Graphene on SiC as a Q-switcher for a 2 μm laser

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Double-layer graphene epitaxially grown on silicon carbide was used to Q-switch a Tm:YAG laser. Stable Q-switched laser pulses at the central wavelength of 2.01 µm were obtained. The maximum average output power, pulse repetition rate, and single pulse energy were 38 mW, 27.9 kHz, and 1.74 µJ, respectively. Our results illustrate that graphene can be used as a saturable absorber at the 2 µm region. © 2012 Optical Society of America

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Recently, graphene has attracted increasing interest because of its two-dimensional nanostructure and promising applications, such as high speed optoelectronic devices and semiconductor devices [1–3]. Moreover, graphene possesses an excellent optical property. It can be used as a saturable absorber due to the filled states of the electrons and holes in both the conduction and valence bands near the Dirac points when it is pumped by high intensity laser, resulting in a saturable absorbing property [4]. Absorption measurements have shown a featureless spectrum from 500 to 2000 nm, which is wavelength insensitive due to its zero bandgap [5,6]. Therefore, unlike conventional saturable absorbers such as Cr:YAGs [7], semiconductor saturable absorber mirrors [8], and GaAs saturable absorbers [9], graphene saturable absorbers can be used for lasers working from the visible to the mid-IR [5]. In particular, due to its ultrafast recovery time [10,11], low saturation intensity [6], low cost, and easy fabrication, graphene has become an ideal saturable absorber for laser applications. Up to now, by using graphene as the saturable absorber, mode-locking and Q-switched operations have been demonstrated in erbium-doped fiber lasers, Nd:YAG lasers, neodymium-doped vanadate lasers, etc. [4,5,12–15].

It has been proved that the modulation depth of graphene decreases with the increase of layers due to the increased nonsaturable loss induced by enhanced scattering of graphene multilayers [14]. Up to now the Q-switched lasers, by using graphene as a saturable absorber, were realized in the wavelength region of 1 μm to 1.5 μm [12–15]. Hence, unlike in the previous works, in this Letter we demonstrated a stable Tm:YAG Q-switched laser with double-layer graphene on silicon carbide (SiC) as the saturable absorber at the central wavelength of 2.01 μm. Under 7.2 W pump power, a pulse energy up to 1.74 μJ was obtained. To the best of our knowledge, this is the first instance of a Q-switched laser in the 2 μm region with graphene as a saturable absorber.

In the experiment, the graphene was epitaxially grown on SiC with a size of 4 mm × 4 mm. The measured Raman spectrum of graphene after subtracting the signal of the SiC substrate is shown in Fig. 1. The G and $2D$ peaks are located at 1617 cm^{-1} with a FWHM of 19 cm^{-1} and 2751 cm^{-1} with a FWHM of 43 cm^{-1}, respectively. From the relative intensities of the G and $2D$ peaks combined with their FWHM, it is inferred the graphene is about two layers [16,17]. There, a weak D peak exists, and that suggests that the graphene is high quality. Also, SiC has a large thermal conductivity of about 318.6 W/m/K at 284 K [18], so the heat on the graphene can be transmitted to the SiC quickly. For this reason, graphene on SiC as a saturable absorber can be used to generate stable Q-switched pulses.

We employed a simple two mirror cavity with a plane–concave configuration for the experiment. Figure 2 is the experimental layout. The Tm:YAG single crystal used in our experiment has a dimension of Φ4 mm × 8 mm and a Tm^{3+} doping concentration of 3.5 at. %. Both faces of the crystal had been polished and antireflection coated at 785 nm ($R \approx 1\%$) and from 1900 to 2100 nm ($R \approx 0.2\%$). The crystal was wrapped with indium foil and mounted

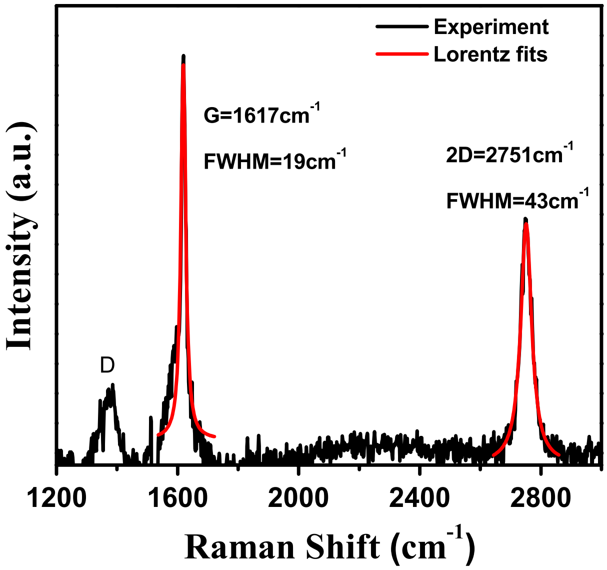

Fig. 1. (Color online) Raman spectrum of graphene after subtracting the signal of the SiC substrate. The red curves are the single Lorentz fit at the G and $2D$ peaks, respectively, which demonstrates that the film is double-layer graphene.

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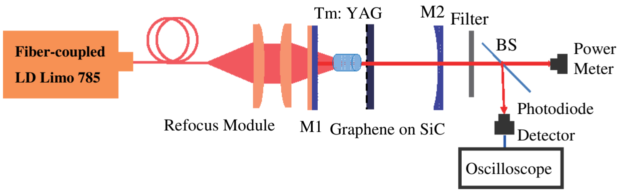

Fig. 2. (Color online) Schematic diagram of the experimental setup. LD, laser diode; BS, beam splitter.

tightly on a thermoelectric-cooler-cooled copper heat sink, and the temperature was maintained at 18 °C during the experiment. M1 is a dichroic plane mirror with high reflectivity from 1900 to 2100 nm and high transmission at 785 nm. M2 is the output coupler, which has a transmission of 1.5% from 1950–2050 nm with a curvature radius of 200 mm. After M2 is a Si filter, which is used to filter out the residual pump laser. The graphenep-on-SiC was used as the saturable absorber, which was set close to the Tm:YAG crystal. The length of the whole cavity was 98 mm. A commercial fiber-coupled diode laser was used as the pump source and emits a laser wavelength at 785 nm with a core diameter of 100 μm and a numerical aperture of 0.22. The spot was focused into the crystal through the refocus module to optimize the pump laser density inside the gain medium.

According to the theory by Spühler *et al.* [19], the following formula can be used to express the condition for Q-switching:

$$-\frac{1}{T_R} I \frac{dq}{dI} > \frac{r}{\tau}, \tag{1}$$

where q is the saturable loss of the absorber, I is the laser intensity incident on the absorber, T_R is the cavity round trip time, r is the pump parameter that determines how many times the laser is pumped above the threshold, and τ is the upper state lifetime of the gain medium. From the formula we can see that the cavity should be short to obtain a small value of T_R, and the upper state lifetime of the gain medium should be long. Fortunately, the upper state lifetime of the Tm:YAG is 10.1 ms [20]; therefore, it is suitable for energy storage in a Q-switched laser [21].

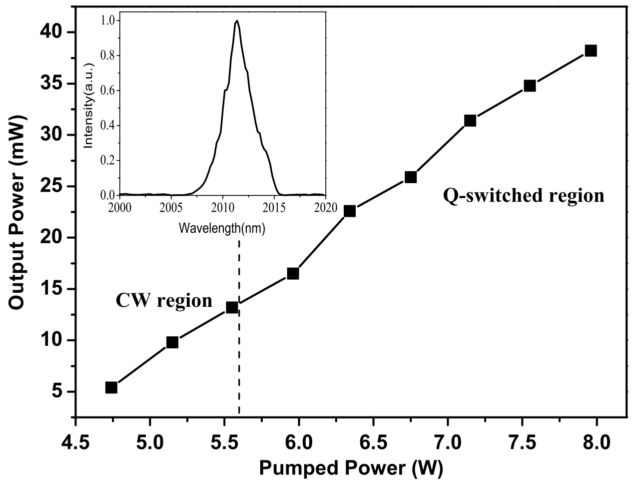

Fig. 3. Output power versus pump power of the Q-switched Tm:YAG laser. The inset is the spectrum of the Q-switched Tm:YAG laser. CW, continuous wave.

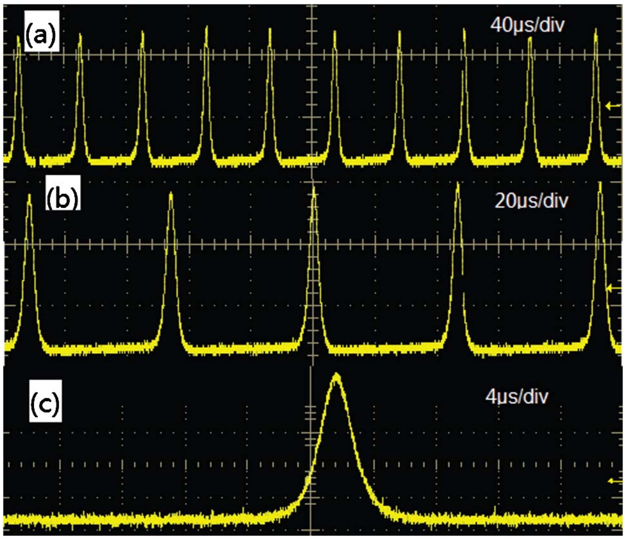

Fig. 4. (Color online) Oscilloscope trace of stable Q-switched laser pulses in different time scales when the pump power is 7.5 W. The pulse width, the pulse repetition, and the pulse energy are 2.25 μs, 22.4 kHz, and 1.55 μJ, respectively.

After finely adjusting the laser cavity and optimizing the position of the graphene, we obtained stable Q-switched laser operation. Figure 3 presents the output power of the laser versus the incident pump power. The inset is the spectrum of the output laser measured by a monochromator with a resolution of 1.6 nm (Omni-λ150, 150 mm focal length, 300 lines/mm, grating blazed at 1250 nm); the central wavelength was located at 2011 nm. The refractive index of the SiC is about 2.6 at 2 μm, so its reflectivity is about 20% when the laser is incident on its surface. This resulted in a high threshold power of about 4.4 W and a low output power of 38 mW under 8.0 W pump power. The Q-switching operation could be observed with an oscilloscope when the pump power was higher than 5.6 W. Figure 4 shows the Q-switched pulse trains at 7.2 W pump power. The dependence of the pulse width and the pulse repetition rate on

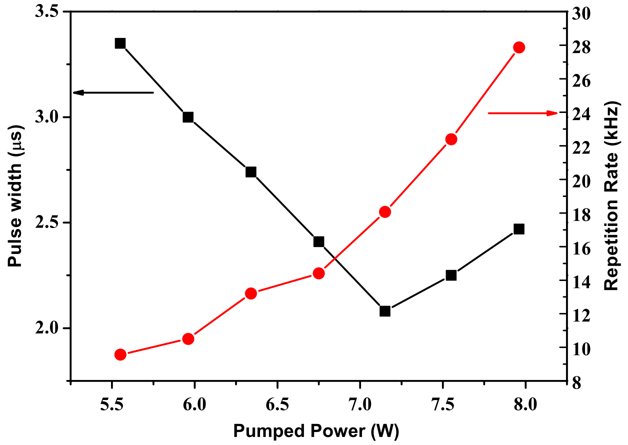

Fig. 5. (Color online) Repetition rate and pulse duration versus pump power.

the pump power is shown in Fig. 5. The repetition rate increased with the increase of the pump power. As for the pulse width, it decreased with a pump power below 7.2 W. When the pump power was above 7.2 W, the pulse duration increased. We attributed it to the absorbed heat on the graphene, since the SiC was not attached to a cooler. In our experiment, the Tm:YAG absorbed about 70% of the pump power. Although the pump laser diverges after the crystal, the residual pump power would be absorbed by the graphene, since it possesses wavelength-insensitive ultrafast saturable absorption. The shortest pulse duration was 2.08 μs at 7.2 W pump power, corresponding to a pulse repetition of 18.1 kHz and single pulse energy of 1.74 μJ. This experiment proved well the saturable absorption effect of the graphene at the 2 μm wavelength region. We believe that it could be used as a saturable absorber for *Q*-switching and even mode-locking at a much longer wavelength.

In conclusion, we demonstrated a Tm:YAG *Q*-switched laser by employing graphene epitaxially grown on SiC as a saturable absorber. Up to 1.74 μJ single pulse energy was obtained at 7.2 W pump power. To the best of our knowledge, this is the first instance of a *Q*-switched laser at a wavelength around 2 μm with graphene as a saturable absorber. With the stable operation of the *Q*-switched laser even at the large loss brought by the SiC substrate, we believe that if we further coat the antireflectivity film at the face of the SiC and wrap the SiC with a cooler, shorter pulses and higher single pulse energy should be possible.

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