Passively Q-switched 2.9 μm Er:YAP single crystal laser using graphene saturable absorber

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A passively Q-switched 2.9 μm Er:YAP laser using a monolayer graphene saturable absorber (SA) was demonstrated in this research. Stable pulsed operation was performed with the shortest pulse duration of 460 ns and the highest repetition rate of 114 kHz. This is the first demonstration of a passively Q-switched mid-IR Er:YAP pulse modulated by graphene SA. In Q-switched operation, the maximum pulse energy of 5.1 μJ and the highest peak power of 10 W were obtained. To our knowledge, these parameters are the highest values in a graphene Q-switched mid-IR Er:YAP laser.

High-power mid-infrared (mid-IR) lasers in wavelength of around 3 μm are suitable for medical and industrial [1, 2] fields because the light with such a wavelength is strongly absorbed by water-containing materials (e.g., skin and glass). Diode-pumped solid state lasers using gain medium such as Er-doped garnets (e.g., Er:YAG) [3], sesquioxides (e.g., Er:Y_2O_3 crystal/ceramics, and Er:Lu_2O_3 crystal/ceramics) have been studied in recent decades [4-10] as promising candidates for the efficient mid-IR laser source with high-power and high-beam quality. Higher thermal conductivity, good mechanical strength, lower phonon energy, and larger emission cross-section are required for the Er-doped materials to achieve stable laser operation under high pump power. Yttrium Aluminum Perovskite (YAP) is expected to be suitable host material for efficient laser emission owing to higher thermal conductivity (~13.3 W/m·K) [11], good mechanical properties, and lower phonon energy (550 cm^{-1}) [12] compared to YAG, Y_2O_3, and Lu_2O_3 [13]. In our previous report [13], the detailed laser-related characteristics of the Er:YAP single crystal were evaluated. We have elucidated that the Er:YAP exhibits the large emission cross-section in 3 μm, which was three times larger than that of Er:YAG. Subsequently, using a 5 at.% Er:YAP single crystal, we also demonstrated continuous-wave (CW) laser operation at 2.92 μm wavelength with output power of 0.674 W and slope efficiency of 31%, which is the highest efficiency obtained by Er:YAP [13]. This result proposed that Er:YAP is one of the most promising laser materials, and can provide high power mid-IR coherent beam. As the next stage of CW operation, pulsed operation of these lasers has attracted attention to obtain higher output peak power with a view to use for laser processing and other applications. A passive Q-switching technique enables compact oscillator setup without additional electro devices resulting in low-cost construction compared with active Q-switching method. The two-dimensional (2D) materials saturable absorber (SA) has attracted attention due to the ease of Q-switching in mid-IR region. Recently, the topological insulator (e.g., Bi_2Se_3 [14]), hexagonal boron nitride (hBN) [15], transition metal dichalcogenides (e.g., MoS_2 [10] and WS_2 [16]), black phosphorus (BP) [17], and graphene [18] have been used for 2D SAs. The graphene is a promising SA for passively Q-switched or mode-locked mid-IR laser owing to wavelength independence for saturating absorption range, fast recovery time, high damage threshold (~ 300 GW/cm^2 [19]), and high-transferability on various substrates. The monolayer graphene exhibits strong saturable absorption of 66% even at 2.9 μm wavelength [20]. The passively Q-switched 3 μm lasers using graphene SA such as Er:Lu_2O_3 [21], Er:Y_2O_3 [22], and Er:CaF_2 [23] were reported in recent years. However, graphene Q-switched Er:YAP laser has not been demonstrated at the present time although the efficient

Q-switching can be expected from the above reason.

In this work, a passively Q-switched 2.9 μm Er:YAP laser by using a monolayer graphene was demonstrated at room-temperature. Stable pulsed operation was performed in compact linear cavity. The shortest pulse duration of 460 ns, the maximum pulse energy of 5.1 μJ, and the peak power of 10 W were successfully obtained. These results are the first performance for a passively Q-switched 2.9 μm Er:YAP laser modulated by a graphene SA.

The 5 at.% Er:YAP single crystal was used as gain medium in order to demonstrate CW and Q-switched laser operation. The Er:YAP has the length of 8 mm and the aperture of 2×5 mm, which was not given antireflection (AR) coating. This crystal was inserted into the plane-plane linear resonator with a length of 21 mm, which consists of a dichroic mirror (DM) and an output coupler (OC), as shown in Fig. 1. The DM possessed high transmittance at 976 nm and high reflection in 2.9 μm wavelength. The Er:YAP was pumped by a fiber-coupled laser-diode (LD: K976A02RN-9.00WN0N-10255I10ESM0, BWT BEIJING) with stabilized wavelength of 976 nm, spectral width of 0.4 nm, core diameter of 105 μm, and numerical aperture (NA) of 0.22. During Q-switched operation, the monolayer graphene deposited on an AR coated sapphire substrate was inserted between the Er:YAP crystal and an OC. The monolayer graphene (Graphene Platform Corp.) fabricated by chemical vapor deposition was used in this experiment. In the reference [21], the quality of this monolayer graphene was confirmed by measurement of the Raman scattering spectrum. Generally, initial absorption in the monolayer graphene is 2.3% and a modulation depth is higher than 1.5% [21]. The total transmittance of the sapphire substrate and graphene was approximately 96%. The pump beam from LD was focused on the gain medium with a beam diameter of approximately 165 μm after passing through a DM. The OC with transmittance (T_{OC}) of 2.5%, which was optimized in our previous research [13], was used for CW operation. On the other hand, OCs with transmittance of 1, 2, and 2.5% at 2.9 μm were used in Q-switched operation to optimize the oscillator constitution. The Er:YAP crystal, which was mounted on a heatsink, was actively cooled by water of 16 °C. The laser output and temporal waveform were measured with power meter (3A-SH, OPHIR) and InAs photodetector (Teledyne Judson Technologies, J12-18C-R250U) with 2.5-3.2 μm band pass filter. In addition, lasing spectra with changing pump power were measured with an optical spectrum analyzer (OSA205C, Thorlabs) with a wavelength resolution of 0.1 nm.

The average output power as a function of absorbed pump power in CW (at T_{OC} = 2.5%)

and Q-switched operation are shown in Fig. 2. The absorbed pump power was defined as the value of absorbed LD power in Er:YAP. In the case of CW operation without graphene, the output power was increased linearly with pump power. The lasing threshold of 0.97 W, the maximum output power of 1.17 W at the pump of 5.28 W, and the slope efficiency of 29% were obtained. The output power was improved by increasing the pump power from 3.49 W to 5.28 W compared to our previous report [13]. To the best of our knowledge, this is the highest CW output power obtained by mid-IR Er:YAP laser. In the case of Q-switched operation, the maximum output power of 503 mW with highest slope efficiency of 13% was obtained using 2% OC. At this time, the stable Q-switched operation was confirmed by temporal waveform, and typical waveform under 5.64 W pumping is shown in Fig. 3. The shortest pulse duration of 460 ns with highest repetition rate of 114 kHz was observed in Q-switched operation. This result indicates the first observation of passively Q-switched operation of Er:YAP laser using a graphene SA in around 3 μm. Figure 4 (a) shows the pulse duration and the repetition rate (RPR) depend on pump power. The pulse duration became shorter from 1336 ns to 460 ns with increasing of pump power from 2.77 W to 5.64 W. On the contrary, the repetition rate increased from 49.9 kHz to 114 kHz with an increase of pump power from 2.77 W to 5.64 W. Figure 4(b) shows the pulse energy and the peak power as a function of pump power. The pulse energy and the peak power increased with increasing the pump power. The maximum pulse energy and the peak power were achieved at 5.1 μJ and at 10 W under 5.28 W pumping, respectively. To the best of our knowledge, these pulse energy and peak power were the highest values reported in graphene Q-switched mid-IR Er:YAP laser. Furthermore, the lasing spectra during Q-switched operation in various pump power were measured as shown in Fig. 5. The lasing wavelength of 2750 nm was observed at pump power of 2.05 W, which is close to laser threshold. Under 2.55 W pumping, the lasing wavelength shifted from 2750 to 2918 nm. Subsequently, the two lasing-wavelengths of 2918 nm and 2921 nm were measured in the pump power above 2.55 W. This red-shifting of lasing wavelength was also observed in our previous report of CW Er:YAP laser [13]. Under lower pumping power, the lower laser level ($^4I_{13/2}$ state) was unoccupied and the shorter wavelength was dominantly emitted because of larger emission cross-section in such wavelength. However, at higher pumping power, longer wavelength was dominantly emitted because lower Stark levels in $^4I_{13/2}$ were populated due to the relatively-longer lifetime of lower laser level [24]. The inset of Fig. 5 is a measured beam profile at 5.64 W pumping and the output beam has Gaussian-like distribution.

Passively Q-switched 3 μm lasers using 2D SA were summarized in Table 1. The significantly high performance in $Er:Lu_2O_3$ was obtained by quite high-power pumping until 11 W [21]. In contrast, this work was carried out in lower pumping region under 5.68 W and the output power was limited by pump power. Further power scaling will be expected by much powerful pumping because no power degradation was observed under 5.68 W pumping in Fig. 2. In the passive Q-switching regime, the relationship among pulse duration (t_P), the resonator round-trip time (T_R), and modulation depth of graphene (ΔR) can be described as following equation [27]

$$t_P \cong \frac{3.52 \cdot T_R}{\Delta R}. \tag{1}$$

The theoretical pulse duration was derived to be 48 ns when ΔR was 1.5 % [21] and T_R was 0.2 ns. The actual modulation depth of graphene was estimated to 0.16% by the expression (1) substituting the pulse duration and the round trip time as 460 ns and 0.2 ns. The reason for the difference between the theoretical and the actual modulation depth value is that the power density on the graphene was not enough to saturate the absorption. In this system, the effective power density on graphene was estimated as follows. The thermally induced focal length (f) of Er:YAP at pump power of 5.64 W was 13 mm from equation (2) [28]

$$f = \frac{\pi K_c {w_p}^2}{P_{ph}(dn/dT)} \left(\frac{1}{1-\exp(-\alpha l)} \right). \tag{2}$$

Here, thermal conductivity (K_c), beam radius at Er:YAP (w_p), heat generated inside Er:YAP as considering quantum defect of 67% (P_{ph}), temperature coefficient of refractive index (dn/dT), and absorption coefficient of 5 at.% Er:YAP at 976 nm (α) were 13.3 W/m·K [11], 82.5 μm [13], 3.8 W, 8×10^{-6} K^{-1} [11], and 1.6 cm^{-1} [13], respectively. The effective mode diameter on graphene was calculated to be 140 μm by ABCD matrix analysis and using f. The internal power in cavity with T_{OC} = 2% was estimated to be 25 W when the output power was 0.5 W. The effective power density on graphene was calculated to be 0.2 MW/cm^2. At this power density, a monolayer graphene SA with saturation intensity of 0.53 MW/cm^2 [20] still has not been fully saturated. The actual power density on graphene achieved only approximately 38% of full saturation intensity. Much shorter pulse duration might be obtained by increasing the power density on graphene adopting the focusing optics into resonator. Shortening the cavity length or increasing the modulation depth using multilayer graphene will be also helpful to generate shorter pulse. The graphene Q-switched Er:YAP laser has the potential for obtaining 100 μJ–level and 10 ns pulse, assuming the shortest cavity length of 11 mm limited by size of the Er:YAP and the graphene deposited substrate and modulation depth of 4.8% that will be achieved by 6-layer graphene. Such a high-peak power 2.9 μm laser with high-beam quality will be expected as light source for laser processing of specific resin materials, e.g., polyethylene terephthalate (PET). It will be promising pump source for various coherent sources emitting much longer wavelengths, e.g., 4-5 μm Fe:ZnSe laser [29-31] and surpercontinuum generation covering the whole mid-IR region [32]. Therefore, the diode-pumped graphene Q-switched 2.9 μm Er:YAP laser has the potential to be a new candidate for mid-IR laser source with high power.

In conclusion, we have performed CW operation and Q-switched operation modulated by graphene using 5 at.% Er:YAP single crystal. In the CW operation, the highest output power of 1.17 W with slope efficiency of 29% was obtained. The stable pulsed operation by passive Q-switching with graphene was demonstrated for the first time in mid-infrared Er:YAP laser. The shortest pulse width of 460 ns, highest repetition rate of 114 kHz, maximum peak power of 10 W, and maximum pulse energy of 5.1 μJ were achieved successfully. The graphene Q-switched 2.9 μm Er:YAP laser pumped by LD has the potential to be a new candidate for high mid-IR laser source.

Acknowledgments

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Figure Captions

Fig. 1. A schematic of laser setup in CW operation and passively Q-switched Er:YAP pulse operation using graphene SA.

Fig. 2. Average output power of the Er:YAP laser with versus various pump power for CW operation using T_{OC} = 2.5% and graphene Q-switched operation using T_{OC} = 1, 2, and 2.5%.

Fig. 3. Typical temporal wave form of the graphene Q-switched Er:YAP laser under 5.68 W pump power using T_{OC} = 2%. Inset: temporal waveform in pulse train.

Fig. 4. (a) Pulse duration and repetition rate and (b) Pulse energy and peak power with versus pump power in graphene Q-switched Er:YAP laser operation using T_{OC} of 2%.

Fig. 5. Lasing spectra of the graphene Q-switched Er:YAP pulse operation using T_{OC} of 2% under various pump power. Inset: typical spatial beam profile of graphene Q-switched Er:YAP laser.

Table I. Comparison of passively Q-switched Er-doped solid-state lasers by 2D SA in around 3 μm.

Material	SA	Average output [mW]	Slope efficiency [%]	Pulse width [ns]	RPR [kHz]	Peak power [W]	Pulse energy [μJ]	RF
Er:Lu_2O_3	Graphene	1300	15	247	174	33	9.4	[21]
Er:Y_2O_3	Graphene	132.5	-	408	51.1	6.35	2.58	[22]
Er:CaF_2	Graphene	172	10.4	1324	62.7	2.07	2.74	[23]
Er:SrF_2	BP	180	7.9	702	77.03	3.3	2.34	[17]
Er:YSGG	Bi2Te_3/G	110	-	243	88	5.14	1.25	[25]
Er:YAP	$ReSe_2$	526	14.8	202.8	244.6	10.6	2.2	[26]
Er:YAP	**Graphene**	**503**	**13**	**460**	**114**	**10**	**5.1**	**This work**

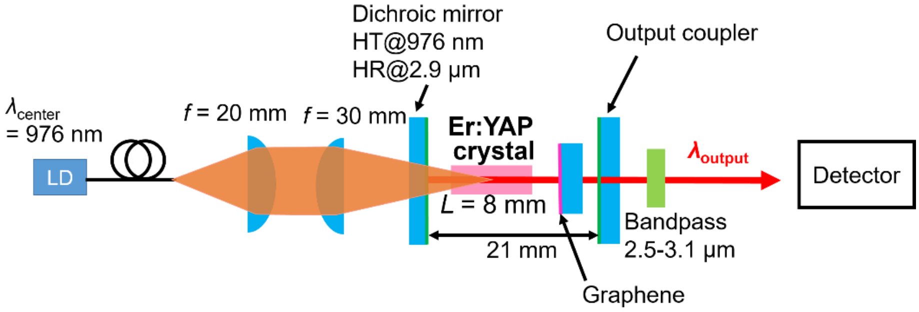

Dichroic mirror
HT@976 nm
HR@2.9 μm
Output coupler
λcenter
= 976 nm
f = 20 mm
f = 30 mm
Er:YAP
crystal
λoutput
Detector
LD
L = 8 mm
21 mm
Bandpass
2.5-3.1 μm
Graphene

Fig.1.

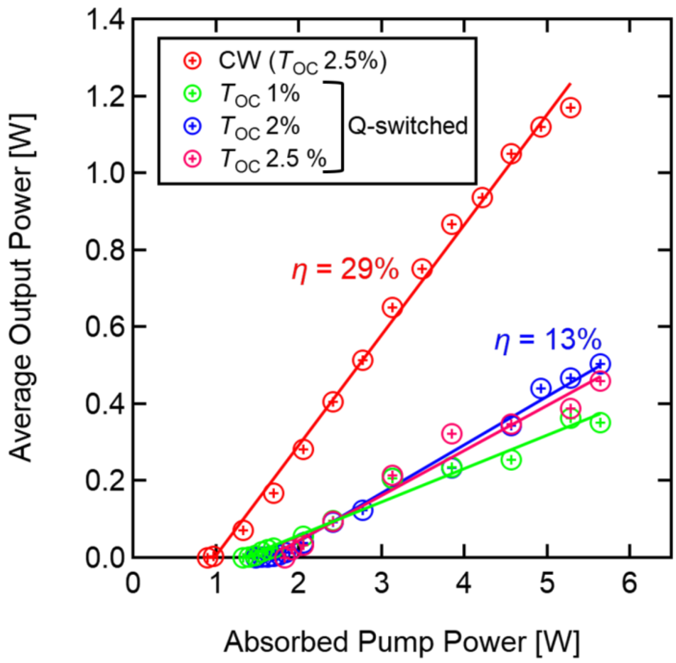
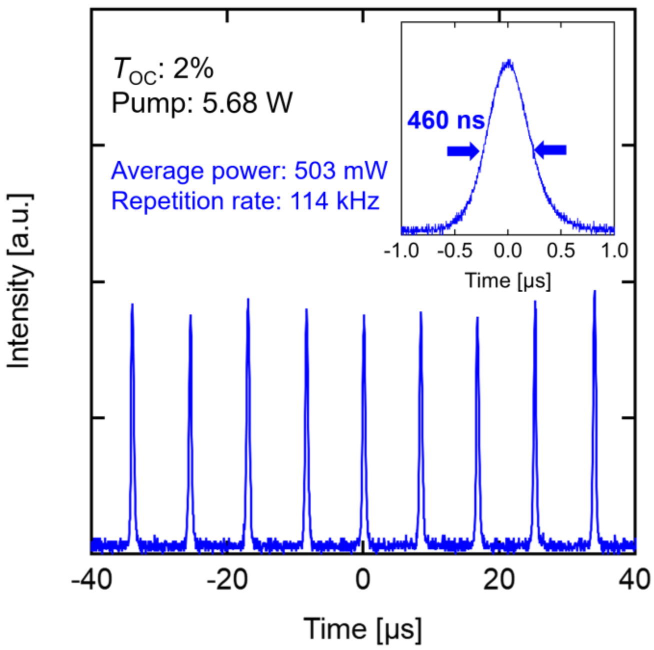
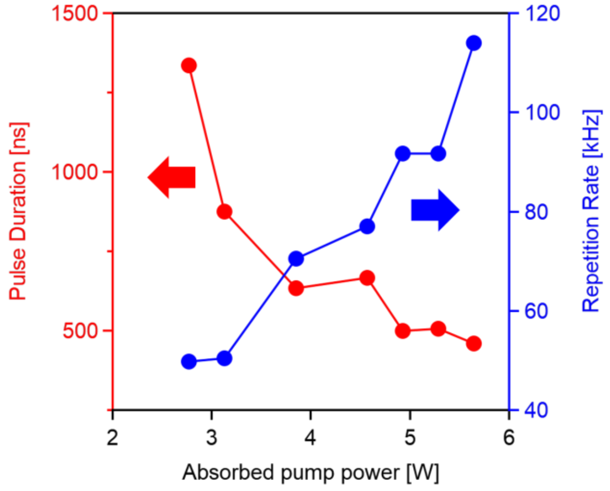

CW (T_{OC} 2.5%)
T_{OC} 1%
T_{OC} 2%
T_{OC} 2.5 %
Q-switched
η = 29%
η = 13%
Average Output Power [W]
Absorbed Pump Power [W]
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0
1
2
3
4
5
6

Fig.2.



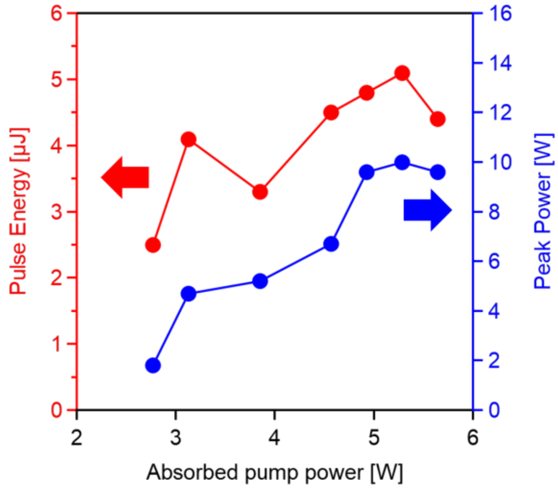
T_{OC}: 2%
Pump: 5.68 W
Average power: 503 mW
Repetition rate: 114 kHz
460 ns
-1.0 -0.5 0.0 0.5 1.0
Time [µs]
Intensity [a.u.]
-40 -20 0 20 40
Time [µs]

Fig.3.



Pulse Duration [ns]
Repetition Rate [kHz]
Absorbed pump power [W]
1500
1000
500
120
100
80
60
40
2
3
4
5
6

(a)



Pulse Energy [μJ]
Peak Power [W]
Absorbed pump power [W]
0
1
2
3
4
5
6
16
14
12
10
8
6
4
2
0
2
3
4
5
6

(b)

Fig.4.

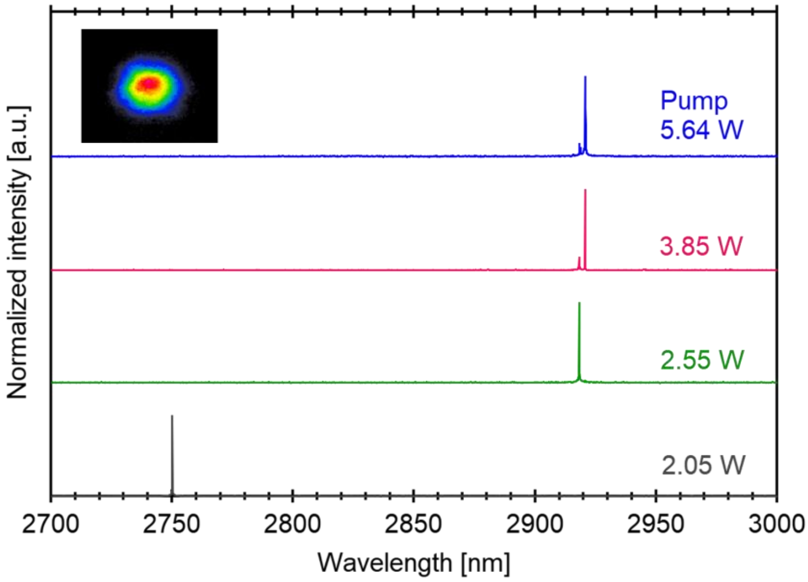

Pump
5.64 W
3.85 W
2.55 W
2.05 W
Normalized intensity [a.u.]
2700
2750
2800
2850
2900
2950
3000
Wavelength [nm]

Fig.5.