

Continuous-wave, 15.2 W diode-end-pumped Nd:YAG laser operating at 946 nm

Rui Zhou, Enbang Li, Haifeng Li, Peng Wang, and Jianquan Yao

Institute of Laser and Optoelectronics, College of Precision Instrument and Optoelectronics Engineering, Tianjin University, Tianjin 300072, China

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A high-power continuous-wave (cw) Nd:YAG laser operating at 946 nm by utilizing a quasi-three-level transition is reported. The laser consists of a composite Nd:YAG rod end pumped by a fiber-coupled diode laser and a simple plane-concave cavity. At an incident pump power of 40.2 W, a maximum cw output of 15.2 W at 946 nm is obtained, achieving a slope efficiency of 45%. To the best of our knowledge, this is the highest output at 946 nm ever generated by diode-pumped Nd:YAG lasers. In addition, at an incident pump power of 15.2 W, a 1.25 W blue output at 473 nm is achieved with a simple compact three-element cavity and a type-I lithium triborate (LiB_3O_5) crystal as a frequency doubler. © 2006 Optical Society of America
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The ${}^4F_{3/2}-{}^4I_{9/2}$ transition of a Nd:YAG crystal can be utilized to generate laser radiation at 946 nm. High-power, highly efficient cw 946 nm lasers are attractive pump sources for Yb-doped materials (e.g., Yb:YAG and Yb:phosphate glasses) and can be used to measure the absorption of water vapor. Furthermore, blue light at 473 nm generated by frequency-doubling 946 nm lasers has numerous applications in high-density optical data storage, biological and medical diagnostics, Raman spectroscopy, color displays, biofluorescence, trace-gas detection, high-resolution printing, and underwater imaging.

Since the first diode-pumped quasi-three-level Nd^{3+} laser operating at 946 nm from the ${}^4F_{3/2}-{}^4I_{9/2}$ transition was demonstrated by Fan and Byer,¹ much work has been done to improve the output power and efficiency.²⁻¹⁰ However, several factors limit the scaling of the output power and the efficiency of this transition. First, since the lower laser level is the upper 857 cm^{-1} crystal-field component of the ${}^4I_{9/2}$ ground-state manifold, there is a significant reabsorption loss that is due to population in this state at room temperature. Second, the stimulated-emission cross section of this transition is only $4 \times 10^{-20}\text{ cm}^2$, which is approximately an order of magnitude lower than that of the ${}^4F_{3/2}-{}^4I_{11/2}$ transition at $1.06\text{ }\mu\text{m}$. Thus it is very difficult to suppress this strong parasitic oscillation. Third, the pump beam waist in the gain medium must be kept small to overcome the shortcomings of the low gain at this transition. Moreover, since the conversion efficiency of a Nd:YAG laser operating at 946 nm is less than 30%, the thermal effect is much more serious than that of normal diode-end-pumped Nd:YAG lasers operating at 1064 nm.

In our previous work we demonstrated a 8.3 W cw Nd:YAG laser operating at 946 nm.¹¹ Limited by the very severe thermal effects of the conventional non-composite Nd:YAG rod, however, we could not scale the output power. In the work reported in this Letter we have experimentally demonstrated much more powerful and efficient cw operation at this transition by use of a composite Nd:YAG rod. At an incident

pump power of 40.2 W, a maximum output power of 15.2 W has been achieved with a slope efficiency of 45%. To the best of our knowledge, this is the highest power generated by diode-end-pumped cw 946 nm Nd:YAG lasers ever reported so far. In addition, through intracavity frequency doubling with a 14 mm long lithium triborate (LiB_3O_5 , LBO) crystal and a compact three-element resonator, a blue laser output power of 1.25 W has also been generated.

A simple plane-concave cavity, as shown in Fig. 1, was used in our experiment. To overcome the thermal effects caused by the deformation of the crystal faces of a conventional Nd:YAG rod,^{12,13} a composite Nd:YAG rod was designed and manufactured. The composite Nd:YAG rod, which consists of a 4 mm long, 1.1% Nd-doped part in the middle and two 4 mm long undoped end caps, has a diameter of 3 mm and a length of 12 mm. The whole rod was tightly wrapped in a water-cooled copper mount. An indium foil was used to improve the thermal contact between the Nd:YAG rod and the copper heat sink. The pump facet of the Nd:YAG rod was coated with a dielectric coating with a low reflection (AR, $T=93.5\%$) at 808 nm and a high reflection (HR, $R>99.8\%$) at 946 and 473 nm. In addition, the coating also has partial transmission (PT, $T=41.5\%$) at 1064 nm to suppress the strong parasitic oscillation at this transition. The other facet of the Nd:YAG rod was AR ($T>99.8\%$) coated for both 946 and 473 nm. A plano-concave (110 mm in radius) mirror with transmissions of 5% and $>50\%$ at 946 and 1064 nm, respectively, was chosen as the output coupler. The laser cavity length is 13 mm.

The pump source is a high-brightness and high-power fiber-coupled 808 nm laser diode with a maxi-

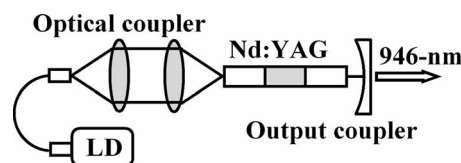


Fig. 1. Schematic of the high-power diode-end-pumped 946 nm Nd:YAG laser.

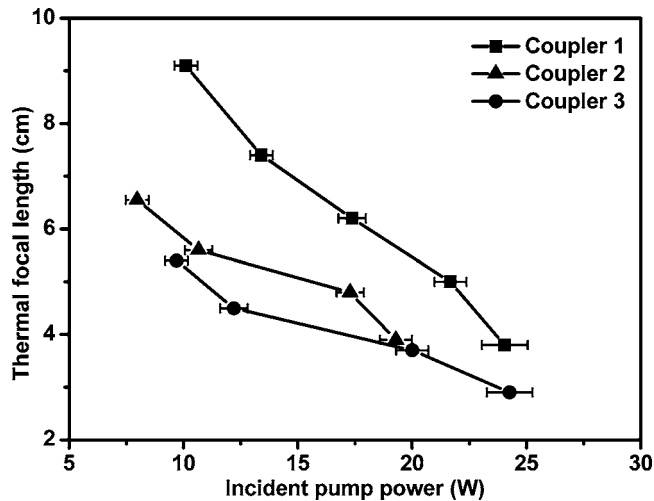


Fig. 2. Thermal focal length versus incident pump power.

imum output power of 50 W. The output fiber has a fiber-core diameter of 400 μm and a numerical aperture of 0.22. Three different optical couplers (couplers 1, 2, and 3) were tested for coupling the pump beam into the Nd:YAG rod, resulting in spot sizes of 440, 300, and 220 μm , respectively.

Tests were first carried out by replacing the output coupler with a flat mirror ($T=4.6\%$ at 946 nm and $T>50\%$ at 1064 nm) to experimentally determine the thermal lensing strengths when different optical couplers were used. During the tests, the incident pump power was increased until the laser oscillation rapidly vanished, while keeping the resonator length unchanged for different couplers. At this point, the thermal focal length should be comparable with the cavity length. The measured thermal focal lengths for the three couplers as functions of pump powers are shown in Fig. 2. These results indicate that the thermal lensing effects are serious issues for the 946 nm laser system and should be carefully considered.

To scale the output power, several compromises were made in the design of the laser. A short plane-concave resonator was used to reduce the thermal lensing effects on the cavity stability at a cost of beam quality. To reduce the reabsorption loss and to enhance laser performance, a cooling system was designed to control the temperature of the Nd:YAG rod. The experimental results indicate that the output power could be increased by more than 10% when the temperature of the Nd:YAG rod was changed from 18°C to 3°C. The laser performances, including output power and beam quality, were evaluated at different cooling temperatures (18°C, 13°C, 8°C, and 3°C) with the three optical couplers. When coupler 1 (producing a 440 μm beam waist) was used, an output of 15.2 W was achieved at an incident pump power of 40.2 W, giving a slope efficiency of 45%. To the best of our knowledge, this is the highest output of diode-pumped Nd:YAG lasers operating at 946 nm. If the low absorption coefficient (3.43 cm^{-1}) of the Nd:YAG crystal is taken into account, the slope efficiency should be 60.3%. Because of the large pump-to-mode size ratio, the beam quality is rather

poor ($M^2=13.1$). The measured output powers at different temperatures and M^2 as functions of the pump power are depicted in Fig. 3. When two other optical couplers were used, the beam quality was improved because of the reduced pump-to-mode size ratio, but the power output decreased because of the more severe thermal effects. With coupler 2 (with a 300 μm pump beam waist), an output power of 12.72 W and a beam quality factor of 10.76 were achieved at an incident pump power of 35.1 W and a cooling temperature of 3.2°C, showing a slope efficiency of 40.1%. When coupler 3 (with a 220 μm pump beam waist) was used, a pumping threshold of 1.44 W was observed owing to the further reduced pump beam size. However, this small pump beam size also makes the thermal lensing effects more serious and thus limits the incident pump power to scale. To avoid any possible damage to the coatings and the Nd:YAG crystal, the maximum pump power for coupler 3 was set at 31.6 W. In this case, an output power of 10.78 W and a beam quality factor of 7.11 were achieved at a cooling temperature of 3.2°C.

Further tests were conducted to obtain a 473 nm blue laser output by frequency doubling the 946 nm Nd:YAG laser. A compact plane-concave linear cavity with a length of 35 mm and a type-I critical phase-matched LBO crystal (2 mm $\times$ 2 mm $\times$ 14 mm, $\theta=90^\circ$, $\varphi=19.4^\circ$) were used to construct an intracavity frequency-doubling system. A plano-concave (50 mm in radius) mirror with transmission values of $<0.2\%$ at 946 nm, $>90\%$ at 1064 nm, and $>96\%$ at 473 nm, respectively, was employed as the output coupler. In the experiments, the temperature of the LBO crystal was controlled and set at 20°C. When coupler 2 was used, an output power of 1.25 W was generated with an incident pump power of 15.2 W, showing an optical-to-optical efficiency of 8.22%. The power instability was measured as less than 1% over 30 min. When the incident pump power was over 15.2 W, the output of the blue laser started to drop. For the cases where couplers 1 and 3 were used, the maximum blue outputs were reduced to 0.7 and 1.02 W, respectively, owing to low intracavity power density or severe

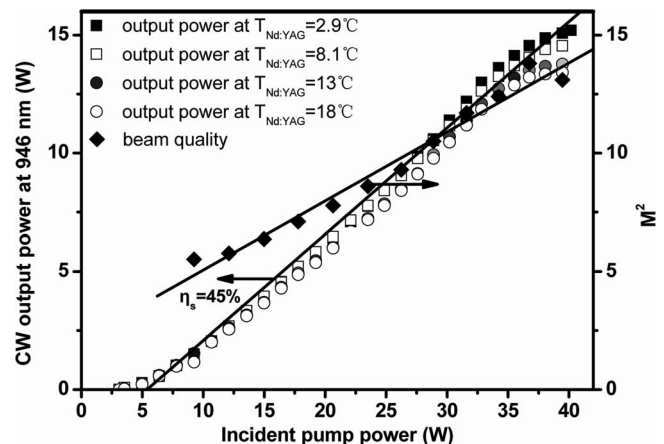


Fig. 3. Measured 946 nm laser powers and beam quality factors under different incident pump powers when an optical coupler (coupler 1), which produced a beam spot size of 440 μm , was used.

thermal problems. The detailed output characteristics are shown in Fig. 4.

In conclusion, we have experimentally demonstrated a high-power, highly efficient diode-pumped 946 nm Nd:YAG laser with an output power of 15.2 W and a slope efficiency of 45%. To the best of our knowledge, this is the highest output ever generated by a diode-pumped Nd:YAG laser operating at 946 nm. Our results show that diode-end-pumped solid-state lasers with quasi-three-level (low gain) transitions can be scaled to high-power levels (>10 W). Research is currently under way to further

scale the output power and to improve the beam quality.

R. Zhou's e-mail address is zhourui_laser@126.com.

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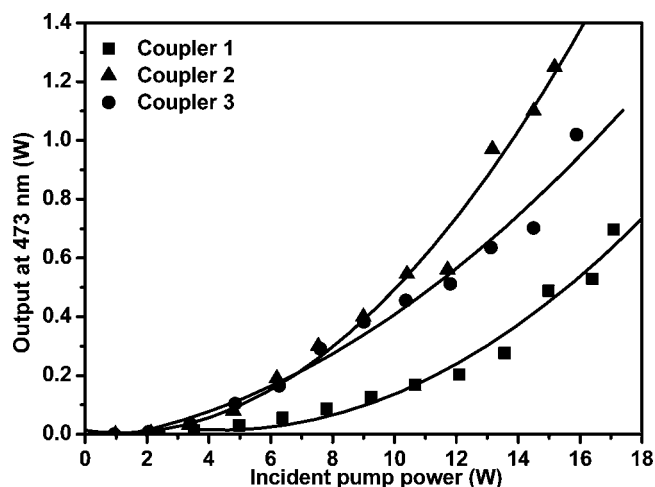


Fig. 4. Output powers of the blue laser with three different optical couplers.