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Continuous-wave diode-laser end-pumped Nd:YVO_4/KTP high-power solid-state green laser

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Abstract

A simple folded-cavity used for intracavity frequency-doubled Nd:YVO_4 laser was analyzed by transmission matrix and numerical calculation. We have selected a set of proper cavity parameters which can be used readily by operating at high power levels with low threshold, high efficiency, and wide dynamic operating range. 5.6-W TEM_{00} green laser has been obtained at a 22-W pumping power and with an optical–optical conversion efficiency of 25.5%. © 2002 Elsevier Science Ltd. All rights reserved.

Keywords: Diode end-pumped; Nd:YVO_4/KTP; All-solid-state; Green laser

1. Introduction

High-power diode-pumped compact visible lasers have attracted much attention [1,2]. Particularly in the recent years, all-solid-state multi-watt level intracavity-doubled green lasers are attractive for applications such as display, ophthalmology, printing, spectroscopy, material processing, biomedical, underwater communications, and pumping ultrashort pulse laser systems. In addition, such lasers could also become critical components of an all-solid-state compact UV or femtosecond UV laser sources and optical parametric oscillators. They have eventually become commercially available for replacing low-efficiency, cumbersome Ar^+ lasers and flashlamp-pumped solid-state lasers in a variety of practical applications. Nd:YVO_4 has often been used in diode-pumped intracavity frequency-doubled lasers because of its high absorption over a wide pumping wavelength bandwidth and its large stimulated-emission cross section at lasing wavelength. In order to obtain higher output powers, many different pumping schemes have been used with diode-pumped solid-state lasers. Longitudinal pumping has been shown to be one of the most efficient methods, as it allows the diode output to be focused on a volume in the active medium that best matches the radius of the TEM_{00} mode in the cavity. Also, longitudinal pumping was often designed to have a restriction of the number of modes in the cavity by focusing the pump radiation to a spot that is slightly smaller than the fundamental mode of the laser. However, as the pump power available from diode lasers increased, the temperature gradient caused by heat deposition in the laser crystals creates a variation in the refractive index of the gain medium as well as mechanical deformation and stress. One important effect, the so-called thermal lens, results from this temperature-induced index changes. In addition to the thermally induced aberration, the temperature gradient may lead to the depolarization of the second-harmonic output in intracavity frequency-doubled green lasers. Many papers have been published regarding the reduction of the thermal inhomogeneity and thermal lensing effect in the gain medium. However, most of these lasers consisted of an aperture to ensure TEM_{00} mode operation, a Brewster plate to compensate for the astigmatism introduced by the folded mirror with a beam waist radius at the end mirror face [3], or composite-rod crystals with undoped endcaps [4]. In this article, we report on a diode-laser-array two-end-pumped Nd:YVO_4/KTP intracavity frequency-doubled green lasers that employed a simple four-mirror folded cavity and consisted of no other

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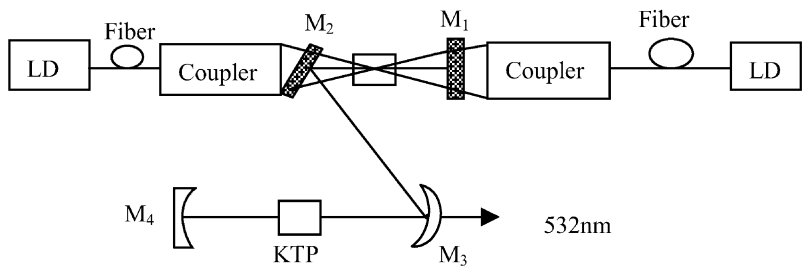

Fig. 1. Experimental setup of LD two-end-pumped Nd:YVO_4 laser.

additional elements except for the laser gain medium and the frequency-doubling crystal in the resonator. In order to reduce the thermal inhomogeneity in the gain medium, we have used two 14 W (at each fiber bundle end) maximum output power laser diode (LD) bars (OPC-BO15-FCPS, Opto-Power Corp.) to pump both ends of the Nd:YVO_4 crystal. Under such high pump power condition, owing to the thermal effects, the fundamental mode radius in the laser crystal should be smaller than pump spot radius [5,6] (mode-to-pump ratio $\omega_o/\omega_p < 1$). And in our experiment, we found that the pump power increases as the mode-to-pump ratio (ω_o/ω_p) decreases over a large range of $\omega_o/\omega_p < 1$, however, a high-order mode appears when ω_o/ω_p is smaller than 0.7. In order to obtain the high output power and to guarantee single-mode operation, we chose 0.7 as the critical value of ω_o/ω_p. At the same time, the TEM_{00} mode operation and the compensation for astigmatism were obtained by the optimization of the resonator through considering the gain medium as a convex lens. Also, it had the advantage of having a beam waist radius of about 50 μm not on the end mirror face but inside the cavity where the frequency-doubling crystal was placed. This system showed good performances, even in the large pumping power range. More than 5.6 W of TEM_{00} mode 532-nm green laser output power was generated with a 22-W (intracavity) pumping power, corresponding to a conversion efficiency of 25.5%.

2. Cavity configuration and analysis

A cavity configuration schematic of the LD two-end-pumped Nd:YVO_4 laser and the corresponding thermal lens equivalent resonator is shown in Figs. 1 and 2, respectively. Here, M_1 and M_2 were plane-coupling mirrors for LD pumping. M_3 was a concave convex lens with the inside radius of curvature of R_3. M_4 was a concave mirror with a radius of curvature of R_4. This kind of folding resonator has many characteristics, such as adjusting the mode parameter very neatly, having a large efficiency space inside the cavity for realizing double-pass frequency doubling and an easy one-end exporting, insulating the process of frequency doubling and laser gain medium. And, also, it consists of no other additional optical elements except for the laser gain medium and the frequency-doubling crystal and has a beam waist not at the end mirror face but inside the cavity where the frequency-doubling crystal is placed.

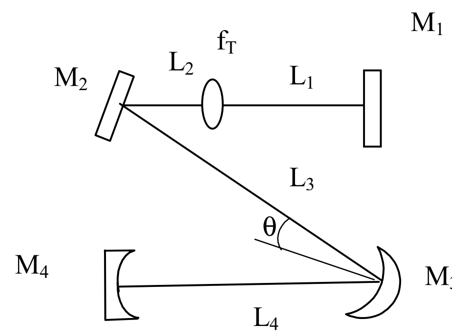

Fig. 2. The corresponding thermal lens equivalent resonator.

Obviously, in a comparison of other traditional neodymium-doped host crystals (e.g., Nd:YAG [7] or Nd:YLF [8]), Nd:YVO_4 offers several advantages including a high absorption coefficient at the 808-nm pump light and a large stimulated emission cross section at the 1064- and 1342-nm operation wavelengths. However, the former has a higher thermal conductance and smaller thermal lens effect than Nd:YVO_4. It was a focus problem that needed to be solved in our resonator designing when thermally induced focusing effect occurred, while the laser crystal Nd:YVO_4 having absorbed the pumping light, for the thermal lens effect, became sufficiently significant in affecting the resonator stability, performance and mode parameters everywhere inside the cavity. At the same time, there was a thermally induced astigmatism, which could also affect the output beam quality. Furthermore, to achieve a good output beam quality, the resonator must work at a TEM_{00} mode. And it is necessary to have a large mode volume in the laser gain medium (in the case of satisfying a better match with the pumping mode) for the oscillator in a high intracavity power. Also, the laser must operate stably in the resonator cavity over a very wide pumping power range and working stability range large enough for an actual application. Lastly, due to a high intracavity power, we must choose a suitable spot size in the frequency-doubling crystal KTP in case it is damaged, and at the same time we also need a conversion efficiency as high as possible for ensuring a great power green laser output. Consequently, we must consider the fact mentioned above during designing and analyzing the resonator cavity following the standard *ABCD* matrix.

In continuous-wave (CW) end-pumping high-power solid laser cavity designing, the laser gain medium acts as a thermally induced self-focusing lens and can be treated as a thin lens with a focal length of f_T (see Fig. 2) [9]. This kind of simplification is sufficiently exact for most practical purposes and is also widely accepted. So in our particular situation, the round trip *ABCD* matrix for the Z-type resonator in Fig. 2 is given by

$$\begin{bmatrix} A_{t/s} & B_{t/s} \\ C_{t/s} & D_{t/s} \end{bmatrix} = \begin{bmatrix} 1 & L_2+L_3 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ -\dfrac{1}{f_{t/s}} & 1 \end{bmatrix} \begin{bmatrix} 1 & L_4 \\ 0 & 1 \end{bmatrix} \times \begin{bmatrix} 1 & 0 \\ -\dfrac{2}{R_4} & 1 \end{bmatrix} \begin{bmatrix} 1 & L_4 \\ 0 & 1 \end{bmatrix} \times \begin{bmatrix} 1 & 0 \\ -\dfrac{1}{f_{t/s}} & 1 \end{bmatrix} \begin{bmatrix} 1 & L_2+L_3 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ -\dfrac{1}{f_T} & 1 \end{bmatrix} \times \begin{bmatrix} 1 & 2L_1 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ -\dfrac{1}{f_T} & 1 \end{bmatrix}, \quad (1)$$

where subscripts t and s express the tangential and sagittal planes, respectively. The spherical face fold-mirror has two different equivalent focal lengths in tangential plane (f_t) and sagittal plane (f_s), they are $f_t = (R\cos\theta)/2$ and $f_s = R/(2\cos\theta)$, respectively. The stability condition of the resonator cavity operation is

$$|(A_t + D_t)/2| \leqslant 1, \qquad |(A_s + D_s)/2| \leqslant 1, \quad (2)$$

that is, the resonator mode operation is stable only when the round trip matrixes for tangential and sagittal planes meet the above condition. The relationship between the q parameters of the TEM_{00} Gaussian mode and every element of the round trip matrixes is

$$\frac{1}{q_{t/s}} = \frac{D_{t/s} - A_{t/s}}{2B_{t/s}} - \mathrm{i}\frac{\sqrt{1 - [(A_{t/s} + D_{t/s})/2]^2}}{B_{t/s}} = \frac{1}{R_{t/s}} - \mathrm{i}\frac{\lambda}{\pi\omega_{t/s}^2}. \quad (3)$$

So the beam waist of the Gaussian mode in the gain medium is

$$\omega_{t/s} = \sqrt{\frac{\lambda|B_{t/s}|}{\pi\sqrt{1 - [(A_{t/s} + D_{t/s})/2]^2}}}. \quad (4)$$

The laser spot size in the resonator can be obtained by changing the inceptive place of the round trip matrixes. Thereby, we can derive the laser beam distribution in the cavity and the optimum position in which the KTP crystal was inserted. According to the results of our numerical computation, a set of perfect resonator parameters was screened out, $R_3 = 100$ mm, $R_4 = 50$ mm, $L_1 = 10$ mm, $L_2 + L_3 = 260$ mm, $L_4 = 115$ mm, and the folding angle at mirror M_3 was smaller than 8° in order to compensate for the thermally induced astigmatism, that was induced by the spherical face of mirror M_3. A main characteristic of this resonator was that the stability region of thermal focal length was found to extend from $f_T = \infty$ to 110 mm. So the stability operation condition was achieved by the insensitivity disturbance resulting from the thermal focal length of the mode volume in the gain medium.

3. Experimental results

The final arrangement layout is shown in Fig. 1. The cavity parameters were given by the data screened out above. The pump sources used in this system were two commercially available fiber-coupled diode-laser-arrays that deliver a maximum CW output power of 14 W at each fiber bundle end. The output beams from two 1.16-mm fiber bundle ends were focused, respectively, into the laser crystal with a spot radius of about 0.58 mm and numerical aperture of 0.12 by focusing optics. The $3 \times 3 \times 5\ \mathrm{mm}^3$, 0.7-at% Nd^{3+}-doped a-cut $Nd{:}YVO_4$ crystal (CASIX Inc.) was antireflection-coated at 808 and 1064 nm on both end surfaces. This laser crystal was wrapped with indium foil and was inlaid in a water-cooled copper block ensuring sufficient cooling for the pump-produced heat to be removed. The $5 \times 5 \times 9\text{-mm}^3$ KTP crystal cut for second-harmonic generation ($\theta = 90^\circ, \phi = 23.4^\circ$) at 532 nm, AR-coated for 1064 and 532 nm on both end faces, was also actively cooled in the same way as the laser gain medium. M_3 and M_4 were concave convex mirror and concave mirror with radii of curvature of 100 and 50 mm, respectively. M_3 as the output couple mirror was HR-coated at 1064 nm and HT-coated at 532 nm on the curved face, and AR-coated at 532 nm on the convex face. M_4 was HR-coated at both 1064 and 532 nm. The KTP crystal was just placed at the waist position between M_3 and M_4 in order to have a relatively high conversion efficiency at 532 nm and to be easily installed upon it. The distance between the KTP and M_3 was approximately 65 mm, and it was approximately 50 mm between the KTP and M_4. The spot diameter, which was determined by M_3 radius of curvature, was about 100 μm. The angle between the field direction of the linearly polarized fundamental wave and the direction of the extraordinary ray in the KTP was 45°. The frequency conversion efficiency was maximum for this angle. The characteristics of TEM_{00} mode output power versus incident pump power are given in Fig. 3. Under an optimum mode-matching condition, in accordance with the theoretical result above, a maximum CW 532-nm green laser output power of 5.6 W was obtained with a pump power of 22 W corresponding to a green conversion efficiency of 25.5%. Particularly, for pump power between 16 and 22 W, the resonator is stable and the laser

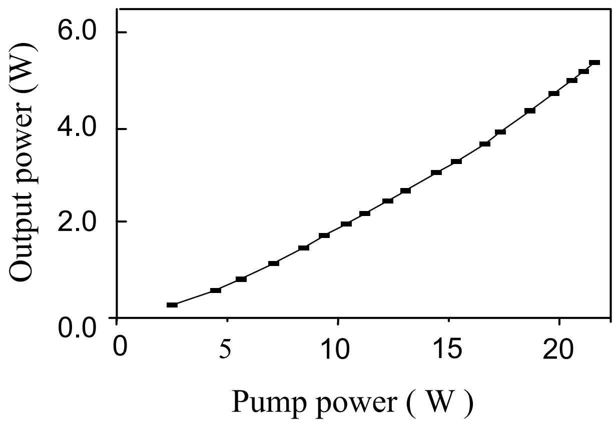

Fig. 3. 532-nm laser output power as a function of diode-laser pump power.

is TEM_{00}. At 22 W pump power, the beam quality M^2 is < 1.5. The relative standard deviation of output power was found to be better than 1.6% during half-hour measurement time (with CW laser Power Meter, Model 407A, Spectra-Physics, Time Constant: < 0.5 s for 1 W scale or higher; < 1 s for 30-mW scale). As a pumping source, this green laser system pumped the Ti:sapphire femtosecond laser successfully.

4. Conclusion

In conclusion, we have demonstrated a diode-laser two-end-pumped $Nd:YVO_4/KTP$ intracavity frequency-doubled green lasers that employed a simple four-mirror folded cavity that consisted of no other additional elements in the resonator except for the laser gain medium and the frequency-doubling crystal. TEM_{00}mode green output power of 5.6 W was reached at a pump power of 22 W, the corresponding optical–optical conversion efficiency being 25.5%. This system showed a good performance even in the large pumping power range.

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