High-power tunable single- and multi-wavelength diode-pumped Nd:YAP laser in the $^4F_{3/2} \rightarrow {}^4I_{11/2}$ transition

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Abstract: We experimentally explore the fluorescent spectrum of the Nd:YAP crystal to manifest the feasibility of tunable single- and multi-wavelength operations in the $^4F_{3/2} \rightarrow {}^4I_{11/2}$ transition. An intracavity etalon is subsequently exploited to effectively select spectral lines at 1073, 1080, and 1084 nm with the tunabilities of 0.56, 1.13, and 0.1 nm, respectively. We also experimentally obtain multi-wavelength oscillations among various intermanifold lines in the Nd:YAP crystal with the output powers on the order of several watts for each group. Employing the Cr^{4+}:YAG crystal to realize the passively Q-switched operation, the maximum average output powers as high as 2.3 and 3.5 W for 1073 and 1080 nm are obtained. The corresponding pulse energies at 1073 and 1080 nm are up to 177 and 159 μJ, respectively.

OCIS codes: (140.3600) Lasers, tunable; (140.3380) Laser materials; (140.3540) Lasers, Q-switched; (140.3480) Lasers, diode-pumped; (140.3530) Lasers, neodymium; (140.3580) Lasers, solid-state.

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1. Introduction

Nowadays, the Nd:YAG crystal is widely used as a gain medium for high-power solid-state laser thanks to its excellent optical and mechanical characteristics. However, the optically isotropic property in the transverse plane usually leads the Nd:YAG crystal to suffer from the thermal depolarization loss when an intracavity polarizer is aimed to force linearly polarized operation. During the early research on the laser crystals, many literatures have indicated that the Nd:YAP crystal, also known as Nd:YAlO or Nd:$YAlO_3$, is a promising replacement for the Nd:YAG crystal, where both of each are derived from the Y_2O_3-Al_2O_3 system except that the composition ratios are different [1–3]. Although the physical properties for the two laser materials are quite similar, the orthorhombic lattice structure of the crystalline host makes the Nd:YAP crystal exhibit the natural birefringence, which is essentially advantageous in avoiding the undesirable impacts caused by the thermally induced birefringence. As a consequence, the Nd:YAP crystal is regarded as one of the competitive candidates for developing a high-power solid-state laser with the constantly polarized output [4–9].

Another feature of the Nd:YAP crystal is the possession of a wealth of sharp fluorescent lines as a result of the relatively strong splitting of the Stark levels [10,11]. Figure 1(a) shows the measured room-temperature fluorescent spectrum for the light polarized parallel to the *c* axis of an 1.0 at. % *b*-cut Nd:YAP crystal, which is used as the gain medium in this work. Note that the crystal axes expressed here are based on the historic Pbnm notation rather than the Pnma notation given in Ref [11]. It can be clearly seen that there are various attainable emission peaks in the range of 1040-1115 nm. Especially, the transition lines at 1073, 1080, and 1084 nm have proved to be helpful for optical pumping of superfluid helium and related scientific studies such as atomic and molecular spectroscopy [12–16]. Therefore, it is practically valuable to develop a compact light source at these spectral lines with the Nd:YAP crystal.

In this work, we successfully demonstrate the tunable single- and multi-wavelength operations in a compact diode-pumped Nd:YAP laser. An uncoated glass plate with the thickness of 160 μm is employed as an intracavity etalon to efficiently select the emission lines at 1073, 1080, and 1084 nm. In addition, the spectral output of our Nd:YAP laser is experimentally found to be tunable over the discrete regions of 1072.87-1073.44, 1079.12-1080.25, and 1084.06-1084.16 nm. Experimental results also reveal that carefully adjusting the tilting angle of the etalon leads the Nd:YAP laser to simultaneously generate multiple wavelengths among various intermanifolds in the $^4F_{3/2} \rightarrow {}^4I_{11/2}$ transition. With the output coupling of 6%, it is found that the output powers for the single- and multi-wavelength operations can generally reach the level on the order of several watts. Compared with the similar studies in the past [10,11], the diode-end-pumped architecture adopted here is more compact and efficient. We further utilize the Cr^{4+}:YAG crystal to design a passively Q-switched Nd:YAP pulsed laser. Maximum average output powers of 2.3 and 3.5 W with the pulse durations of 16 and 17 ns and the pulse repetition rates of 13 and 22 kHz are achieved for 1073 and 1080 nm under an incident pump power of 15.4 W. The corresponding pulse energies and peak powers are up to 177 and 159 μJ and 11 and 9.4 kW for 1073 and 1080 nm, respectively. To the best of our knowledge, this is the first demonstration of the continuously diode-pumped passively Q-switched Nd:YAP laser with the Cr^{4+}:YAG saturable absorber to date.

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2. Experimental setup

The experimental setup for our compact diode-pumped Nd:YAP laser is schematically shown in Fig. 1(b). A concave mirror with the radius of curvature of 500 mm was used as the input mirror. It was antireflection coated at 803 nm on the entrance face and was coated to be highly transmissive at 803 nm and highly reflective in the range of 1040-1115 nm on the second face. The gain medium was an 1.0 at. % *b*-cut Nd:YAP rod with the diameter of 3.7 mm and the length of 5.9 mm. The crystal was fabricated by the Fujian Institute of Research on the Structure of Matters, Chinese Academy of Sciences. Both surfaces of the laser crystal were coated to be antireflective in the range of 1040-1115 nm. The Nd:YAP crystal was wrapped with indium foil and mounted in a water-cooled copper holder with the temperature of 16þC. An uncoated glass with the thickness of 160 μm was employed as an intracavity etalon for accomplishing tunable single- and multi-wavelength operations, which has proved to be a simple and convenient method to achieve the wavelength selectivity and tunability for laser output [17,18]. We did not try the etalons with other thickness due to the availability of the experimental components. The pump source was a fiber-coupled laser diode with a core diameter of 600 μm and a numerical aperture of 0.16, and the emission wavelength could be finely tuned to the best absorption peak around 803 nm for the Nd:YAP crystal by varying the temperature of the laser diode. A pair of the plano-convex lenses with the focal lengths of 25 mm and the total coupling efficiency of 88% were exploited to reimage the pump beam into the Nd:YAP crystal with the pump radius of approximately 300 μm. A flat mirror with the reflectivity of 94% in the range of 1040-1115 nm was employed as the output coupler, which was experimentally found to give the best performance in output power. The cavity length was set to be 24 mm for establishing a compact linear oscillator. An optical spectrum analyzer (Advantest, Q8347) that is constructed with a Michelson interferometer was used to monitor the spectral information of the laser output with the resolution of 0.05 nm.

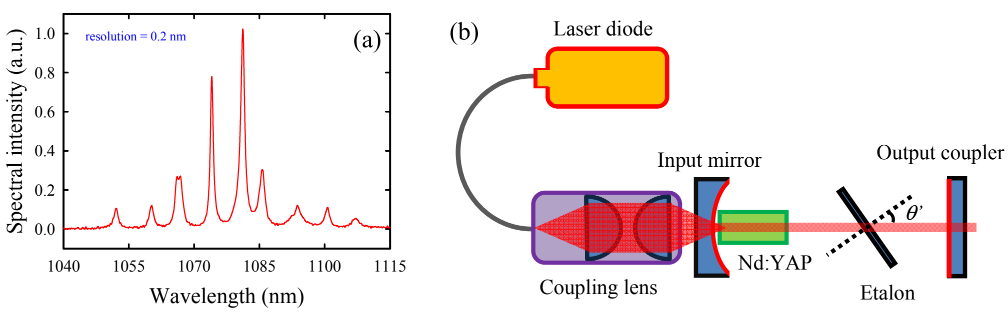

Fig. 1. (a) Room-temperature fluorescent spectrum for the light polarized parallel to the *c* axis of an 1.0 at. % *b*-cut Nd:YAP crystal. (b) Configuration of the cavity setup for the tunable diode-pumped Nd:YAP laser.

3. Experimental results and discussions

First of all, the laser operation without an intracavity etalon was performed to examine the quality of the Nd:YAP crystal. At this time, the output wavelength was obtained to be 1080 nm thanks to the largest gain for this emission line, as can be indicated from Fig. 1(a). Figure 2(a) illustrates the dependence of the output power at 1080 nm on the incident pump power at 803 nm. The threshold pump power is around 0.6 W, and the maximum output power is found to be up to 6.9 W at an incident pump power of 15.4 W. The corresponding slope and optical conversion efficiencies are evaluated to be 46.7 and 44.8%, respectively. The output spectrum with the central wavelength of 1079.98 nm is sketched in Fig. 2(b).

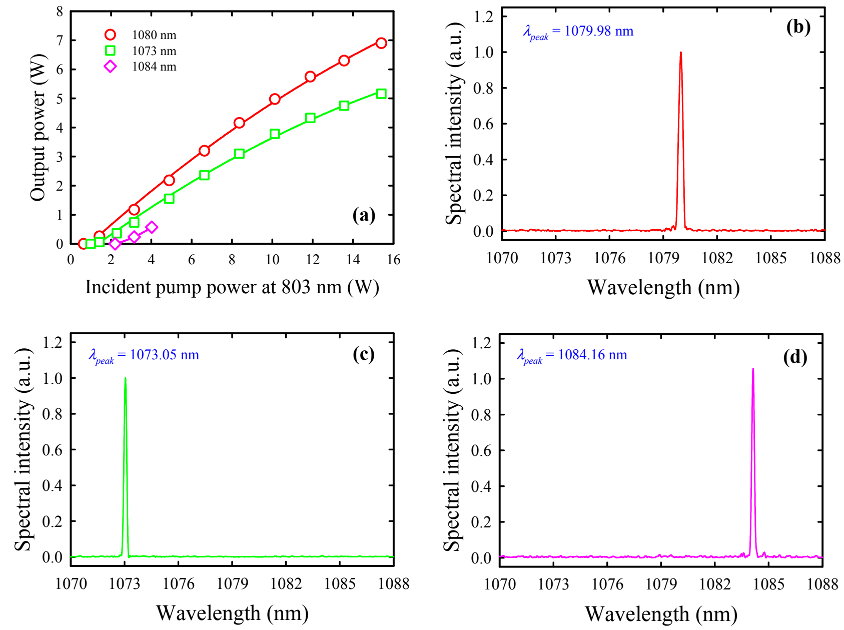

Fig. 2. (a) Output powers at 1073, 1080, 1084 nm with respect to the incident pump power at 803 nm; Output spectra for (b) 1080 nm, (c) 1073 nm, and (d) 1084 nm.

When the intracavity etalon was subsequently inserted in the laser resonator, it is experimentally found that the single-wavelength operations at 1073 and 1084 nm rather than 1080 nm could be achieved with suitably adjusting the tilting angle of the etalon. The characteristics for these two emission lines are also described in Fig. 2(a). The threshold pump power and the maximum output power for 1073 nm are 1 and 5.2 W with the slope and optical conversion efficiencies of 35.8 and 33.5%. On the other hand, the single-wavelength output at 1084 nm is found to be acquired with the incident pump power in the limited range from 2.2 to 4 W partly because of the small wavelength separation between the high-gain 1080-nm and low-gain 1084-nm spectral lines. As a consequence, the maximum output power at 1084 nm is 0.57 W under an incident pump power of 4.5 W. The output spectra for each wavelength are demonstrated in Figs. 2(c) and 2(d) with the emission peaks of 1073.05 and 1084.16 nm, respectively. It is worthwhile to mention that the electric fields of all above-mentioned emission wavelengths were polarized along the *c* axis of the Nd:YAP crystal. Also note that if the etalon was introduced inside the cavity under the single-wavelength operation at 1080 nm, the maximum output power would reduce to be around 6.5 W as a result of additional intracavity loss.

Moreover, we observed that with carefully varying the tilting angle of the etalon, the output peaks of our Nd:YAP laser could be flexibly tuned around 1073, 1080, and 1084 nm. The performance of the tuning characteristics for these intermanifold transitions are illustrated in Figs. 3(a)-3(c), where θ' is the experimentally measured angle between the optical axis of the resonator exterior to the etalon and the surface normal of the etalon, as indicated in Fig. 1(b). It can be seen that the tuning ranges of 0.56, 1.13, and 0.1 nm could be accomplished for 1073-, 1080-, and 1084-nm lines, respectively. For an etalon with the same reflectivities on the both sides, the transmitted intensity T can be expressed as:

$$T = \frac{(1-R)^2}{(1-R)^2 + 4R\sin^2\left(\frac{2\pi Ln\cos(\theta)}{\lambda}\right)}. \qquad (1)$$

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where R is the reflectivity for one surface of the etalon, L and n are the thickness and the refractive index of the etalon, λ is the wavelength, and θ is the angle between the optical axis of the resonator exterior to the etalon and the surface normal of the etalon. From Eq. (1), the maximum transmission occurs when the condition given by Eq. (2) is satisfied:

$$\lambda_{peak} = \frac{2Ln\cos(\theta)}{m}. \tag{2}$$

where λ_{peak} is the wavelength corresponding to the maximum transmission, and m is an arbitrary integer except zero. It is obvious that increasing θ leads to the decrease of λ_{peak}, which is in qualitative agreement with the experimental observation of the continuous variation of the spectral output toward the shorter wavelength as the tilting angle θ' is increased. Note that although the wider tuning range could be achieved with the increase of the reflectivity of the output coupler, this would accompany with the expense of the reduced output power.

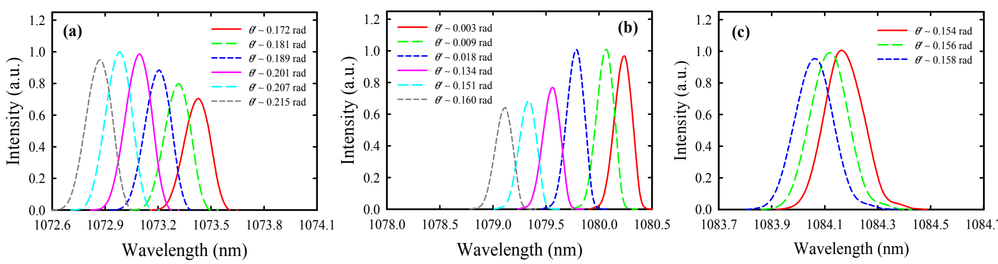

Fig. 3. Tuning ranges of the Nd:YAP laser for (a) 1073 nm, (b) 1080 nm, and (c) 1084 nm.

Finely adjusting the tilting angle of the etalon to certain values for balancing the gain and loss between these intermanifold lines can further make our Nd:YAP laser to be operated in the multi-wavelength states. Figures 4(a)-4(c) describe the output spectra of the experimentally obtained dual-wavelength groups with the balanced intensities for each spectral line. The maximum output powers are found to be 4.4, 1.8, and 3.2 W for the dual-wavelength pairs of (1072.28, 1080.44), (1073.45, 1084.11), and (1078.96, 1084.20) nm, respectively. As depicted in Fig. 4(d), the Nd:YAP laser could also simultaneously operates at 1073.45, 1078.92, and 1084.11 nm with the maximum output power of 2.1 W. The multi-wavelength operations became unstable when the output powers were beyond the maximum values due to the strong gain competition among different spectral emissions. Note that the beam quality factors for the single- and multi-wavelength operations are measured to be in the range of 1.5-1.9, depending on the tilting angle of the etalon and the emission state.

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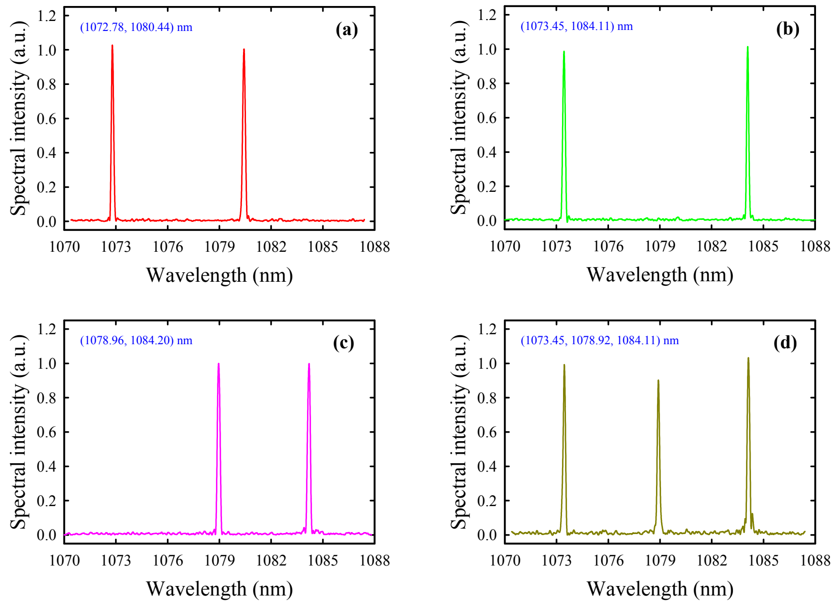

Fig. 4. Output spectra of the multi-wavelength Nd:YAP laser obtained with the groups of (a) (1072.78, 1080.44) nm, (b) (1073.45, 1084.11) nm, (c) (1078.96, 1084.20) nm, and (d) 1073.45, 1078.92, 1084.11) nm.

Finally, we inserted the Cr^{4+}:YAG crystal with an initial transmission of 90% to accomplish the passively Q-switched operation of the Nd:YAP laser. The Cr^{4+}:YAG crystal was coated to be antireflective in the range of 1040-1115 nm on the both sides, and it was wrapped with indium foil and mounted in a water-cooled copper holder at 16þC. The radius of curvature of the input concave mirror, the length of the laser cavity, and the reflectivity of the output coupler were chosen to be 200 mm, 53 mm and 90% for achieving a high-quality passively Q-switched laser.

Figure 5 illustrates the output performance in the passively Q-switched operations at 1073 and 1080 nm. It is experimentally found that the emission line at 1084 nm could not be attained in the passively Q-switched operation due to the relatively high output coupling as well as the existence of additional saturable loss of the Cr^{4+}:YAG crystal. The maximum average output powers at 1073 and 1080 nm are found to be up to 2.3 and 3.5 W under an incident pump power of 15.4 W, as shown in Fig. 5(a). By increasing the incident pump power from 7.4 to 15.4 W, the pulse widths decrease from 17 to 16 ns for 1073 nm and from 20 to 17 ns for 1080 nm, and the pulse repetition rates at 1073 and 1080 nm change from 6 to 13 kHz and from 11 to 22 kHz, as described in Figs. 5(b) and 5(c). Accordingly, the pulse energies can be calculated to increase from 102 to 177 μJ for 1073 nm and from 76 to 159 μJ for 1080 nm, and the peak powers at 1073 and 1080 nm are estimated to be in the range of 6-11 and 4-9.4 kW, respectively, as depicted in Figs. 5(d) and 5(e).

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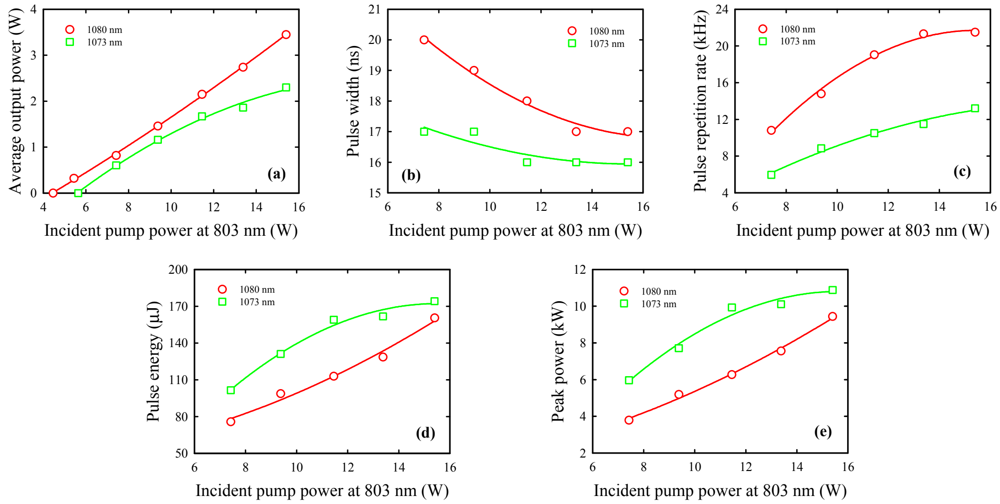

Fig. 5. Dependences of the (a) output power, (b) pulse width, (c) pulse repetition rate, (d) pulse energy, and (e) peak power, on the incident pump power.

Figure 6 demonstrates the typical temporal behaviors for passively Q-switched Nd:YAP laser recorded with a fast Si photodiode, whose output signal was connected to a digital oscilloscope (LeCroy, WaveRunner) with the electrical bandwidth of 1 GHz and the sampling interval of 0.1 ns. It is experimentally found that the amplitude fluctuations at 1073 and 1080 nm are generally better than ± 3%. For the dual-wavelength passively Q-switched operation at 1073 and 1080 nm, the pulse-to-pulse stability is observed to be relatively poor with the amplitude fluctuation of typically larger than 30%. Besides, the pulses for the two wavelengths are not well synchronized in time. The pulses with higher and lower amplitudes generally correspond to the oscillations for 1073-nm and 1080-nm emission lines. Moreover, it is experimentally observed that the time-delay between these two pulses, which is typically in the range from several hundred ns to several μs, relies on the tilting angle of the etalon. Even so, the simultaneously dual-wavelength operation at 1073 and 1080 nm could still be achieved with the maximum average output power of 2.3 W for the passively Q-switched Nd:YAP laser.

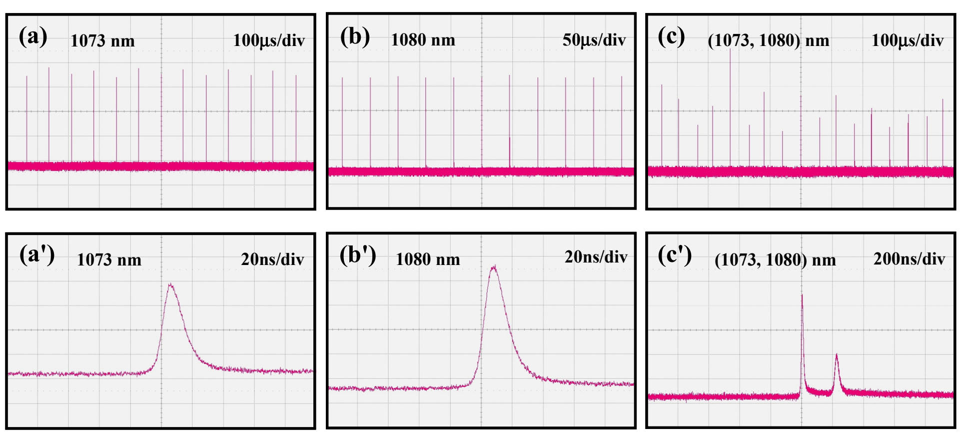

Fig. 6. Pulse trains of the passively Q-switched Nd:YAP laser in the single-wavelength operations at (a) 1073 nm, and (b) 1080 nm, and (c) dual-wavelength operation at 1073 and 1080 nm; (a')-(c') Temporal behaviors in small time scale corresponding to the cases (a)-(c).

4. Conclusion

In summary, the fluorescent spectrum of the Nd:YAP crystal has been experimentally investigated to demonstrate the feasibility of tunable single- and multi-wavelength operations in the $^4F_{3/2} \rightarrow {}^4I_{11/2}$ transition. We have successfully utilized an intracavity etalon with the thickness of 160 μm to accomplish the single-wavelength oscillations at 1073, 1080, and 1084 nm with the tunabilities of 0.56, 1.13, and 0.1 nm, respectively. Multiple wavelength lasers among various intermanifolds in the Nd:YAP crystal have also been experimentally achieved with the output powers on the order of several watts for each group. Furthermore, we have originally employed the Cr^{4+}:YAG saturable absorber to achieve the passively Q-switched operation in the diode-pumped Nd:YAP laser. Under an incident pump power of 15.4 W, the compact pulsed laser is able to efficiently generate maximum average output powers of 2.3 and 3.5 W with the pulse durations of 16 and 17 ns and the pulse repetition rates of 13 and 22 kHz for 1073 and 1080 nm. The corresponding pulse energies and peak powers are up to 177 and 159 μJ, and 11 and 9.4 kW for 1073 and 1080 nm, respectively. Simultaneously dual-wavelength passively Q-switched Nd:YAP laser at 1073 and 1080 nm has also been observed experimentally with the maximum average output power of 2.3 W.

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