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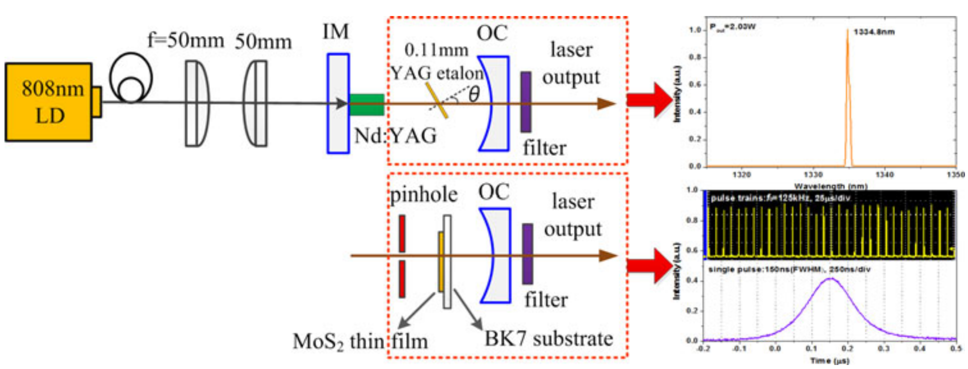

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Abstract: We report on our latest experimental results concerning laser oscillations at low-gain lines of diode-pumped Nd:YAG crystal lasers on $^4F_{3/2} \rightarrow {}^4I_{13/2}$ transition and MoS_2-based dual-wavelength passively Q-switched Nd:YAG laser on this transition, for the first time to our knowledge. Using an undoped YAG as etalon to promote the intracavity loss modulation, three new lasing lines of about 1333, 1334, and 1340 nm have been achieved. Especially, the 1334-nm laser can be operated at single wavelength mode with maximum output power of 2.03 W. Dual-wavelength passively Q-switched Nd:YAG laser at 1318 and 1338 nm has also been obtained with maximum average output power of 0.44 W. The shortest pulse width is about 150 ns at pulse repetition rate of 125 kHz, leading to single pulse energy of 3.5 μJ and pulse peak power of 23.4 W.

Index Terms: Nd:YAG crystal, $^4F_{3/2} \rightarrow {}^4I_{13/2}$ transition, passive Q-switching.

1. Introduction

During the past decades, trivalent neodymium (Nd^{3+}) lasers operating at 0.9, 1.06, 1.3 and 1.4 μm spectral domains have attracted a lot of attention and a great number of Nd^{3+}-doped host materials have been developed. Up to now, the old Nd:YAG is still one of the most popular and best performed laser materials because of its excellent mechanical, thermal, optical properties and easy commercial availability. Using Nd:YAG as laser gain medium, new lasing wavelengths, having relatively low gains, have been realized from time to time based on several types of methods.

Intracavity wavelength selectors with fixed transmission spectra with respect to different wavelengths have been often adopted. For instance, in 2008, Huang *et al.* [1] reported a Nd:YAG laser at 1444 nm by using an AlGaInAs intracavity selective absorber to suppress those high-gain lines. Cr:YAG was also once used as wavelength selector to achieve a dual-wavelength laser at 1052 and 1064 nm [2]. However, on the one hand, inserting these selectors, like the AlGaInAs and Cr:YAG, leads to large intracavity loss and therefore degrades laser performances. On the other hand, more importantly, these special wavelength selectors are only effective for specific laser emissions. The second method to operate low-gain lasers is by means of specific coating on the laser cavity mirrors. For example, recently, using special coating to suppress the 1444 nm line with relatively high gain, Lee *et al.* [3] demonstrated a 6.3-W Nd:YAG laser at 1415 nm. Very recently, by suppressing the 0.9, 1.06, 1.3 and 1.4 μm emission lines, a Nd:YAG laser at 1834 nm was also investigated [4]. However, the same, the special coating only takes effect for lasing at specific wavelengths. Additionally, in general, the special coating is not cost-effective. Researchers also often resort to intracavity wavelength selectors with variable transmission spectra to realize low-gain laser operation. Intracavity Fabry-Pérot etalon is an important representative of such selectors. Recently, using a BK7 thin plate as etalon, Lan *et al.* [5] achieved Nd:YAG laser emissions not only at 1443 nm, but also at 1413 and 1431 nm. For intracavity etalon, if the optical quality of the etalon itself could be guaranteed, the extra loss induced by the etalon could be very low and consequently efficient laser operation at low-gain lines could be realized [5]. The function of etalon could be enhanced by using materials with high refractive index. For instance, an very low-gain line at 1078 nm compared with the typical 1064 nm line can be realized by using a YAG thin plate as etalon [6].

Passive Q-switching has been widely admitted to be an effective method for high energy pulse laser generation with merits of compactness and cost effectiveness. Compared with conventional saturable absorbers, like Cr:YAG, V:YAG, Cr:ZnSe and SESAM, two dimensional nanomaterials acting as saturable absorbers have attracted great attention because of their broadband absorption, low cost and easy fabrication [7]–[10]. MoS_2 is one of the two dimensional nanomaterials, which has already been explored to Q-switch at 0.9 μm [11], 1.06 μm [12], 1.5 μm [13], [14], 2.0 μm [15] and 2.8 μm [16]. Very recently, Wang *et al.* [17] reported a Q-switched Nd:LuAG laser at 1.3 μm using few-layer MoS_2. Note that, all these above mentioned MoS_2-based passively Q-switched laser emissions have only concerned single-wavelength laser emission. Compared with single-wavelength laser generation, dual-wavelength lasers have special applications that single-wavelength laser cannot provide, e.g., THz wave generation via difference frequency of two high-energy pulse lasers [18].

In this paper, we chose an undoped YAG etalon to modulate the intracavity loss for wavelength tuning because of its variable transmission related to tilt angle and also because of its relatively low cost. With this YAG etalon, we realized the first continuous-wave operation at 1333, 1334 and 1340 nm from a diode-pumped Nd:YAG crystal laser resonator. Based on the 1.3-μm continuous-wave laser experiments and our previous work regarding MoS_2-based passive Q-switching at 0.9 μm [11], we further demonstrated the first dual-wavelength passively Q-switched Nd:YAG laser with MoS_2 saturable absorber.

2. Experimental Setup

The arrangement of the experimental setup is shown schematically in Fig. 1. A fiber-coupled 808 nm (at maximum output power) diode laser was used as pump source with core diameter of 400 μm and NA of 0.22, which emits a maximum output power of about 23 W. The pump beam was first collimated by a 50-mm (focal length) doublet lens and then was focused by another 50-mm doublet lens into the laser crystal. The laser cavity is a simple and compact two-mirror configuration, i.e., flat input mirror and 50-mm (radius of curvature) concave mirror. In order to obtain laser oscillations at the considered 1.3 μm spectral domain, the input mirror was coated with 90% transmission at pump wavelength and high reflection of more than 99.9% at laser wavelengths. Moreover, the input mirror has high transmission of close to 90% at the high-gain 1.06 μm spectral domain in order to suppress those potential lasers. In terms of the considered laser wavelengths, the output coupler has a gradually decreasing transmission from 2.2% at 1318 nm to 1.8% at 1356 nm. In addition, the output coupler has a transmission of more than 90% for the high-gain 1.06 and 1.1 μm spectral domains.

The laser crystal is a 0.5at% doped Nd:YAG with dimension of $3 \times 3 \times 5\,mm^3$. Under this situation, the single pass absorption ratio of the pump power was measured to be about 61% at maximum pump power. At pump power a little bit higher than threshold, the absorption ratio

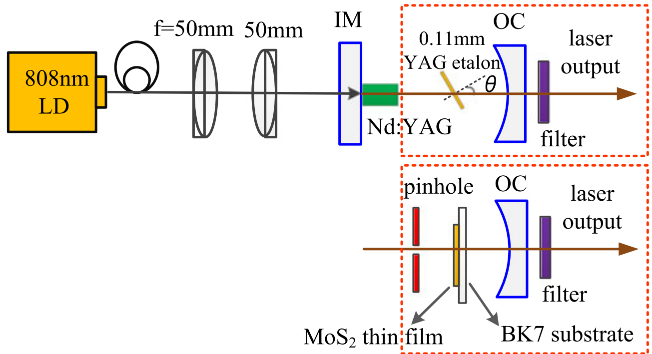

Fig. 1. The schematic of diode-pumped Nd:YAG laser experimental setup.

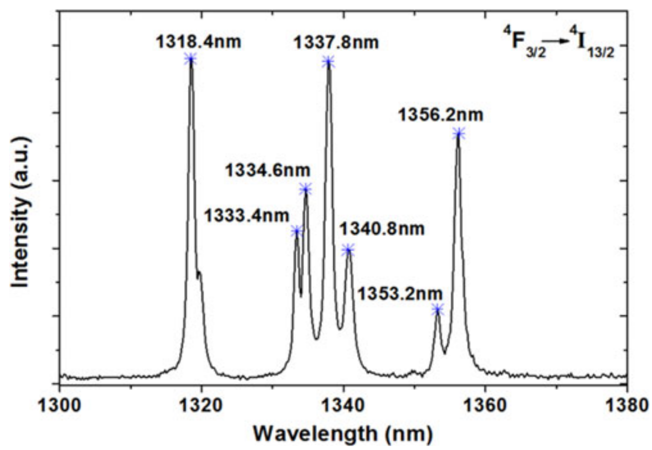

Fig. 2. Emission spectrum of Nd:YAG at 1.3 μm spectral region.

was found to reduce to about 43%, which is because of the mismatching between the pumping wavelength (shift to 803-804 nm) and absorption peak of Nd:YAG. In order to mitigate the so-called thermal lensing effect, the laser crystal was wrapped inside a piece of indium foil and then mounted inside a copper block. The copper block was connected to a chiller with temperature set at 18 °C of the circular cooling water. During the wavelength tuning to those low gain lines, a 0.11 mm undoped YAG plate was used to fill the role of etalon. Few-layer MoS_2 was fabricated by using a liquid-phase exfoliation method. The bulk MoS_2 was firstly put into a dimethyl formamide (DMF) solution. After a 20-hour sonication, the few-layer MoS_2 suspension was centrifuged for 30 minutes at 1000 rpm to remove the residual bulk MoS_2. The as-fabricated few-layer MoS_2 suspension was then transferred to a BK7 glass substrate by spin-coating method. First, the glass substrate with suitable amounts of few-layer MoS_2 suspension was rotated at low speed to uniformly disperse the MoS_2 solution. After, we dried it inside an oven with a constant temperature of 60 °C for three hours. The dried few-layer MoS_2 thin film will serve as saturable absorber during the operation of Q switching. Moreover, we measured the as-prepared MoS_2 thin film onto the BK7 substrate with initial transmission of about 88.6% at 1.32 μm.

3. Results and Discussion

Fig. 2 shows the emission spectrum of the Nd:YAG crystal, from which one can see about seven emission peaks. The 1318.4 nm line has the most intense emission intensity, almost the same as the 1337.8 nm line, which indicates that Nd:YAG crystal should be capable of producing dual-wavelength laser source at the two lines. In fact, simultaneous dual-wavelength lasers at these two

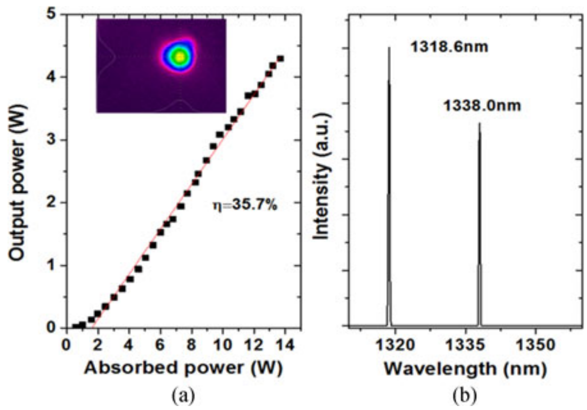

Fig. 3. (a) Output power versus absorbed power of diode-pumped Nd:YAG laser in free-running mode, inset: laser beam spot at maximum output and (b) corresponding laser spectrum.

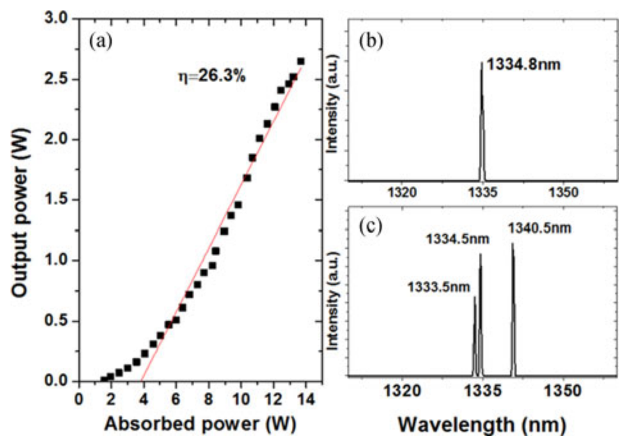

Fig. 4. (a) Laser output powers versus absorbed powers, (b) laser spectrum at 1334.8 nm and (c) tri-wavelength laser spectrum at 1333.5, 1334.5 and 1340.5 nm.

lines have already been reported (see e.g., Ref. [19]). It should be pointed out that, under the help of a 0.1-mm etalon, Marling reported almost all these 1.3-μm laser operation except the two lowest gain lines at 1340 and 1353 nm lines [20]. However, the used pump source was a continuous-wave 5-kW krypton arc lamp, not compact, low-cost and high-efficiency diode laser.

Nd:YAG laser operating in free-running mode was first operated. Fig. 3(a) shows the output power dependent on absorbed power and Fig. 3(b) shows the corresponding laser spectrum at maximum output power. The maximum output power reached 4.3 W with slope efficiency of about 35.7%. The laser threshold was only 0.56 W of absorbed pump power and the output laser wavelengths peaked at 1318.6 and 1338.0 nm. The output power stability was measured to be about 2.40% (RMS) in half an hour. Taking into account unavoidable mode competition of the inversion population arising from the 1319 nm and 1338 nm sharing the same upper level $^4F_{3/2}$ of Nd^{3+} ion, the stability was still pretty good. At the maximum output power, we measured the beam quality to be about 3.8 of M^2 factor.

The YAG etalon was inserted into the cavity almost perpendicularly to the cavity axis to check the optical loss of the etalon itself. A power attenuation of about 4% was found, which indicated a pretty good optical quality of the YAG etalon. By tilting the etalon progressively, at a tilt angle (θ, see in Fig. 1) of about 5°, a simultaneous tri-wavelength laser at 1333.5, 1334.5 and 1340.5 nm (see Fig. 4(a) for output powers, Fig. 4(c) for laser spectrum) can be obtained with maximum output power of 2.65 W, slope efficiency of about 26.3% and laser threshold of 1.57 W. Despite mode

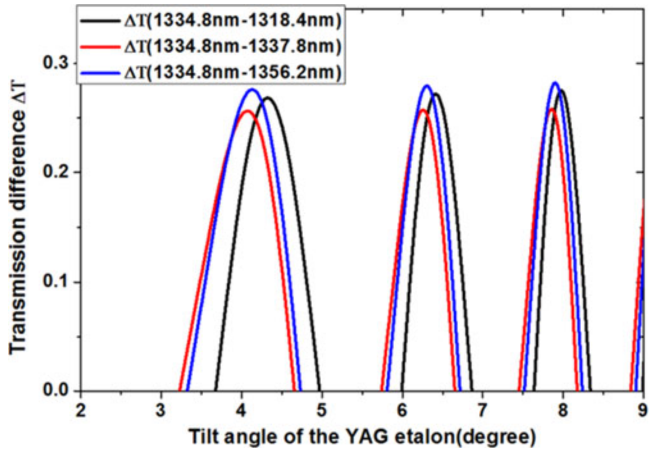

Fig. 5. Transmission differences versus tilt angles of the YAG etalon between the 1334.8 nm line and other three high-gain lines at 1318.4, 1337.8 and 1356.2 nm.

competition among the three wavelengths, the three wavelengths can maintain all the time during the experiment. Stability of the tri-wavelength laser was measured to be about 5.75% in half an hour. For diode-pumped Nd:YAG laser, the three wavelengths indeed were obtained for the first time. Moreover, by finely tilting the etalon at maximum output power, we found that the 1334 nm line can even operate singly but with a peak wavelength at 1334.8 nm (see Fig. 4(b)), i.e., a 0.3 nm of wavelength shift compared with the 1334.5 nm wavelength in tri-wavelength case because of the reorientation of the YAG etalon. However, the maximum output power reduced to 2.03 W.

According to the emission spectrum of Nd:YAG (see Fig. 2), the emission intensity of 1334 nm line is just weaker than that of 1318, 1338 and 1356 nm lines. Hence, the single wavelength laser operation at 1334.8 nm indicated completely suppression of the three high-gain lines. The transmission of etalon can be written as

$$T(\lambda, \theta) = \left\{ 1 + \left[\frac{2F(\theta)}{\pi} \right]^2 \left[\sin\left(\frac{\delta(\lambda, \theta)}{2} \right) \right]^2 \right\}^{-1} \quad (1)$$

where $\delta(\lambda, \theta) = 4\pi nl\cos\theta/\lambda$ is the additional phase difference for a round-trip, $F(\theta) = \pi\sqrt{R(\theta)}/[1 - R(\theta)]$ is the finesse, $R(\theta)$ the reflectivity of the etalon, l the thickness, and n the refractive index of the etalon. Thus, using this expression, we can calculate the transmission differences between the 1334.8 nm and the three high-gain lines. Fig. 5 plots the variations of transmission differences with the tilted angles of the YAG etalon, from which we can see that the transmission differences can reach about 25% for all three curves if the etalon is tilted at about 4.2 degree, which is basically in good agreement with the actual tilt angle in experiment. The experimental result confirmed that the three high-gain lines can be suppressed owing to the additional 25% loss. Furthermore, fulfilling a similar simulation for the low-gain 1340.5 nm line and the high-gain 1337.8 nm line, we estimated that the difference between the two lines are about 22.3% at 5°.

Replacing the YAG etalon with the as-prepared MoS_2 saturable absorber, passive Q-switching of Nd:YAG laser was then achieved with maximum output power of 0.44 W, as shown in Fig. 6(a). Compared with the continuous-wave case, threshold of dual-wavelength laser increased to about 3.0 W. The relatively high threshold should originate from the uncoated substrate and non-saturable loss of the MoS_2 saturable absorber. The laser spectrum shows two peak wavelengths at 1318.8 and 1338.1 nm with comparable intensities (see Fig. 6(b)). Difference frequency of the two wavelengths could lead to a 3.28 THz wave generation. It should be pointed out that the two wavelengths cannot be separated easily in our lab because they are not orthogonally polarized. In fact, according to the measurement, they have no polarizations, which is understandable because the Nd:YAG is isotropic and the present resonator is symmetric. As a consequence, at the maximum output power,

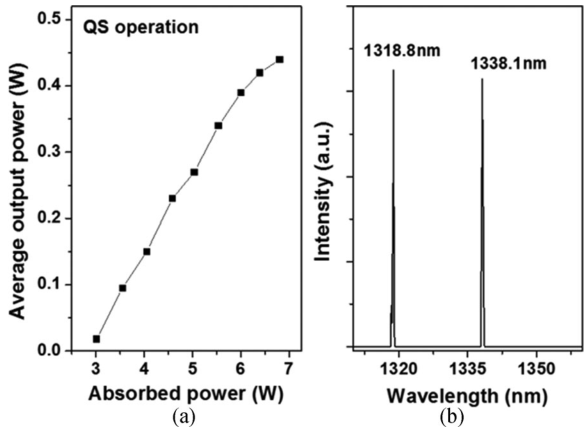

Fig. 6. (a) Average output power versus absorbed power of Q-switched Nd:YAG laser and (b) corresponding laser spectrum.

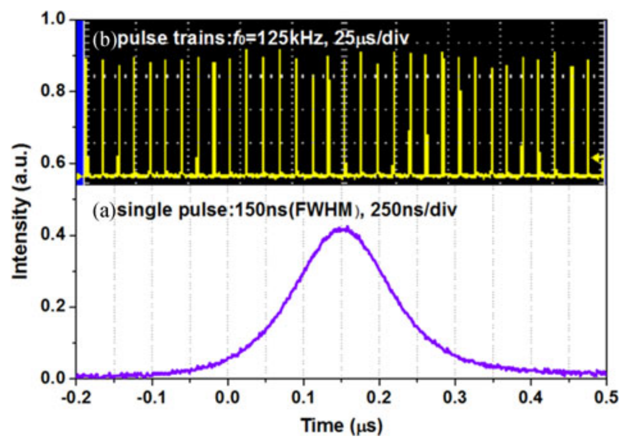

Fig. 7. (a) Typical single pulse profile and (b) pulse trains at maximum output power.

the pulse-to-pulse amplitude fluctuation of the Q-switched pulse train for the two combined lasers was measured to be less than ±9%. Further increasing the pump power was artificially terminated because the pulse trains showed degraded stability. In general, such instability should ascribe to the thermal effect of the MoS_2 film despite that special care has already been paid by placing a pinhole to stop the residual pump power heating the MoS_2 and the substrate.

The typical single pulse profile is shown in Fig. 7(a) with time duration of about 150 ns at maximum output power and the corresponding pulse train is shown in Fig. 7(b) with repetition rate of about 125 kHz. Fig. 8(a) shows the dependence of pulse width on absorbed power, from which one can see that the pulse width decreased quickly at first and then decreased slowly when the absorbed power was more than about 5 W. Namely, the pulse width exhibited a saturation trend. The corresponding pulse repetition rate dependent on absorbed power is shown in Fig. 8(b). Basically, with the increase of the absorbed power, the pulse repetition rate monotonously increased. However, the saturation trend is still obvious despite not as obvious as the variation of pulse width.

With these data, we estimated the pulse energy and pulse peak power as functions of absorbed powers, as plotted in Fig. 8(c) and (d). The maximum single pulse energy is about 3.5 μJ and the pulse peak power is about 23.4 W. At present, to the best of our knowledge, MoS_2-based 1.3-μm passively Q-switched laser operation has only been one-time reported (see [17]) with maximum single pulse energy of 2.53 μJ and pulse peak power of about 9 W. Therefore, it is clear that our investigation has shown the better results than that achieved in the previous report.

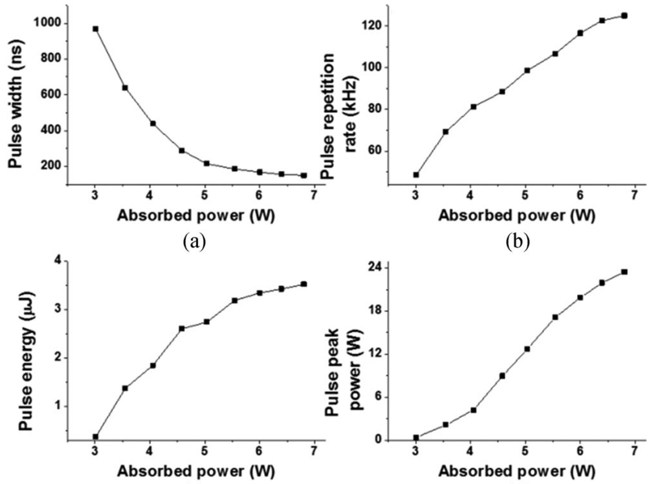

Fig. 8. The dependences of (a) pulse width, (b) pulse repetition rate, (c) pulse energy and (d) pulse peak power on absorbed powers.

4. Conclusion

In conclusion, continuous-wave and passively Q-switched Nd:YAG laser at 1.3 μm have been investigated. In free-running mode, simultaneous dual-wavelength laser at 1318.6 and 1338.0 nm was obtained with maximum output power of 4.3 W and slope efficiency of about 35.7%. Using a YAG etalon, simultaneous tri-wavelength laser at 1333.5, 1334.5 and 1340.5 nm was achieved with a maximum output power of 2.65 W and a slope efficiency of about 26.3%. In addition, single wavelength laser at 1334.8 nm was also achieved with maximum output power of 2.03 W. Using MoS_2 saturable absorber, simultaneous dual-wavelength passively Q-switched laser operation at 1318 and 1338 nm was realized with maximum average output power of 0.44 W. The corresponding pulse width was 150 ns at 125 kHz repetition rate, which led to 3.5 μJ of single pulse energy and 23.4 W of pulse peak power. The dual-wavelength pulse laser could provide a 3.28 THz wave source by difference frequency.

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