Single, composite, and ceramic Nd:YAG 946-nm lasers*

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Single, composite crystal and ceramic continuous wave (CW) 946-nm Nd:YAG lasers are demonstrated, respectively. The ceramic laser behaves better than the crystal laser. With 5-mm long ceramic, a CW output power of 1.46 W is generated with an optical conversion efficiency of 13.9%, while the slope efficiency is 17.9%. The optimal ceramic length for a 946-nm laser is also calculated.

Keywords: crystal laser, ceramic laser, thermal diffusion

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1. Introduction

High power 946-nm lasers have wide applications in many fields, such as the measurement of the water–vapor absorption and the direct pump source of the Nd^{3+}-doped laser.[1,2] It is also a promising source for blue laser generation. People can obtain 473-nm laser by frequency doubling of the 946-nm fundamental wave,[3,4] which has wide applications in high-density optical data storage, Raman spectroscopy, color displays, bio-fluorescence, and underwater imaging. The 946-nm lasers can be obtained with Nd^{3+}-doped crystals via the $^4F_{3/2}$–$^4I_{9/2}$ transition, which is a quasi-three-level system. As is well known, there are three main factors which restrict the 946-nm laser scaling, i.e., the re-absorption loss, the serious thermal effect, and the low stimulated-emission cross section. The re-absorption loss was determined by a quasi-three-level system, which is hard to change. The composite crystal and ceramic were both proved to be effective in reducing thermal effect of the 946-nm lasers.[5–10] Moreover, the ceramic has the advantage of the high doping concentration level, which can further balance out the low stimulated-emission cross section influence. Therefore the ceramic has become a more promising candidate for a 946-nm laser.

In this paper, we demonstrate CW 946-nm lasers by using Nd:YAG single crystal, YAG-Nd:YAG-YAG composite crystal and Nd:YAG ceramic, respectively. The highest optical conversion efficiency and slope efficiency are obtained to be 13.9% and 17.9% with a 5-mm long ceramic. The advantage of ceramic in reducing thermal effect is obvious. With theoretical analysis, the optimal ceramic length for 946-nm laser is calculated to be 6.6 mm.

2. Experimental setup

The laser cavity was a plano-concave resonator, the pump source employed in the experiment was a fiber-coupled laser diode with a central wavelength around 808 nm. Through the focusing optics (N.A. = 0.22), the output of the source was put into the laser medium with a spot radius of 0.25 mm. The rear mirror was a concave mirror with a curvature radius of 150 mm. The flat face was anti-reflection (AR) coated at 808 nm, the concave face was high reflection coated at 946 nm and high transmissions coated at 808 nm, 1.06 μm, and 1.3 μm. The output coupler was a flat mirror with a transmission of 2% at 946 nm. The laser materials were 1%-Nd-doped YAG single crystal with a dimension of 3 mm×3 mm×3 mm, 1%-Nd-doped YAG-Nd:YAG-YAG composite crystal with a dimension of $\phi 3\times 7$ mm^3 and 2%-Nd-doped YAG ceramics with dimensions of 3 mm×3 mm×1.3 mm, 3 mm×3 mm×2.6 mm, and 3 mm×3 mm×5.0 mm. The single and composite crystals were polished and AR coated at 946 nm, the ceramics were polished but not coated. In order to remove the heat generated in the experiment, the laser materials were wrapped with indium foil and held in a water-cooled copper block. The length of the cavity was measured to be 20 mm. The output power was measured by the power meter (EPM 2000. Melectron Inc.), the laser spectra were recorded by a spectrum analyzer (HR 4000CG-UV-NIR, Ocean Optics Inc.).

3. Results and discussion

First, we demonstrate the 946-nm Nd:YAG single and composite crystal lasers. Figure 1 shows the output powers versus absorbed pump power under different experimental temperatures. The crystals have the same doping length (the

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composite crystal was 3-mm long doped with two 2-mm long un-doped end caps) and the same doping level (1 at.%), so the output improvement with composite crystal is caused by its good heat diffusivity.

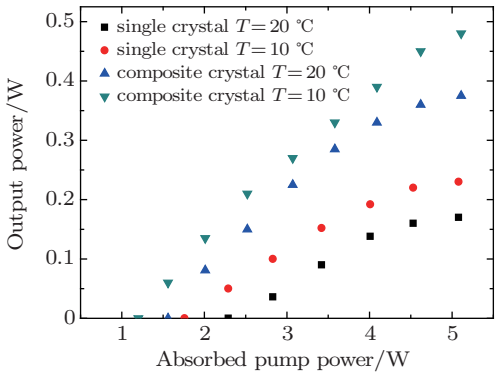


Fig. 1. (color online) Single and composite laser output powers versus absorbed pump power.

As can be seen in Fig. 1, cooling water can lower the laser threshold and increase the output power for both of the crystals, especially when the cooling temperature is 10 °C, the saturation is greatly weakened. But under high pump power, the cooling is not so efficient that the output power is still saturated. The detailed laser data are shown in Table 1.

Then we demonstrate the ceramic lasers. Figure 2 shows the 946-nm output powers versus the absorbed pump power with three Nd:YAG ceramics, and the experimental temperature is maintained at 10 °C. Unlike Fig. 1, only at high pump power the 1.3-mm and 2.6-mm long ceramic lasers have slightly saturated phenomenon. The output power is not saturated with 5-mm long ceramic, which implies that further power scaling could be expected. The obvious improvement of the laser efficiency with the ceramics may be mainly due to the high Nd^{3+} doping level in ceramic (2 at.%), which can assure a sufficient absorption of the pump power and an increase of the stimulated-emission cross section. The corresponding laser data are also shown in Table 1. We can see that the ceramics have better performances in general except for the laser threshold; this may be attributed to the fact that the ceramics are not coated on the end faces. Lower threshold and higher laser output power should have been obtained if the ceramics are coated.

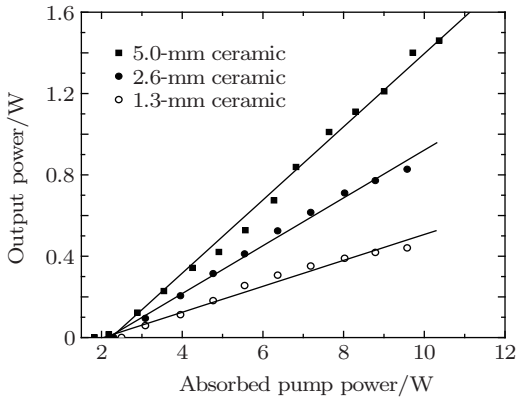


Fig. 2. Ceramic laser output powers versus the absorbed pump power.

Table 1. The 946-nm laser results with different laser materials.

	Threshold/W	Max output power/W	Optical conversion efficiency	Slope efficiency
Nd:YAG single crystal 20 °C	2.29	0.17	3.5%	8.0%
Nd:YAG single crystal 10 °C	1.76	0.23	4.8%	8.3%
Nd:YAG composite crystal 20 °C	1.56	0.37	8.1%	11.7%
Nd:YAG composite crystal 10 °C	1.20	0.48	9.5%	14.7%
Nd:YAG ceramic 1.3 mm 10 °C	2.50	0.44	4.6%	6.4%
Nd:YAG ceramic 2.6 mm 10 °C	2.30	0.83	8.7%	11.8%
Nd:YAG ceramic 5.0 mm 10 °C	2.15	1.46	13.9%	17.9%

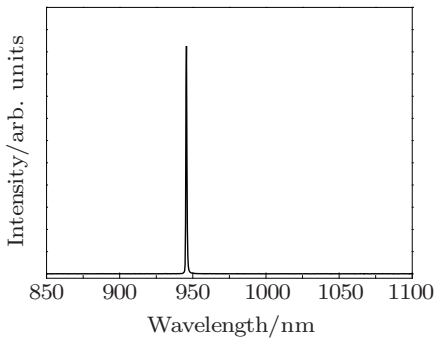


Fig. 3. The 946-nm laser spectrum.

The output laser spectrum was shown in Fig. 3, there was only 946-nm wave observed, the 1064 nm and 1.3-μm lasers were well depressed.

In the ceramic lasers, with increasing the ceramic length, the laser threshold becomes lower and the optical efficiency and slope efficiency turn higher. The optimal laser material length for a 946-nm laser can be calculated from the following formula:

$$\frac{f_a N_0 \sigma}{\alpha} = \frac{\exp(-\alpha L_0)}{1-\exp(-\alpha L_0)}(f_a N_0 \sigma L_0 + \delta/2), \qquad (1)$$

in which f_a is the Boltzmann occupation factor of the lower laser level, N_0 the total Nd^{3+} ion population density, σ the stimulated emission cross section, α the absorption coefficient

of the laser gain medium, δ the roundtrip dissipative optical loss and L_0 the optimal laser material length. Through the data given in Table 2, we can calculate L_0 to be 6.6 mm, which is very close to our experimental ceramic length.

Table 2. Values of the parameters.

f_a	0.74%[11]
N_0	4×10^{20} cm^{-3}
σ	4.5×10^{-20} cm^2[12]
α	5 cm^{-1}
δ	0.04

4. Conclusions

In this paper, we demonstrate the 946-nm laser with three Nd:YAG counterparts. A comparison of the laser output curves shows that the ceramic laser has better performance than the crystal ones. With a 5-mm long uncoated ceramic, the best laser results are obtained in our experiments. The maximum output power is 1.46 W, corresponding to an optical conversion efficiency of 13.9% and a slope efficiency of 17.9%. Through theoretical calculation, the optimal ceramic length was estimated to be 6.6 mm. If we further optimize the laser cavity design, higher laser efficiency could be expected.

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