# Highly efficient diode-pumped seven-rod resonator with a 3.79-kW output

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Thermally stable region of a seven-rod resonator is theoretically investigated. A plane-plane symmetric resonator, where the distance between two neighbor rods is two times of that between the rods and the mirrors, is adopted because of its large stable range. Based on the investigation, a seven-rod resonator with an average output power of 3.79 kW and an optical-to-optical efficiency of 53% is developed.

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Many applications of solid-state laser in material processing and advanced science research areas require a high average power with high beam quality and broad output power range[1−4]. There are mainly two methods to obtain higher output power from a diode-pumped solid-state laser (DPSSL). One is the master-oscillator power-amplifier (MOPA) design[5−6]. However, the efficiency of the MOPA system is low, and the output intensity is small compared with the saturation intensity of the active medium (about 2.9 kW/cm$^2$ for the Nd:YAG crystal). The MOPA system is also complicated, since the mode-matching telescope, the spatial filter, and the Faraday isolator are often used in the system. In comparison with the MOPA system design, the multi-rod resonator design is more efficient and simple[7−9]. By use of $N$ rods inside the resonator, in principle, the output power can be increased by $N$ times. However, some discrete unstable zones may exist within the stable region if the multi-rod resonator parameters are not optimum. This will cause unwanted output power drop with the pump power increasing[10]. So it is necessary to optimize the resonator parameters and control the stable region for a multi-rod resonator.

In this letter, we theoretically and experimentally study the stable region control of a seven-rod resonator. For the seven-rod resonator, the largest range of the stable oscillation region can be obtained if the rods are separated by $L/7$ and the mirror-rod distance are $L/14$, where $L$ is the resonator length. Under this arrangement, the seven-rod resonator is equivalent to seven single-rod plane-plane symmetric resonators matched together with the overlapped mirrors between the neighbor rods removed. Based on theoretical results, a seven-rod plane-plane symmetric resonator with an output power of 3.79 W and an optical-to-optical efficiency of 53% is developed.

Figure 1 shows the schematic of a plane-plane symmetric resonator with seven Nd:YAG rods in the cavity. For such a seven-rod resonator, a broad stable region means a high power output and a broad output power variation range. By use of the ray propagation matrix, we investigate the stable region of this seven-rod plane-plane symmetric resonator. Figure 2(a) shows the beam radius in the Nd:YAG rod of the laser head 1 as a function of the thermal focal length for the case of the mirror-rod distance $d_{\rm m}$=50 mm and the rod-rod distance $d = 2d_{\rm m}$. In Fig. 2, $f_{\rm t}$ is the thermal focal length of the crystal rod, and $W_{\rm R}$ is the beam radius in the rod. It can be seen from Fig. 2(a) that, for such an arrangement, the seven-rod resonator has a continuous stable region, corresponding to the thermal focal length continuously varying from $\infty$ to 25 mm ($d_{\rm m}/2$). So the output power of the resonator can increase continuously with the pump power before the thermal focal length approaching 25 mm. The beam radii in other six rods are calculated, which are identical to that in the rod of the laser head 1. This means that, under the same thermal focal length, the beam radii in the seven rods are all identical. Figures 2(b)−(d) show the stable regions of the seven-rod resonator with the rod-rod distance $d$=100 mm, and mirror-rod distance $d_{\rm m}$=60, 40, and 100 mm, respectively. It can be seen that, in these resonator arrangements, the stable region are all un-continuous.

The stable region of a single-rod plane-plane symmetric resonator with the mirror-rod distance $d_{\rm m}$=50 mm is also calculated. The calculation shows that, although the numbers of thermal lenses in two resonators are different, the stable region of the single-rod resonator is identical to that of the seven-rod resonator arranged in Fig. 2(a). This single-rod resonator also has continuous stable region with the thermal focal length varying from 25 mm to $\infty$. Under the same pump power, the beam radii in

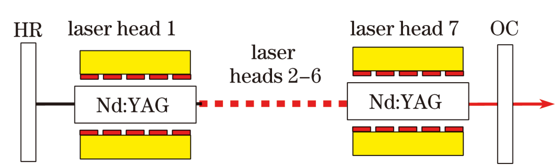


Fig. 1. Schematic diagram of the seven-rod resonator. HR: high-reflection mirror; OC: output-coupling mirror.

 

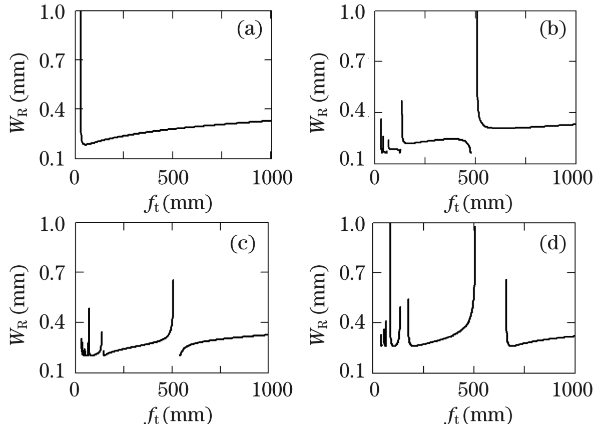


Fig. 2. Stable region of the seven-rod resonator. (a) The rod-rod distance $d$=100 mm, the mirror-rod distance $d_m$=50 mm; (b) $d$=100 mm, $d_m$=60 mm; (c) $d$ =100 mm, $d_m$=40 mm; (d) $d$=100 mm, $d_m$=100 mm.

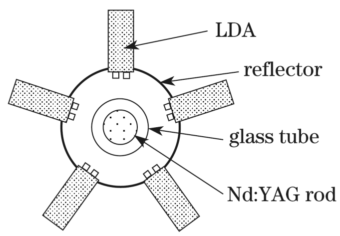


Fig. 3. Schematic of the laser head.

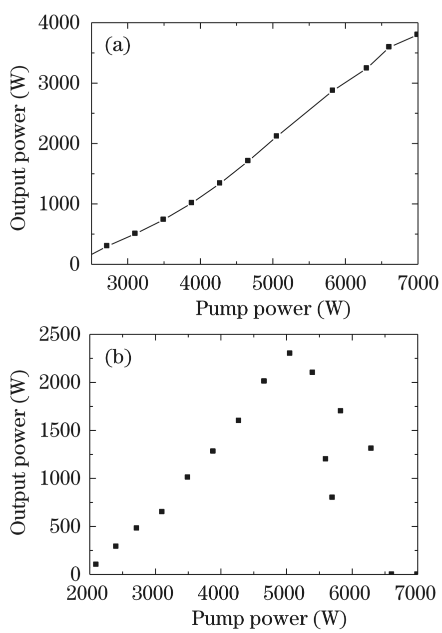


Fig. 4. Output power of the seven-rod resonator versus pump power. (a) $d$=100 mm, $d_m$=50 mm; (b) $d$=100 mm, $d_m$= 60 mm.

all rods of the two resonators are identical. The seven-rod resonator arranged as Fig. 2(a) is equivalent to seven single-rod plane-plane symmetric resonators matched together with the overlapped mirrors being removed.

In theory, the number of the laser heads used in the resonator is infinite. However, two factors limit the number of laser heads. One is that, when too many high power laser heads are used in the resonator, the laser intensity in the resonator will be very high, which may damage the resonator mirrors and other components in the resonator. The other is that too many laser heads in the resonator may cause strong thermally induced aberrations in the laser rods, which limits the obtainable maximum average output power and decreases the laser beam quality. So the high power multi-rod resonator is mainly used in the process where a very high beam quality is not necessarily required.

Figure 3 shows the schematic of the laser head used in the seven-rod resonator. Five quasi-continuous-wave (quasi-CW) laser diode arrays (LDAs) symmetrically surround the Nd:YAG rod (7 mm in diameter and 100 mm in length with 0.6% $Nd^{3+}$ doping concentration). One LDA comprises ten laser diode (LD) bars arranged in two rows. The slow axis of every bar is parallel to the axis of the Nd:YAG rod. Under a repetition rate of 1000 Hz and a duty cycle of 20%, five LDAs in one laser head deliver a maximum average pump power of 1 kW at 808 nm. Placing the laser head in a plane-plane short cavity, about 430-W output at 1064 nm can be obtained from the short cavity. In the short cavity, an output-coupling mirror (OC) with a transmittance of 10% at 1064 nm is used.

The schematic of the seven-rod resonator has been shown in the Fig. 1. The resonator is operated at a repetition rate of 1100 Hz with a pulse width of 172 $\mu$s. The maximum total average pump power reaches 7 kW, and the peak pump power is 35 kW. So the intensity in the resonator is very high, which results in the components in the cavity easily being damaged. To reduce the intensity in the cavity and ensure the laser to operate safely, an OC with a transmittance of 90% at 1064 nm is used. Although the transmittance of OC in the resonator is so high, a high output power can still be achieved due to very high gain in the cavity. The average output power from the seven-rod resonator arranged as Fig. 2(a) was measured, as shown in Fig. 4(a). As expected, the output power continuously increases with the pump power because of the continuous stable region in the resonator. A maximum output power of 3.79 kW at 1064 nm was obtained at an average pump power of 7 kW. The corresponding optical-to-optical efficiency was 53%. The average output power versus the pump power for the seven-rod resonator arranged as Fig. 2(b) was also measured, as shown in Fig. 4(b). It can be seen that there is a dip on the plot. The maximum output power was 2.3 kW, corresponding to a pump power of about 5.1 kW. The main reason for the dip is that there are gaps between the discrete stable regions as shown in Fig. 2(b). Once the resonator enters into the gap, it becomes unstable, and the output power decreases.

In conclusion, for a multi-rod resonator, its output power and output power variation range are closely related to its stable region variation range. A high power with a broad variation range can be achieved from a plane-plane symmetric multi-rod resonator, in which the rod-mirror distance is half of the rod-rod distance. A seven-rod plane-plane symmetric resonator with an output power of 3.79 kW and an optical-to-optical efficiency of 53% is developed, in which the rod-mirror distance is 50 mm and the rod-rod distance is 100 mm.

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