

High power CW and Q-switched operation of a diode-side-pumped Nd:YAG 1319-nm laser

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We demonstrated the highly efficient continuous wave (CW) and Q-switched infrared laser from a diode-side-pumped Nd:YAG crystal. A CW output as high as 66 W at 1319 nm was achieved under the pump power of 460 W, corresponding to a conversion efficiency of 14.3%. A maximum average power of 8.9 W of TEM₀₀ mode was obtained in Q-switched operation at the repetition rate of 8 kHz. The performance of the laser considering the thermal lens effect induced by pump power was also analyzed.

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Efficient and compact diode-pumped solid-state lasers with high output power and good beam quality operating in continuous wave (CW) or pulse operation at 1.3- μm spectral range have important applications in several fields. For example, they can be employed to pump fiber optical parameter amplifiers and Raman amplifiers^[1], optical fibers, Cr³⁺ solid-state tunable lasers and some special solid-state lasers, such as Co:MgF₂ lasers. The wavelength of 1319 nm is located in the low loss, low dispersion range of SiO₂ fiber, so it has important value in fiber transmission. Red light at 660 nm can be generated by second harmonic generation (SHG) of 1319 nm, which has extensive applications in high brightness display and photon dynamic therapy^[2,3], for 660-nm light possesses twice the visual brightness of that at 671 nm which is usually obtained by SHG of 1342-nm Nd³⁺:YVO₄ laser for the same power level. Considering the extensive military application of 1.3- μm chemical oxygen-iodine laser, it is worth studying the performance of laser diode (LD) pumped all-solid-state 1319-nm lasers. Owing to the extensive applications, 1319-nm laser has been an interest of scientific research^[4-8].

1.3- μm lasers could be obtained by LD-pumped Nd³⁺ doped crystals, such as Nd:YVO₄, Nd:YLF or Nd:YAG. LD end-pumped Nd:YVO₄ can produce lasers with good beam quality, but cannot achieve high output power because of the inherent large thermal lens effect and limitation of the end-pump mode in the gain crystal. Nd:YAG crystal has better thermal performance and longer upper-state lifetime than Nd:YVO₄, therefore it is more suitable for high power and high pulse energy operation. Side-pump technique has shown a reduction in thermal lens effect by spreading the thermal load along a crystal edge, and does not require the pump light to transmit through the resonator mirrors, which can reduce the complexity of the cavity structure. However, this technique also has its disadvantages, and the most notable one is the relatively poor beam quality. In this paper, we report the generation of multi-mode 66-W power of stable CW 1319-nm laser with an optical-to-optical efficiency of 14.3% using side-pump Nd:YAG technique. Inserting an

aperture into the cavity, a maximum power of 12.6 W with TEM₀₀ mode at CW operation and a maximum average power of 8.9 W at Q-switched operation are obtained. The laser configuration is simple, compact, and easy to regulate.

The thermal lens effect, due to the heat flow in the gain crystal, crucially determines the cavity stability and the size of lasing mode. In order to calculate the cavity stability condition and the lasing mode size, we measured the thermal focal length at different pump powers using a He-Ne laser^[9] with the setup as shown in Fig. 1(a). According to the geometric formula $\frac{f_{\text{therm}}}{d} = \frac{L - f_{\text{therm}}}{D}$, we could get $f_{\text{therm}} = \frac{d \cdot L}{D + d}$. Substituting the experimental data $d = 4$ mm and $L = 3050$ mm into the formula, we got $f_{\text{therm}} = \frac{12200}{D + 4}$ (mm). We measured the value of D at different pump powers and calculated the corresponding thermal focal length f_{therm} , and the results are shown in Fig. 1(b).

The experimental setup for generating the 1319-nm

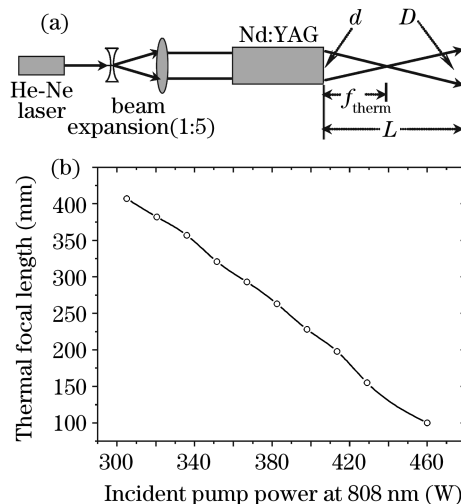


Fig. 1. (a) Measurement setup and (b) result of thermal focal length of Nd:YAG.

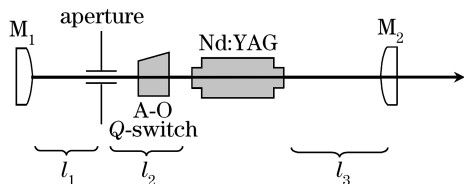


Fig. 2. Cavity configuration. A-O: acoustic-optic.

laser is illustrated as Fig. 2. The convex-convex cavity can effectively increase the lasing mode volume in Nd:YAG crystal and raise the utilization of pump energy. The cavity mirror M_1 had a curvature radius of -600 mm, and the surface was high-reflectivity coated for 1319 nm ($R > 99.8\%$), partly-reflectivity coated for 1064 nm ($R = 20\%$) and 946 nm ($R = 40\%$). The cavity mirror M_2 was convex with a curvature radius of -750 mm and was coated with $R = 92\%$ for 1319 nm and $R = 20\%$ for 1064 nm. As is well known, the three most commonly used wavelengths in Nd^{3+} :YAG crystal are 1064 , 946 and 1319 nm, with the branch ratio being $0.6:0.25:0.15$ ^[10], and the emission cross section of 1064 nm is much bigger than that of 1319 nm. Employing the above coating can guarantee the suppression of lasing at 1064 and 946 nm, meanwhile obtain the strong emission of 1319 -nm light. The Nd:YAG rod with Nd doping of 0.6 at.-% was anti-reflection coated for 1064 and 1319 nm, and had a cross section of diameter of 4 mm and length of 116 mm. The Nd:YAG rod was side-pumped by six modules, each of which contained five 1 -cm-long CW laser-diode array (LDA, 808 -nm wavelength, 20 -W output power) which had relatively broader linewidth and less sensitivity to temperature variation in comparison with a single LD bar, so the requirement of precision of temperature control can be alleviated. The temperature of water for cooling Nd:YAG rod and LD module was set at 26 ± 0.1 °C.

As we know, there are two major adjacent lines (i.e. 1319 and 1338 nm) around 1.3 μm band range, which can be achieved by the transition from ${}^4F_{3/2} \rightarrow {}^4I_{13/2}$ in Nd:YAG crystal^[11]. The stimulated-emission cross sections for 1319 and 1338 nm have almost identical values: 1.0×10^{-19} and 0.95×10^{-19} cm^2 , respectively, and the one for 1319 nm is just a little larger than that of 1338 nm. In common linear standing-wave cavities, the two wavelengths will oscillate simultaneously, so it is difficult to achieve 1319 -nm lasing only under high pump power. One method of depressing the lasing of 1338 nm is to insert an etalon module into the cavity, but it brings intra-cavity loss and increases the cavity complexity at the same time. In our experiment, we coated the cavity mirrors M_1 and M_2 with transmittivity of $> 40\%$ for 1338 nm to depress its lasing under relatively high pump power.

Combining the measurement result of thermal focal length and the other cavity parameters, such as the curvature radius of the mirrors and cavity length, we analyzed the cavity stability by G_1G_2 factor under different pump powers. The calculation result is shown in Fig. 3. It can be found that the behavior of the cavity in the pump range near 429 -W pump power is unstable due to the thermal lens effect. Over 429 W, the cavity can

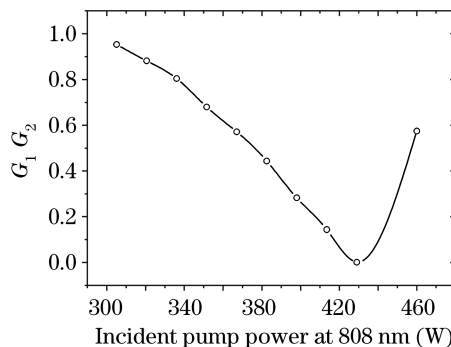


Fig. 3. Product of cavity parameters G_1G_2 versus pump power.

operate in the second stability range, and the output power can remain stable even at high pump power of 460 W.

The performance of CW operation was studied when no acoustic-optic (A-O) Q -switch was introduced into the cavity. The CW multi-mode and TEM_{00} mode outputs were obtained by reducing the aperture size gradually. An output as high as 66 W was obtained at the pump power of 460 W with multi-mode operation, corresponding to 14.3% efficiency of diode pump power to 1319 -nm laser. The beam quality factor was measured with M^2 values of ~ 15 . A maximum power of TEM_{00} mode was measured to be 12.6 W when adjusting the aperture size to 1.2 mm, as shown in Fig. 4. The two-dimensional (2D) distribution of TEM_{00} mode with $M^2 \leq 1.3$ is shown in Fig. 5, and it proves that the function of aperture to produce laser beam with good quality is satisfying.

Inserting an A-O Q -switch, and setting the repetition rate to be 8 kHz, an average power of 8.9 W with the pulse width of 150 ns was obtained under the pump power of 460 W, corresponding to the single pulse energy as high

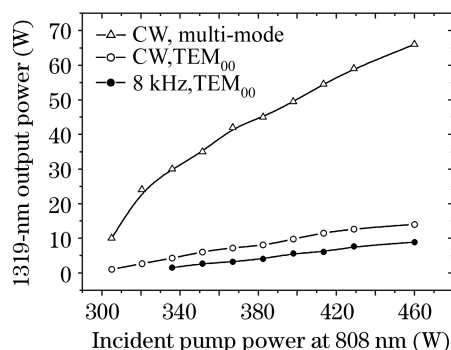


Fig. 4. CW and Q -switched output power versus pump power.

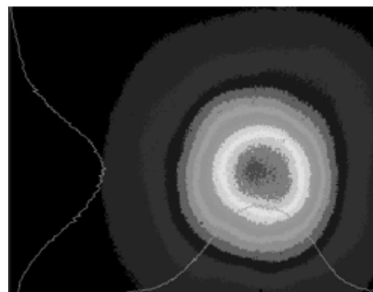


Fig. 5. 2D distribution of the TEM_{00} mode 1319 -nm output.

as 1.1 mJ, and the output beam was proved to be TEM₀₀ mode. The pulse width was reduced to be 70 ns at the repetition rate of 1 kHz under pump power of 460 W. The experimental result is also shown in Fig. 4.

In summary, the performance of CW and pulse operation of a Nd:YAG 1319-nm laser was experimentally studied. The thermal lens effect induced by pump power was measured and the cavity stability under different pump powers was calculated for cavity design. A CW multimode output as high as 66 W at 1319 nm was obtained under the pump power of 460 W, corresponding to 14.3% optical-to-optical efficiency. Utilizing an aperture, TEM₀₀ mode was obtained with the highest output of 12.6 W. Introducing an A-O Q-switch, a maximum average power of 8.9 W of TEM₀₀ mode with the pulse width of 150 ns was achieved under pump power of 460 W at the repetition rate of 8 kHz. The pulse width was reduced to 70 ns at the repetition rate of 1 kHz under pump power of 460 W. This high power and high efficient laser will be valuable for many applications, such as frequency conversion to red and blue wavelengths as well as laser therapeutics.

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