Compression of the self-Q-switching in semiconductor disk lasers with single-layer graphene saturable absorbers*

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(Received 26 March 2014; revised manuscript received 28 April 2014; published online 23 July 2014)

We demonstrate the first use of single layer graphene for compressing self-Q-switching pulses in semiconductor disk lasers. The gain region of the semiconductor disk laser used InGaAs quantum wells with a central wavelength of 1030 nm. Due to self saturable absorption of the quantum wells, the disk laser emitted at the self-Q-switching state with a pulse width of 13 μs. By introducing the single layer graphene as a saturable absorber into the V-shaped laser cavity, the pulse width of the self-pulse was compressed to 2 μs with a lower pump power of 300 mW. As the pump power was increased, multiple pulses with the pulse width of 1.8 μs appeared. The compression factor was about 7.2.

Keywords: semiconductor disk laser, graphene, compression

PACS: 42.55.Px, 81.05.ue **DOI:** 10.1088/1674-1056/23/9/094206

1. Introduction

Diode laser pumped semiconductor disk lasers (SDLs) have become an active research field and they have attracted considerable attention in recent years.[1–5] In contrast to vertical cavity surface emitting lasers (VCSELs), SDLs use an external mirror as an output coupler instead of the top distributed Bragg reflector. They also use laser pumping instead of electric pumping, which allows the optical components to be inserted in the cavity of SDLs and this makes intra-cavity frequency doubling, tunable operation, and passively mode-locking possible.[6] For these reasons, SDLs may find many applications in laser communication,[7] laser display,[8] biochemistry analysis, etc.[9] Self-pulses in the MHz range are well known for quantum well lasers.[10] The mechanism is a self-Q-switching, which is due to the saturable absorption of the quantum well region. Commonly, the pulse width of the self-Q-switching was tens of microseconds, which were too broad. If another saturable absorber (SA) was introduced into the laser cavity, then the pulse width should be compressed. In recent decades, semiconductor saturable absorber mirrors (SESAMs) have been used as a SA to obtain short pulse SDLs. However, SESAMs are limited by their narrow operation wavelength range, as well as by their expensive fabrication processes.[11] Recently, carbon nanotubes,[12,13] grapheme,[14] and graphene oxide[15,16] have been used as a SA to produce pulses. Compared with SESAMs, carbon nanotube saturable absorbers and graphene based materials exhibit fast recovery time, broad spectral range (roughly between 1–2 μm), and they are much simpler to fabricate and thus are cost effective. Carbon nanotubes,[17] graphene,[18–20] graphene oxide,[21] topological insulator[22] and MoS_2[23] have also been used to obtain pulsed output in various types of fiber lasers and solid lasers. In consideration of the lower gain of our SDL, we chose a SA with lower saturable optical intensity. In the mentioned SAs, the single layer graphene had the lowest saturable optical intensity of 0.61 MW/cm^{-2}.[24] In addition, the Kerr nonlinearity in the graphene was large, which would greatly benefit self pulse compression in the SDLs.[25]

In this paper a reflective type graphene absorber was used in the pulsed SDLs system to compress the self-Q-switching pulses. The pulse width was compressed from 13 μs to 1.8 μs. The compression factor was about 7.2. To the best of our knowledge, this is the first time that a single layer graphene absorber in a semiconductor disk laser has been used.

2. Preparation of the graphene saturable absorber mirror

SA single layer graphene was obtained by the chemical vapor deposition method on a copper substrate. The graphene layer was covered with polymethyl methacrylate (PMMA) film by the spin-coating method. After which, the copper substrate was chemically etched. The graphene/PMMA film was then obtained. The graphene/PMMA film can be easily transferred to the reflective mirror. At last, the PMMA was washed away by acetone. Figure 1 shows the Raman spectrum of the single layer graphene. The prominent G band at 1593 cm^{-1} and 2D band at 2652 cm^{-1} were clearly resolved. The relatively weak D band at 1332 cm^{-1} indicated a low density of defects and the high crystallinity of the CVD grown graphene.

*Project supported by the National Basic Research Program of China (Grant No. 2013CB922404), the National Natural Science Foundation of China (Grant No. 61177047), and the Key Project of the National Natural Science Foundation of China (Grant No. 61235010).

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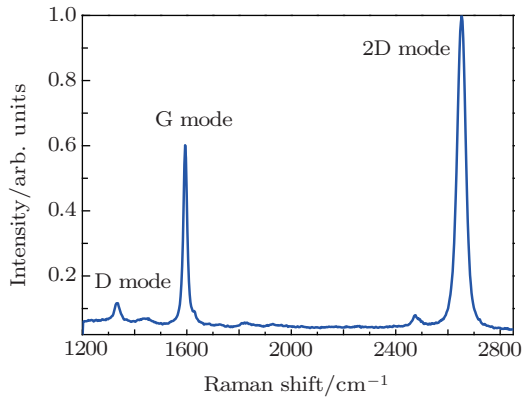


Fig. 1. (color online) Raman spectrum of the single layer graphene.

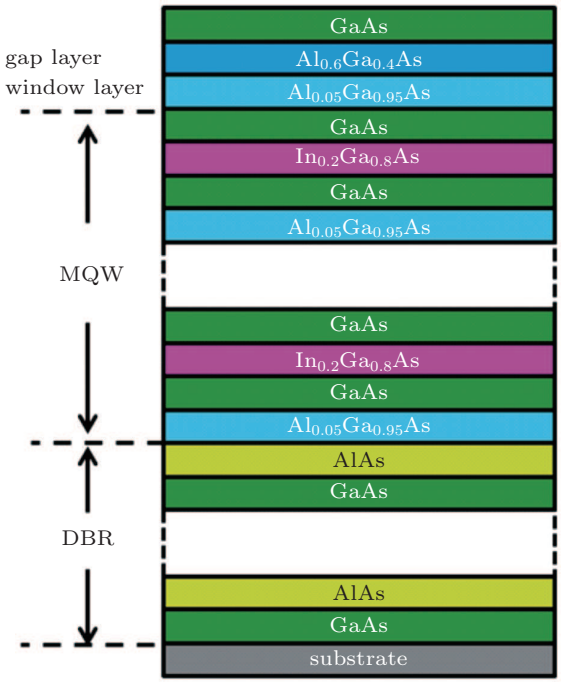


Fig. 2. (color online) The epitaxial structure of the semiconductor wafer.

Figure 2 shows the epitaxial structure of the semiconductor wafer, including the following parts: the substrate, DBR, multiple quantum wells (MQWs), window layer, and cap layer. The DBR works as one of the reflectors of the laser; the MQWs are the active region; the window layer is used to prevent the carriers from the non-radiative combination at the surface; and, the cap layer is added to protect the epitaxial structure against the oxidation. In our wafer design, the DBR contains 30 pairs of alternating GaAs and AlAs layers. The active region consists of 16 non-compensated compressively strained $In_{0.20}Ga_{0.80}As$ quantum wells (QWs), which are spaced by the $Al_{0.05}Ga_{0.95}As$ barriers and located at the antinodes of the standing wave of the laser to form the well-known periodic resonant gain structure. Between the well and the barrier, there is a GaAs buffer layer (a buffer layer is helpful in improving the quality of wafer growth and has been proven to enhance the capture of the carriers into the well). The $Al_{0.6}Ga_{0.4}As$ layer (which is transparent for laser and pump wavelengths) provides a high barrier, which is used as the window. Finally, a GaAs cap layer is added to finish the growth.

3. Experimental setup and results

The experimental setup is shown in Fig. 3, in which a compact V-shaped resonator was employed. The cavity for the fundamental laser was composed of a distributed Bragg reflector (DBR), which was highly reflective ($R > 99.9\%$) at 1030 nm, a concave mirror (radius of curvature 50 mm) M3, with high-reflectivity ($R > 99.5\%$) at 1030 nm, and a plane high reflective mirrors M1 or M2 ($R > 99.99\%$) at 1030 nm. The pump was focused and the incident on the gain structure was at 45°, the pump spot radius was estimated to be 55 μm. The temperature of the heat sink of the semiconductor disk was set to 10 °C while the gain structure was pumped at 1.5 W with a commercial 10 W 808 nm fiber coupled diode. The laser was coupled out from mirror M3.

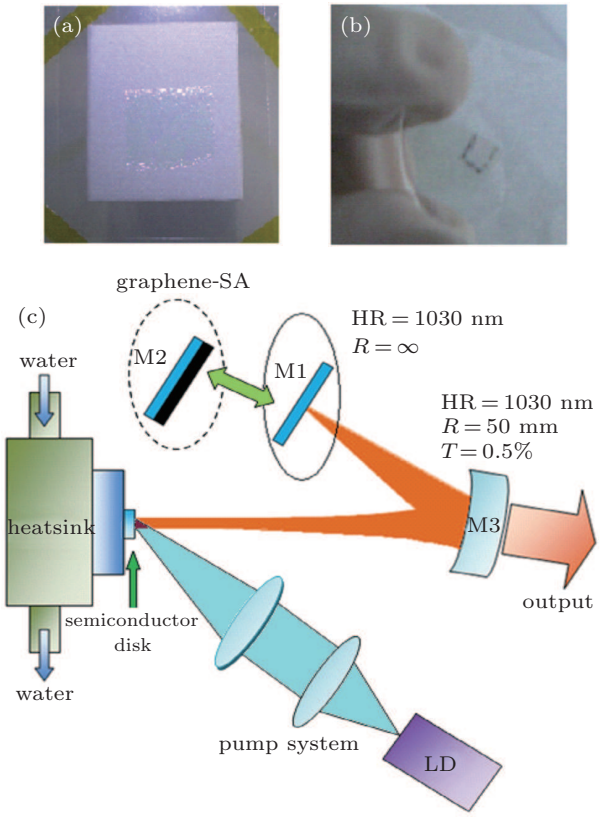


Fig. 3. (color online) (a) The single layer graphene film. (b) Graphene-SA mirror. (c) Experimental setup of the laser.

In experiment, a high reflective mirror (M1) was used for laser oscillation. After optimization, a graphene-SA mirror M2 was used to replace mirror M1, and pulse trains were obtained. For comparison, the output power of the SDLs with and without graphene-SA mirror were measured, respectively,

the results are shown in Fig. 4 Continuous wave laser operation was realized at the threshold pump power of 0.25 W. When the graphene-SA mirror was introduced, the pump threshold was increased to 0.296 W, which was attributed to the loss of the graphene-SA mirror, this was further confirmed by the slope efficiency of the curves shown in Fig. 4. However, the threshold pump power with the graphene-SA mirror was close to the threshold without the SA, which indicated that the non-saturable losses introduced by the graphene-SA mirror was very low. After the graphene-SA mirror was introduced, the maximum average output power of the pulsed SDL was 8.2 mW.

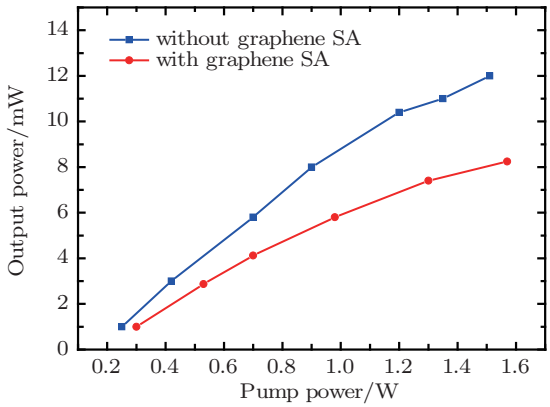


Fig. 4. (color online) Output power before (red line) and after (blue line) graphene saturable absorber was introduced.

The spectrum of the laser with graphene-SA mirror was detected by spectrometer, the results are shown in Fig. 5. It can be seen that the pulsed laser emission was centered at 1040 nm, and the full width half maximum (FWHM) was estimated to be 2.5 nm, which is similar to that without the graphene-SA mirror. This can be justified because the emission spectrum was primarily up to the multiple quantum wells' structure, thus the influence of the graphene-SA was not obvious.

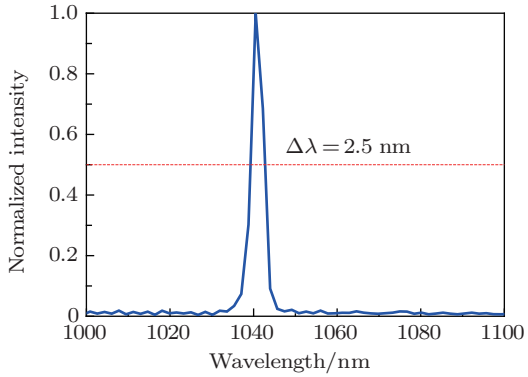


Fig. 5. (color online) Spectrum of pulsed SDL laser.

The pulse width changed obviously when the graphene-SA mirror was introduced. Figure 6 shows the pulse trains before and after graphene-SA mirror was introduced. Before the graphene-SA mirror was introduced, the laser operated in a self-Q-switching state with a pulse width of 13 μs and a repetition rate of 500 kHz (Fig. 6(a)). When the graphene-SA was introduced into the laser cavity, the self-Q-switching pulse widths were obviously compressed. The pulse width after compressing was about 2 μs (Fig. 6(b)). The repetition rate of the pulse trains was unchanged. The optical spectrum after using graphene-SA mirror was detected as shown in Fig. 7. Compared with the original spectral width of 2.5 nm (Fig. 5), the optical spectrum after using graphene-SA mirror was broadened to 4.8 nm. The center of the spectrum drifted from 1040 nm to 1037 nm, which was due to interaction between the graphene saturable absorber and semiconductor laser.

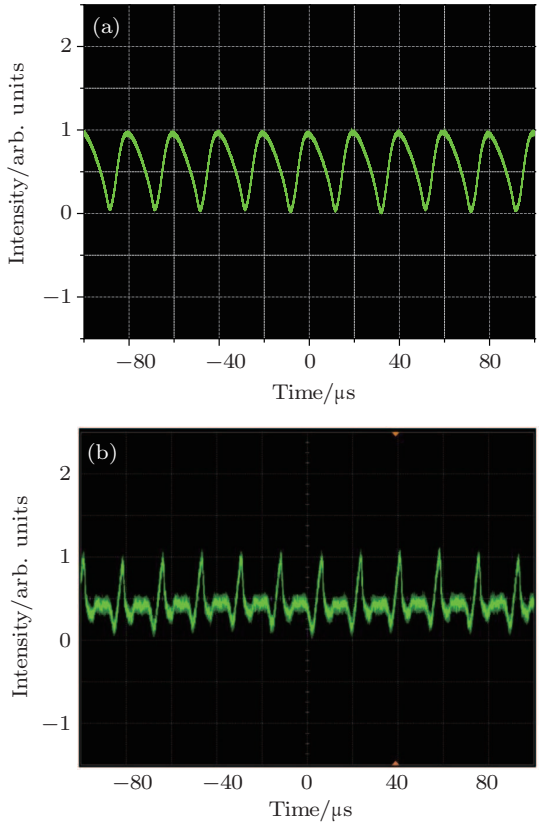


Fig. 6. (color online) Pulse trains: (a) self-Q-switching state; (b) compressing state.

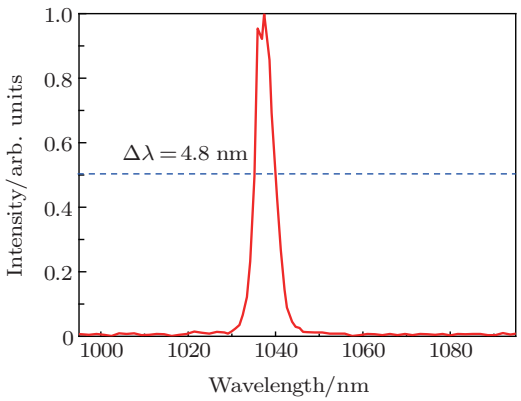


Fig. 7. (color online) Spectrum of the SDL after using graphene-SA mirror.

When the pump power was increased to 1.5 W, the self-Q-switching pulse envelope was split into multiple-peaks, as shown in Fig. 8, from which it can be deduced that each multiple-pulse has almost the same pulse width of 1.8 μs. When the position of the graphene-SA mirror was changed, the compression effect would sometimes disappear, which was primarily due to the non-uniformity of the graphene-SA mirror. However, the compression effect could work stably at most positions of the graphene-SA mirror.

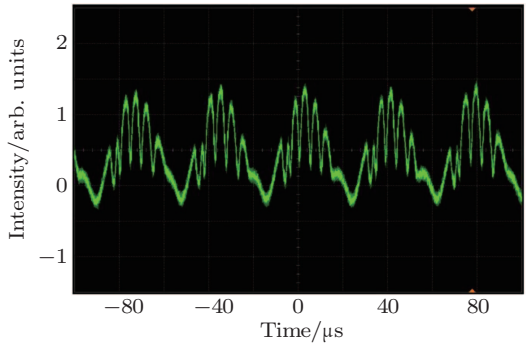


Fig. 8. (color online) Multiple pulse trains with incident pump power of 1.5 W.

4. Conclusions

The first use of the single layer graphene for compressing self-Q-switching pulses in semiconductor disk lasers was demonstrated. Due to self saturable absorption of the quantum wells, the disk laser emitted at the self-Q-switching state with a stable pulse train, with a pulse width of 13 μs. By introducing the single layer graphene into the V-shaped laser cavity, the pulse width of the self-pulse was compressed to 2 μs with the lower pump power of 300 mW. When the pump power was increased, multiple pulses with a pulse width of 1.8 μs appeared. The compression factor was about 7.2. The experimental result shows that graphene could be introduced into a semiconductor laser for pulse compression. We believe that, as the performance of graphene saturable absorbers improves, the pulse width could be further compressed into nanoseconds.

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