A tunable corner-pumped Nd:YAG/YAG composite slab CW laser*

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A corner-pumped Nd:YAG/YAG composite slab continuous-wave laser operating at 1064 nm, 1074 nm, 1112 nm, 1116 nm, and 1123 nm simultaneously and a laser that is tunable at these wavelengths are reported for the first time. The maximum output power of the five-wavelength laser is 5.66 W with an optical-to-optical conversion efficiency of 11.3%. After a birefringent filter is inserted in the cavity, the five wavelengths can be separated successfully by rotating the filter. The maximum output powers of the 1064 nm, 1074 nm, 1112 nm, 1116 nm, and 1123 nm lasers are 1.51 W, 1.3 W, 1.27 W, 0.86 W, and 0.72 W, respectively.

Keywords: corner-pumped, solid-state, composite slab, tunable laser

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1. Introduction

Corner-pumping is a new diode-pumping scheme for slab lasers, which was first demonstrated by our group.[1−3] In recent years, we have reported some corner-pumped solid-state lasers operating at 1030 nm, 1064 nm, 1.3 μm, and 1.1 μm respectively.[3−7] Compared with other pumping methods, the corner-pumping scheme uses a laser diode (LD) bar to directly pump the slab crystal and adopts a simple optical coupler, which can reduce the cost of the laser effectively.[7]

Besides the well-known diode-pumped Nd:YAG 1064-nm, 1319-nm, and 946-nm lasers, efficient and compact diode-pumped Nd:YAG lasers operating at 1074-nm and 1.1-μm wavelength regions have also attracted increasing attention recently.[7−14] The fifth harmonic generation of the 1074-nm laser is applied in nitric oxide (NO) detection.[10] The 1123-nm laser is applied in differential absorption lidars and used as the pump source for thulium upconversion fiber lasers.[8,9] The yellow–green output from the frequency-doubled 1.1-μm laser can play important roles in laser display, detection of poison gas, medical and dermatology applications, bio-fluorescence experiments, and holographic storage.[15,16] Therefore, lasers that can operate or be tunable at these wavelengths are highly desirable. In this paper, a corner-pumped Nd:YAG/YAG composite slab simultaneous five-wavelength continuous-wave (CW) laser and a laser tunable at these five wavelengths (1064 nm, 1074 nm, 1112 nm, 1116 nm, and 1123 nm) are presented for the first time.

2. Corner-pumped Nd:YAG/YAG composite slab CW five-wavelength laser

First, a corner-pumped Nd:YAG/YAG composite slab CW laser operating simultaneously at 1064 nm, 1074 nm, 1112 nm, 1116 nm, and 1123 nm is studied. The simple linear two-mirror cavity used in the experiment is shown in Fig. 1. The slab is a diffusion-bonded composite crystal of undoped YAG and at 1.0 % Nd:YAG. The Nd:YAG crystal measures 1 mm in thickness (H), 0.8 mm in width (W_1), and 14 mm in length (L), which is shown in Fig. 2. Two pieces of undoped YAG crystals of dimensions 1 mm × 3.5 mm (W_2) × 14 mm are thermally bonded to the Nd:YAG crystal at two 1 mm × 14 mm faces. After bonding,

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the slab is polished, and one corner of the slab is chamfered to a 45° angle. A 3-mm (W_3) × 1 mm plane is formed, from which the pump light is incident to the slab. The two end surfaces of the Nd:YAG slab are well polished and coated with films antireflective at 1.1 μm. A coating with a high transmission ratio ($T > 99.8\%$) at 808 nm is coated on the incident plane of the Nd:YAG/YAG composite slab. A CW LD bar with a maximum 808-nm output power of 50 W is used in the experiment. The rectangular chamfer of the slab is chosen to be 3 mm × 1 mm. For 10 mm×0.7 mm of the light-emitting area of the LD bar and a certain angle of divergence of the pump light, an optical coupling system including three cylindrical lenses is employed to shape the pump light emitted from the LD bar.

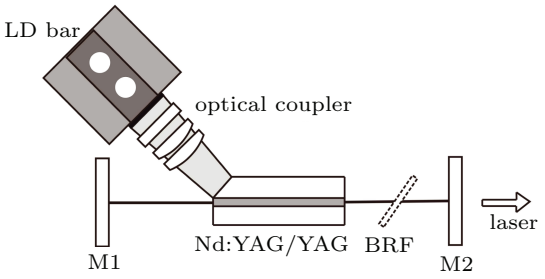


Fig. 1. Experimental setup of the corner-pumped Nd:YAG/YAG composite slab CW five-wavelength laser without a birefringent filter.

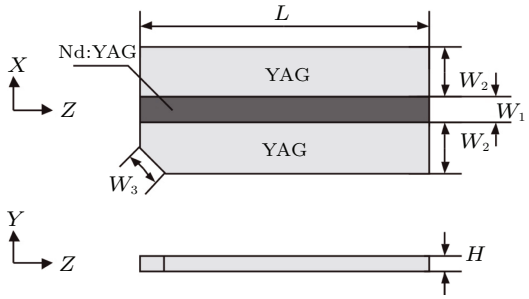


Fig. 2. Schematic diagram of the Nd:YAG/YAG composite slab.

In order to have five laser wavelengths (1064 nm, 1074 nm, 1112 nm, 1116 nm, and 1123 nm) stimulated simultaneously, special films are coated on the two mirrors (M1, M2). The M1 is a planar mirror with high reflectivity coatings at 1112 nm ($R > 99.8\%$), 1116 nm ($R > 99.8\%$), and 1123 nm ($R > 99.8\%$) and partial reflectivity coatings at 1064 nm ($R = 57\%$) and 1074 nm ($R = 79\%$). The M2 is also a planar mirror with partial transmission coatings at 1064 nm ($T = 26\%$), 1074 nm ($T = 10\%$), 1112 nm ($T = 1.5\%$), 1116 nm ($T = 1.4\%$), and 1123 nm ($T = 1.3\%$). The temperature of the pump source is maintained at 25 °C by water cooling. The larger surfaces of the composite slab are wrapped by two pieces of indium and cooled through thermal conduction using two heat sinks made of red copper. The temperature of the slab is kept at 13 °C by water cooling.

The output power versus the pump power is shown in Fig. 3. The threshold pump power is 8.8 W. When the pump power is increased to 50.3 W, the output power goes up to 5.66 W with an optical-to-optical conversion efficiency of 11.3%. Figure 4 shows the spectrum from 1060 nm to 1160 nm at an output power of 5.66 W. The five laser lines at 1064 nm, 1074 nm, 1112 nm, 1116 nm, and 1123 nm are present simultaneously. As is seen from Fig. 3, the output power is not saturated with the increase of the pump power. It is possible to obtain a higher output power and a higher conversion efficiency with a higher pump power. In addition, the cavity length of 82 mm is relatively long so as to have enough space for a birefringent filter (BRF) in the cavity, which results in more diffraction loss and a decrease of output power. If the cavity length is shortened, a higher output power can be expected.

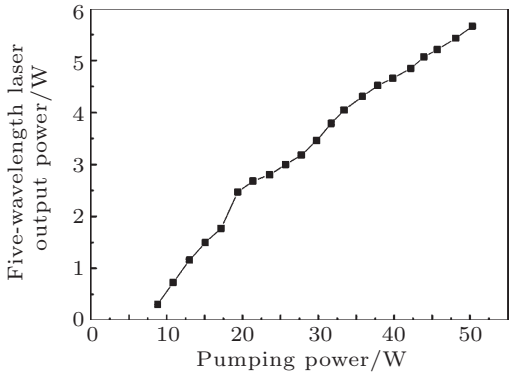


Fig. 3. Output power of the five-wavelength CW laser versus pump power.

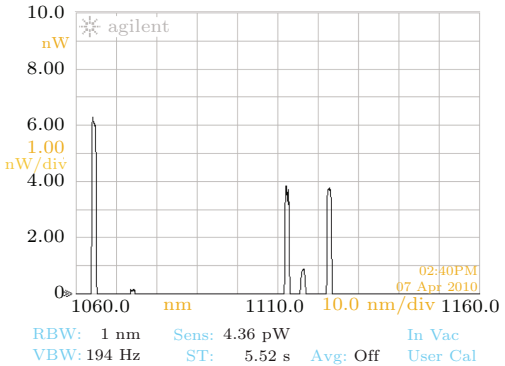


Fig. 4. Spectrum from 1060 nm to 1160 nm at an output power of 5.66 W.

Because the relative performances of the three laser lines at 1112 nm, 1116 nm, and 1123 nm and their stimulated emission cross sections are close to each other, the three laser lines can be easily stimulated simultaneously under a certain pump power. If a frequency selective component is not used in the laser cavity, the laser is difficult to operate with a single wavelength output by only coating special films on the cavity mirrors.

3. The tunable corner-pumped Nd:YAG/YAG composite slab CW laser

Next, we insert a BRF in the cavity and study the tunable corner-pumped Nd:YAG/YAG composite slab CW laser, which can operate at 1064 nm, 1074 nm, 1112 nm, 1116 nm, and 1123 nm respectively. The experimental setup is shown in Fig. 1. The laser cavity length is still 82 mm and the other experimental conditions are not changed. The BRF made of quartz measures 10 mm in radius and 4 mm in thickness and is placed in the cavity with the Brewster angle. Our calculations indicate that the output wavelength can vary from 1064 nm to 1123 nm only by rotating the BRF about 4°–5°. Different laser lines will correspond to different angles. When the BRF is set at a certain angle, one corresponding wavelength is generated from the corner-pumped Nd:YAG/YAG composite slab CW laser and the other laser lines can be suppressed successfully. The tunable method is simple and convenient.

Table 1 shows the experimental and theoretical results, where the experimental rotation angle is the real record of the dial fixed on the BRF in the experiment when a desired wavelength is selected to oscillate in the cavity. The experimental results indicate that the output wavelength can vary from 1064 nm to 1123 nm by rotating the BRF about 5°, while the theoretical results show that the output wavelength can vary from 1064 nm to 1123 nm by rotating the BRF about 4.4°. The small difference is due to the low accuracy of the dial scale. The maximum output powers of 1064 nm, 1074 nm, 1112 nm, 1116 nm, and 1123 nm lasers are 1.51 W, 1.3 W, 1.27 W, 0.86 W, and 0.72 W, respectively. Figure 6 shows the spectra from 1060 nm to 1160 nm at those rotation angles and maximum output powers.

Table 1. Output parameters of the tunable laser.

Output wavelength /nm	Experimental rotation angle/(°)	Theoretical rotation angle/(°)	Maximum output power/W
1064	226	43.2	1.51
1074	224.5	44.8	1.3
1112	223	45.9	1.27
1116	222	46.5	0.86
1123	221	47.6	0.72

Take the corner-pumped Nd:YAG/YAG composite slab CW laser emitting at 1112-nm for example. When the BRF is set at 223°, the laser can output at the single wavelength of 1112 nm. The output power of the 1112-nm laser versus the pump power is shown in Fig. 6. The threshold pump power is 25 W. When the pump power is increased to 45 W, the output power goes up to 1.27 W. Figure 5(c) shows the spectrum of the 1112-nm laser at the output power of 1.27 W. The line width of the laser is only 0.06 nm, which is up to the resolution limit of our spectrum analyzer (Agilent 86140B). The reason is that the BRF inserted in the cavity plays an important role not only in distinguishing some close laser lines, but also in decreasing the number of longitudinal modes in the cavity. The characteristics of the longitudinal modes of the laser without and with the BRF at the pump power of 45 W are both measured using a scanning confocal F-P interferometer and the results are shown in Fig. 7. A comparison of Figs. 7(a) and 7(b) shows that the laser can operate not only at the single wavelength of 1112 nm but also at two longitudinal modes after the BRF is inserted in the cavity. In addition, because of the decrease of the number of longitudinal modes, the stability of the output power is improved significantly.

When the pump power is 42 W, the short-term instability of the output power is measured, and the result is shown in Fig. 8. We record the output power of the 1112-nm laser every minute using a calibrated thermal power meter head from OPHIR NOVA II in a time period of fifteen minutes. The instability of the output power can be obtained from the following formula

$$\Delta P/\overline{P} = \sqrt{\frac{\sum_{i=1}^{n}\left(P_i - \overline{P}\right)^2}{n-1}} \cdot \frac{1}{\overline{P}} \approx 0.4\%, \qquad (1)$$

where n is defined as the number of samples. The result indicates that the output power of the CW 1112-nm laser is very stable.

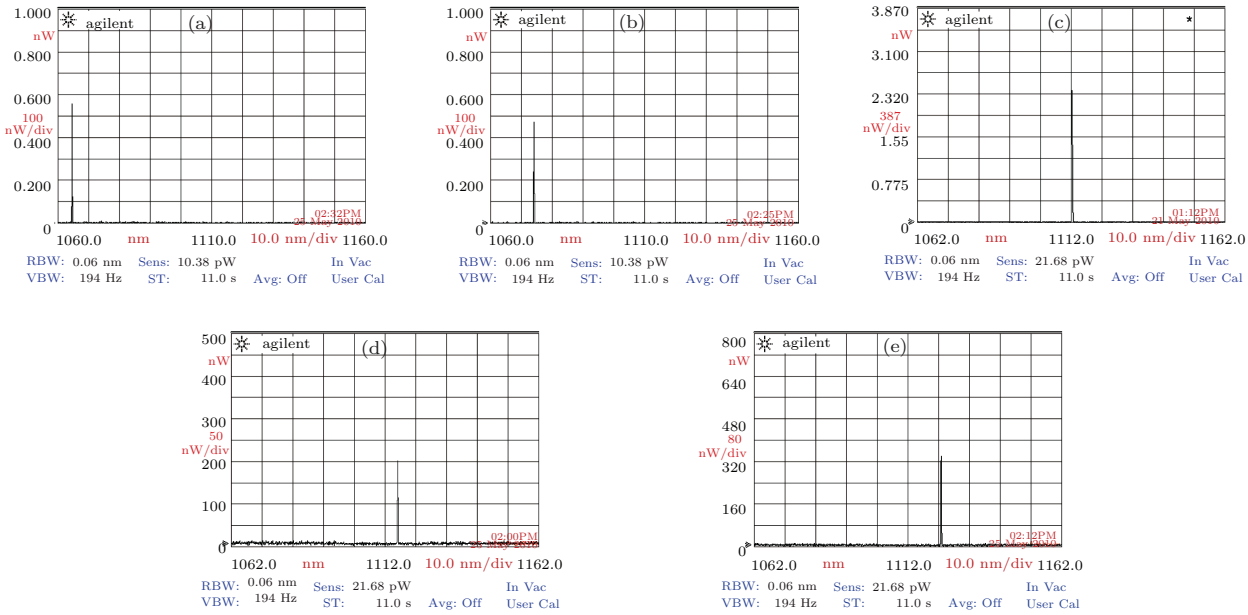


Fig. 5. Spectra of (a) 1064 nm; (b) 1074 nm; (c) 1112 nm; (d) 1116 nm; (e) 1123-nm laser lines.

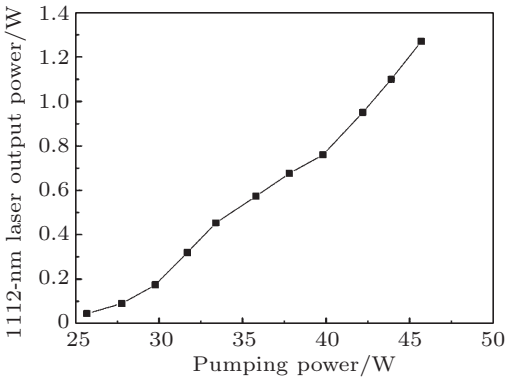
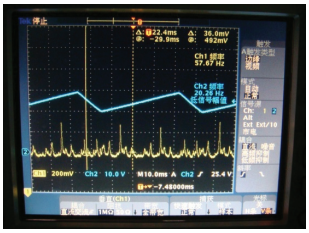


Fig. 6. Output power of the CW 1112-nm laser versus pump power.



(a)



(b)

Fig. 7. Longitudinal-mode operation observed by a scanning confocal F-P interferometer (a) without and (b) with the BRF.

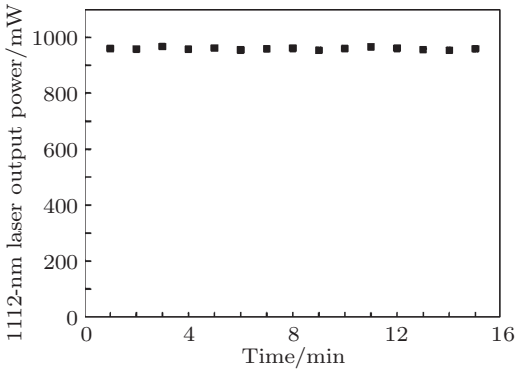


Fig. 8. Short-term instability of the output power when the pump power is 42 W.

4. Conclusion

In summary, we have reported a corner-pumped Nd:YAG/YAG composite slab CW laser operating at 1064 nm, 1074 nm, 1112 nm, 1116 nm, and 1123 nm simultaneously and a tunable laser at these wavelengths for the first time. Based on the corner-pumping scheme, the lasers are both compact and low cost. The maximum output power of the five-wavelength laser is 5.66 W with an optical-to-optical conversion efficiency of 11.3%. The multi-wavelength laser can be an important pump source for generating THz waves. With a BRF inserted in the cavity, the laser can operate at a single wavelength. The maximum output powers of 1064-nm, 1074-nm, 1112-nm, 1116-nm, and 1123-nm lasers are 1.51 W, 1.3 W, 1.27 W, 0.86 W, and 0.72 W, respectively. By further extra-cavity frequency doubling, green and yellow-green lasers with

different wavelengths can be obtained conveniently and quickly, which will have broad applications in laser displays and the detection of poison gas.

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