# High repetition rate graphene passively Q-switched $YVO_4$/Nd:$YVO_4$ laser

J. W. ZHANG, M. B. LI[a,*], N. ZHANG[b], K. X. LI, W. Z. JIANG[c]
*College of Mechanical and Electrical Engineering, Northeast Forestry University, Harbin 150040, China*
[a]*College of Civil Engineering, Northeast Forestry University, Harbin 150040, China*
[b]*Robot Science and Technology, Harbin Far East Institute of Technology, Harbin 150025, China*
[c]*Department of Electrical and Computer Engineering, Rice University, Houston 77005, USA*

In this letter, a diode-pumped graphene passively Q-switched 1064 nm laser using composite $YVO_4$/Nd:$YVO_4$ crystal as laser medium was demonstrated for the first time. The average output power of 463 mW was obtained at an incident pump power of 3 W when the output coupler with transmission of 15% was used. The pulse width and the pulse repetition rate was 53 ns and 643 kHz, respectively, at the incident pump power of 3 W. The maximum output energy was about 0.79 μJ.

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*Keywords:* Graphene passively Q-switched, Composite $YVO_4$/Nd:$YVO_4$ crystal, High repetition rate

## 1. Introduction

1.06 μm laser with narrow pulse width and high repetition rate has a broad range of uses in many fields such as micro-machining, microsurgery, laser ranging, and so on [1,2]. Passively Q-switched techniques have the advantages of obviously lower cost, compactness, simplicity since they do not require external control. $Cr^{4+}$:YAG as the usually used saturable absorber has advantages of low saturable intensity and high damage threshold. Passively Q-switched lasers with semiconductor saturable absorber mirrors (SESAMs) as Q-switching elements were reported widely. However, these SESAMs require complex fabrication and packaging [3]. Graphene as a saturable absorber for pulsed laser generation was appeared recently. It has advantages over conventional semiconductor saturable absorbers of large optical absorption and modulation depth [4]. In 2016, a monolayer graphene-based passively Q-switched Nd:YAG was reported [5]. The Q-switched largest output power of 266 mW, the maximum repetition rate of 436 kHz, and the narrowest pulse duration of 753 ns have been obtained when the pump power is 3 W. In Ref. [6], a passively Q-switched laser with multilayer graphene as a saturable absorber was demonstrated and the largest output power of 305 mW, a maximum repetition rate of 145 kHz, and the narrowest pulse width of 572 ns was achieved. Dual-wavelength of 1082 and 1092 nm Nd, Mg:$LiTaO_3$ laser with a monolayer graphene passively Q-switched operation was reported by Hongwei Chu, et. al [7]. The maximum output power of the Q-switched laser was 365 mW with a repetition rate of 133 kHz. The minimum pulse duration was measured to be 176 ns. The corresponding maximum pulse energy and peak power were 2.75 μJ and 15.7 W, respectively.

The thermal lens effect of laser medium can not only decrease the stability of oscillator but change the spot size of the TEM00 mode. These effects have influence on the performance of passively Q-switched laser. For example, single TEM00-mode is beneficial for the stable operation of passively Q-switched laser. Some effective methods such as composite crystal were introduced to reduce the thermal lens effect [8]. Compared to non-composite crystals, composite crystals are excellent alternative to alleviate the thermal lens effect owing to the undoped end acting as an effective heat diffuser. Furthermore, the laser efficiency can be improved when composite crystals are employed. In Ref. [9], for example, the slope efficiency was improved from 75.0% to 82.7% when $YVO_4$/Nd:$YVO_4$ crystal was used to replace Nd:$YVO_4$ crystal under the same conditions.

In this paper, a diode laser pumped graphene passively Q-switched 1064 nm $YVO_4$/Nd:$YVO_4$ laser was demonstrated for the first time. The output performance such as average output power, pulse width, the pulse repetition rate, pulse energy was investigated.

## 2. Experimental setup

The experimental configuration of the passively Q-switched $YVO_4$/Nd:$YVO_4$ laser is shown in Fig. 1. The pumping source was a fiber coupled laser diode (LD) emitting at 808 nm. The fiber had a numerical aperture of 0.22 and a core diameter of 400 μm. The output beam of LD was collimated and focused by using a set of plano-convex lenses $L_1$ and $L_2$. The diameter of beam size at the focal point was 500 μm. The dimensions of the composite $YVO_4$/Nd:$YVO_4$ crystal was 3 mm x 3 mm x 10 mm with an undoped cap of 2 mm long. The doped part

had a $Nd^{3+}$ ion concentration of 0.3 at.%. The absorption efficiency of the pump power in the $YVO_4$/Nd:$YVO_4$ laser crystal was about 80%. The laser cavity was constituted by two plano-plano mirrors. The input mirror $M_1$ was high-reflection coated at 1064 nm (> 99.8%), and $M_2$ was the output coupler with transmission of 15% at 1064 nm. The graphene absorber was coated at a BK7 glass mirror and optical transmission of graphene at 1064 nm is about 91%. The modulation depth of the graphene oxide absorber is about 8%. The cavity length was 60 mm.

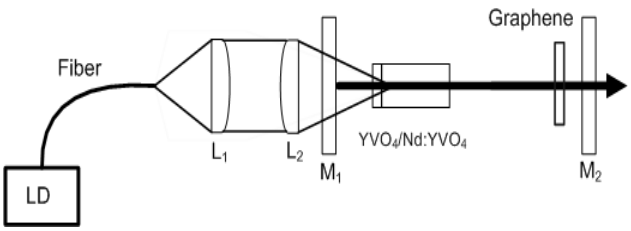


*Fig. 1. Schematic of the passively Q-switched $YVO_4$/Nd:$YVO_4$ laser*

## 3. Experimental results and discussions

Without graphene absorber, the continuous-wave (CW) operations were made firstly. The measured result is shown in Fig. 2. From Fig. 2, we can see, with increasing of the incident pump power, the CW output power increased. The maximum CW output power of 1.53 W was obtained at the incident pump power of 3 W, which resulted in an optical conversion efficiency of 51%. The threshold pump power was 0.77 W.

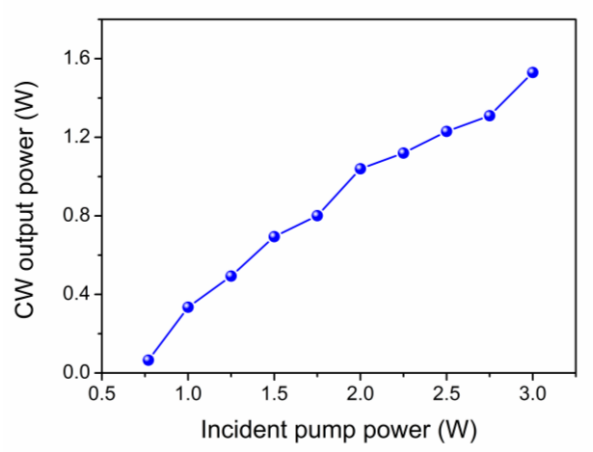


*Fig. 2. CW output power as a function of incident pump power*

The average output power as a function of incident pump power for graphene passively Q-switched $YVO_4$/Nd:$YVO_4$ laser is shown in Fig. 3. The threshold power was about 1 W. The average output power increased with increasing of the incident pump power, and at the incident pump power of 3 W, the output power was 463 mW.

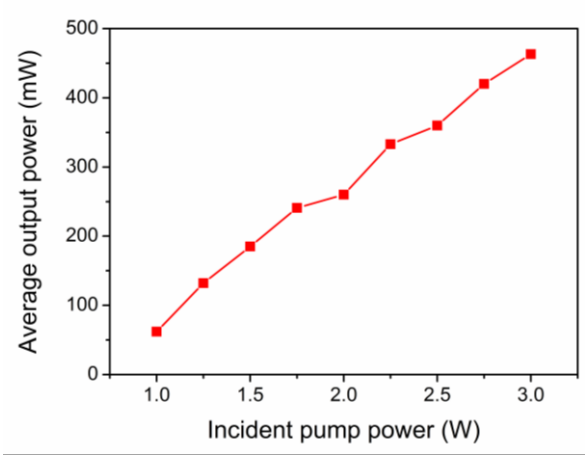


*Fig. 3. Average output power as a function of incident pump power for passively Q-switched $YVO_4$/Nd:$YVO_4$ laser*

The laser beam profile was captured by a CCD camera and the picture was shown in Fig. 4. We can see that the laser beam was in Gaussian distribution.

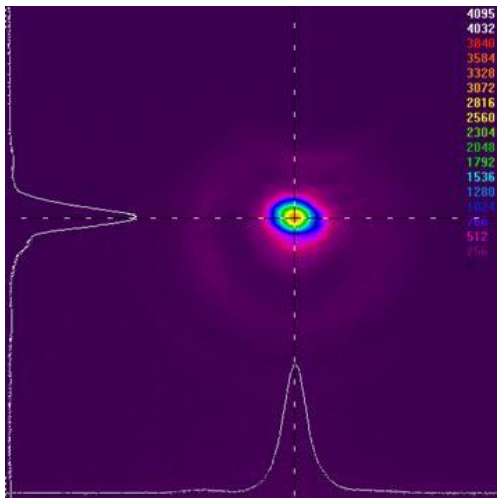

*Fig. 4. The laser beam profile for passively Q-switched $YVO_4$/Nd:$YVO_4$ laser at the maximum output power*

The pulse width, pulse repetition rate, pulse energy, and pulse peak power for graphene passively Q-switched $YVO_4$/Nd:$YVO_4$ laser is shown in Fig. 4 and Fig. 5, respectively. From Fig. 4, we can find that the pulse width decreased with increasing of the incident pump power. At the incident pump power of 3 W, the output pulse width was 53 ns. The repetition rate increased with increasing of the incident pump power. At the incident pump power of 3 W, the pulse repetition rate of 643 kHz was obtained.

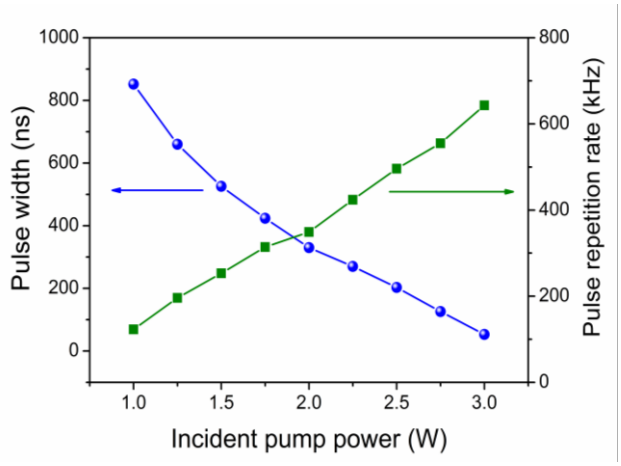


*Fig. 5. Pulse width and pulse repetition rate as a function of incident pump energy for passively Q-switched $YVO_4$/Nd:$YVO_4$ laser*

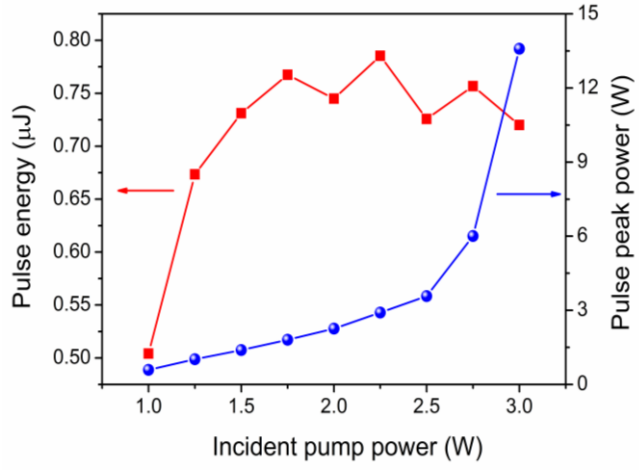


*Fig. 6. Pulse energy and pulse peak power as a function of incident pump energy for passively Q-switched $YVO_4$/Nd:$YVO_4$ laser*

The pulse energy and pulse peak power for graphene passively Q-switched $YVO_4$/Nd:$YVO_4$ laser is shown in Fig. 6. The output energy and pulse peak power was about 0.72 μJ and 13.6 W, respectively, at the incident pump power of 3 W.

## 4. Conclusions

In summary, we have studied a diode-pumped graphene passively Q-switched 1064 nm laser with composite $YVO_4$/Nd:$YVO_4$ crystal as laser medium for the first time. The average output power of 463 mW was obtained at an incident pump power of 3 W when the output coupler with transmission of 15% was used. The pulse width, pulse repetition rate, pulse energy and pulse peak power was 53 ns, 643 kHz, 0.72 μJ and 13.6 W, respectively, at the incident pump power of 3 W.

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*Corresponding author: zjwls123@163.com