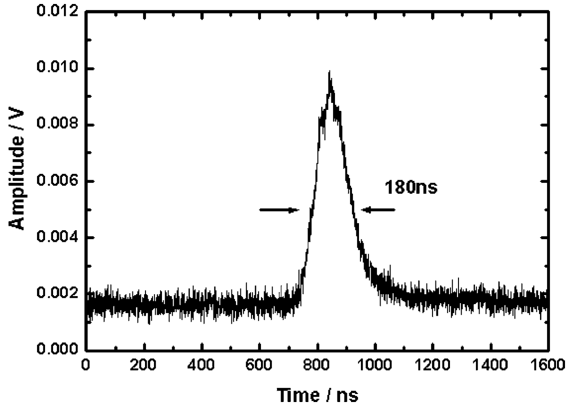

Fig. 6. The temporal profile of red beam.

transverse directions. The characteristic test results of beam quality of laser at maximum output power were shown in Fig. 7. The upper figure (a) shows the beam transmission profile measured by Spir-

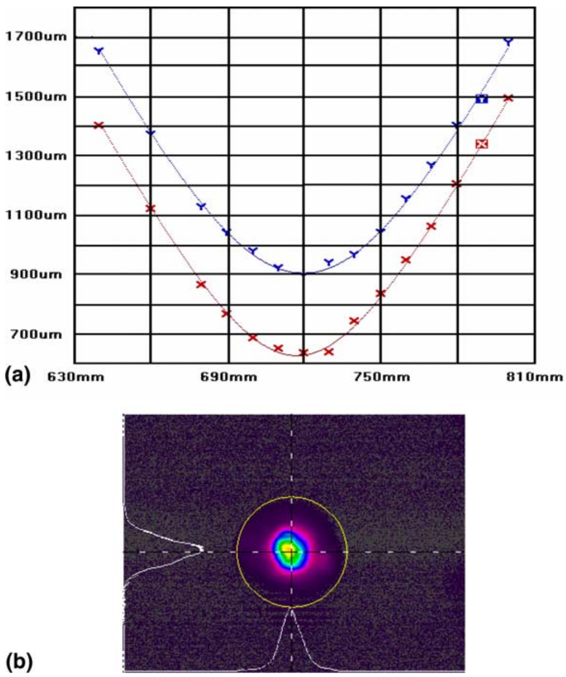

Fig. 7. The characterizations of beam quality of laser at maximum output power: (a) The measured beam radius with fitted curves for both transverse directions along the direction of propagation: X, the beam widths at x-direction; Y, the beam widths at y-direction directions. (b) Far-field intensity distribution of the beam.

icon beam analyzer after curve-fitting for both transverse X and Y directions at the maximum output power. Far-field intensity distribution of the beam was displayed in the lower figure (b). At a lower output, the beam quality is much better. For example, at an output littler than 5 W, the value of M^2 is reduced to about 5 ± 1 in both directions. The poorer quality at higher output is mostly due to that the laser tends to oscillate in higher-order transverse modes under high pump power without any mode-selecting technique in the cavity.

4. Conclusion

In conclusion, a diode-pumped Nd:YAG laser system operated at 1.3 μm has been demonstrated with the output up to 11.5 W red beam by utilizing two compact and simple side-pumped laser modules and intracavity frequency-doubling in a 4-cm LBO crystal. The power fluctuation of less than 1% at an output of 9 W was obtained. At maximum output, the beam quality of M^2 value was about 15 ± 3. This excellent performance of the laser system demonstrates that the side-pumped Nd:YAG laser with LBO intracavity frequency doubling is an promising method for generating high-power red light with high beam quality.

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