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Reflective graphene oxide absorber for passively mode-locked laser operating at nearly 1 μm*

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A low cost and simply fabricated reflective graphene oxide is successfully made. By using this absorber, as well as an end reflector, we obtain a passively mode-locked Yb:$LuYSiO_5$ laser operating at nearly 1 μm. When the pump power is increased up to 5.73 W, stable mode locking is achieved. The central wavelength of the laser spectrum is 1043.2 nm with a pulse duration of 5.0 ps. When the pump power reaches 8.16 W, dual-wavelength mode locking laser pulses at 1036.3 nm and 1043.5 nm are simultaneously detected.

Keywords: passively mode-locked dual-wavelength laser, graphene oxide, Yb:$LuYSiO_5$ crystal

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1. Introduction

Ultrashort pulses at megahertz repetition rates, produced by lasers operating in the 1 μm spectral region, have important applications in material processing, optical communications, medicine, etc.[1] Diode-pumped passively mode-locked lasers can supply these kinds of pulses and have the advantages of simplicity, compactness, low cost, and high efficiency. So far, semiconductor saturable absorption mirrors (SESAMs) for mode-locked lasers have been successfully investigated.[2–8] However, the fabrication of SESAMs requires complicated deposition techniques, which have the disadvantage of relatively narrow and limited recovery times. In recent years, carbon nanotube saturable absorbers (CNT-SAs) have been applied to mode-locked fiber lasers and solid-state lasers since the first demonstration of mode-locking in a fiber laser in 2004.[9,10] However, the band gap of a CNT depends on the nanotube diameter and chirality. A wide saturable absorption band can only be realized by mixing CNTs of different tube diameters. However, a CNT with a certain diameter only provides saturable absorption at a particular wavelength of light and the CNT bundles will act like a scattering site, resulting in extra energy loss. Graphene is a two-dimensional (2D) material that contains several layers of carbon atoms. A single layer of graphene absorbs about 2.3% of the light incident on it. Graphene has no band gap and thus its absorption spectrum is very broad.[11–15] Recently, mode-locked solid-state lasers were also obtained by using graphene as the saturable absorber.[16,17] Graphene oxide is another kind of graphene based material. In most cases, the graphene oxide has served as a precursor for graphene because it is simple to be fabricated with low production cost. The dispersion of graphene oxide in the form of nanosheets in water can be very easy due to the carboxyl and hydroxyl group in its structure, which leads to a high deposition efficiency in the vertical evaporation method.[18–20] It is expected that the graphene oxide absorber can be used in a broad wavelength range too because of its conical band structure. These features make the graphene oxide a good material for commercial photonic device fabrication compared with graphene.

Dual-wavelength synchronously mode-locked lasers are attractive due to their applications in the generation of ultra-high repetition rate pulse terahertz (THz) radiation. Terahertz waves have attracted great attention for their many practical applications in various fields including biology, medical imaging, communication, security, etc.[21,22] So far most of the experimental work on dual-wavelength synchronously mode-locked lasers has mainly focused on the system in which the Ti:sapphire is used as the laser gain medium.[23] Recently, SESAMs for dual-wavelength synchronous ultrashort laser pulses at 1 μm wavelength were reported.[24–27]

As a promising laser crystal, ytterbium-doped alloyed oxyorthosilicate crystal Yb:$LuYSiO_5$ (Yb:LYSO) has advantages of broad absorption and emission spectra, large ground-state splitting, and excellent mechanical properties. The ultra-

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fast laser performance of the Yb:LYSO was experimentally investigated previously.[28–30] In the present paper, the first graphene oxide based passively mode-locked Yb:LYSO laser is reported. The stable mode locking is achieved at the pump power up to 5.73 W. The central wavelength of the laser spectrum is 1043.2 nm with a pulse duration of 5.0 ps. When the pump power reaches up to 8.16 W, dual-wavelength mode locking laser pulses at 1036.3 nm and 1043.5 nm are simultaneously detected. The maximum output power of the mode-locked laser is 180 mW.

2. Fabrication and characteristics of graphene oxide

The graphene oxide nanosheets were fabricated by ultrasonic agitation after the chemical oxidation of graphite. The graphene sheets were about one to three atomic layers in thickness and 0.1–5 μm in diameter. At the first step, several milligrams of graphene oxide powder were poured into 10 ml 0.1% sodium dodecyl sulfate (SDS) aqueous solution. Here SDS was used as a surfactant. In order to obtain a graphene oxide aqueous dispersion with high absorption, the graphene oxide aqueous solution was ultrasonically agitated for 10 h. After the ultrasonic process, the dispersed solution of graphene oxide was centrifuged to remove the sedimentation of large graphene oxide clusters. The upper portion of the centrifuged solution was diluted and poured into a polystyrene cell, and then a hydrophilic quartz substrate was inserted vertically into the cell. The polystyrene cell was placed on a table in air atmosphere for gradual evaporation. It took about two weeks to transfer the graphene oxide on both sides of the quartz substrate to form the transmission type absorber with a layer structure of graphene oxide/quartz/graphene oxide. The reflective absorber can be fabricated by coating a layer of 150 nm thick gold on one side of the transmission type absorber.

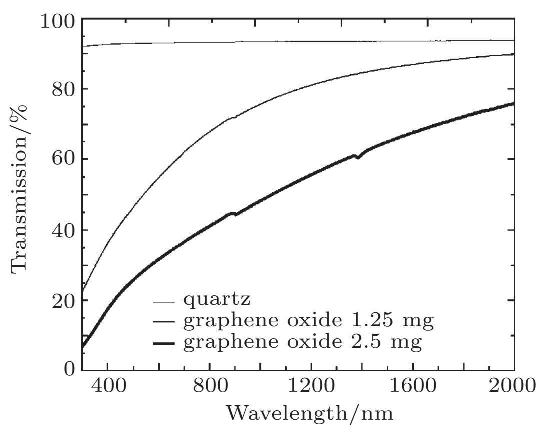

Fig. 1. Wavelength-dependent linear transmissions of quartz substrate and transmission type graphene oxide absorbers fabricated by graphene oxide aqueous dispersion at different concentrations. The quantity of graphene oxide is marked in the diagram, and the solvent is 10 ml SDS aqueous dispersion.

The linear optical transmissions of the transmission type graphene oxide absorbers with various concentrations were measured by using an UV–visible–NIR spectrophotometer, and the results are shown in Fig. 1. For a low gain solid-state laser, a lower initial transmission of absorber is usually not preferable. Therefore, the sample with 1.25 mg graphene oxide is expected to have a better performance than the sample with 2.5 mg graphene oxide. So, it was chosen and coated with a gold film to form the reflective absorber for our laser experiments.

3. Experiment and results

The W-type cavity shown in Fig. 2 was designed to optimize the spot size on the laser crystal and the graphene oxide saturable absorber. The laser gain medium, Yb:LYSO, was fabricated by the Czochraski method, with 5 at.% dopant Yb^{3+} (with dimensions of 3 mm×3 mm×3 mm). To avoid thermal damage to the laser crystal, it was mounted on a water-cooled copper heat sink, and the thermal contact was enhanced by an indium foil between the copper heat sink and the laser crystal. The temperature of the laser crystal was maintained at 14 °C to reduce the laser threshold. The pump source was a 977 nm fiber coupled laser diode with a fiber core diameter of 400 μm and a numerical aperture of 0.22. The input flat mirror M1 was high transmission coated at 977 nm and high reflection coated from 1030 nm to 1080 nm. The radii of curvature of the concave mirrors M2 and M3, which were also high-reflection coated at 1030–1080 nm, were 200 mm and 800 mm, respectively. The reflective graphene oxide saturable absorber acted as a flat mirror and a saturable absorber. To sustain a high intracavity circulating power, the mirror with 1% transmission and radius of curvature of 80 mm was selected as the output coupler (OC). The distances from M1 to M2, from M2 to M3, from M3 to OC, and from the graphene oxide saturable absorber to the OC were 80 mm, 440 mm, 932 mm, and 42 mm, respectively. The total cavity length was 1500 mm. The beam waists in the laser crystal and the graphene oxide saturable absorber were calculated by the ABCD analysis to be about 83 μm and 20 μm, respectively.

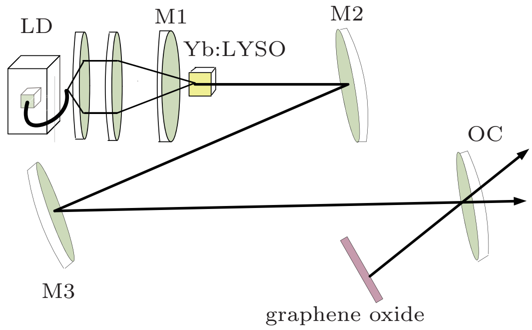

Fig. 2. (color online) Schematic diagram of the passively mode-locked laser.

Using the graphene oxide as the end reflector, with an appropriate alignment of the cavity, stable mode locking pulses were achieved immediately after the pump power had increased up to 5.73 W. The continue-wave (cw) mode-locked pulse trains achieved at the pump power of 7.54 W are shown in Fig. 3. Figure 3(a) was recorded with a time scale of 10 ns/div, while figure 3(b) was recorded with a time scale of 2 μs/div. The pulse repetition rate was 100 MHz in the laser, the result is in good agreement with the theoretical result obtained with $f = c/2L$ (c is the speed of light, L is the optical length of the resonator). Figure 4 shows the autocorrelation trace of the mode-locked pulses measured at the pump power of 7.54 W. Under the assumption of a Gaussian shape pulse, the autocorrelation trace gives a pulse width of 5 ps. The optical spectrum of the mode locked pulses is shown in Fig. 5. The spectral band centered at 1043.2 nm has a mode locked full-width half-maximum (FWHM) spectral bandwidth of 1.26 nm. The time-bandwidth product is calculated to be 1.73, which is larger than the transform-limited value of 0.44 for the Gaussian shape pulse, indicating that the mode-locked pulses are frequency chirped and their duration could be further narrowed.

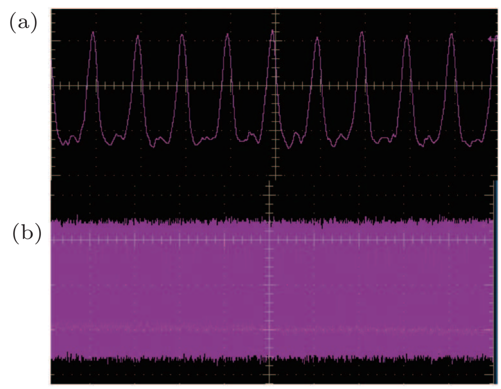

Fig. 3. (color online) The cw mode-locked pulse train at the pump power of 7.54 W: (a) at time span of 10 ns; (b) at time span of 2 μs.

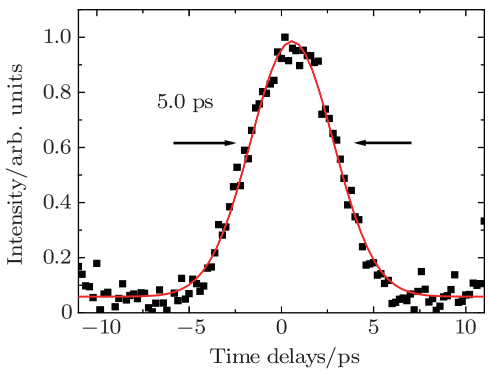

Fig. 4. (color online) Autocorrelation trace of the pulse at the pump power of 7.54 W.

When the pump power reached 8.16 W, dual-wavelength mode locking at 1036.3 nm and 1043.5 nm was found. The optical spectrum of the mode-locked pulses is shown in Fig. 6. The spectral band centered at 1036.3 nm has an FWHM of 0.93 nm and the spectral band centered at 1043.5 nm has an FWHM of 1.15 nm. Their spectral intensity ratio is about 0.7:1, and the spectral width ratio of the two pulses is about 0.8:1. The central frequency difference between the two bands is 2.00 THz. The pulse trains were fully modulated with good pulse stability. However, the autocorrelation trace indicates that the two mode-locked pulses are neither synchronized nor temporally overlapped. Synchronization between the two different wavelength mode locked pulses could not be achieved in the laser. The dual-wavelength mode locking operation lies in two aspects, one is the nonliear effect of light pulses in the laser crystal, and the other is the interaction between the two different wavelength pulses. Maybe the effect of the cavity dispersion is to separate the pulses. Eventually a balance between them could not be reached and consequently a stable pulse evolution was not formed in the cavity. Further theoretical analysis and experimental demonstration are in progress.

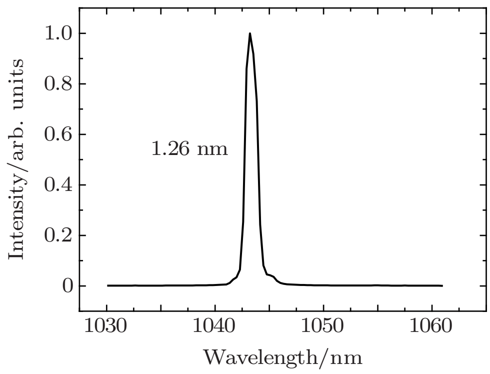

Fig. 5. Optical spectrum intensity for the mode-locked laser at 1043.2 nm at the pump power of 7.54 W.

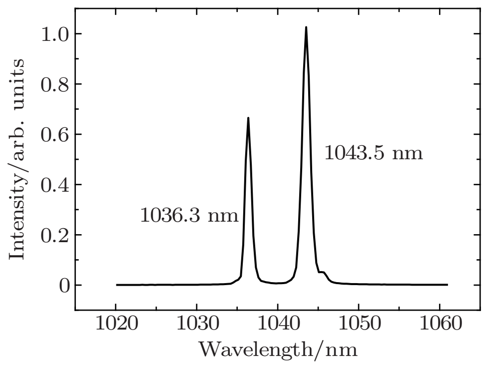

Fig. 6. Optical spectrum for the mode-locked laser at 1036.3 nm and 1043.5 nm.

The behavior of average laser output power as a function of pump power was investigated, and the results are shown in Fig. 7. At the pump power of 13.23 W, the maximum output power of the mode-locked laser is 181 mW.

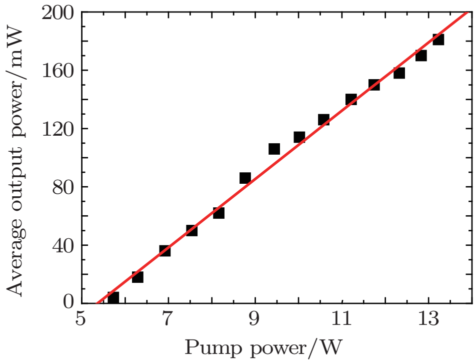

Fig. 7. (color online) Average output power versus the pump power.

4. Conclusion

With a lower cost and simpler fabrication reflective graphene oxide saturable absorber, we obtain a passively mode-locked Yb:$LuYSiO_5$ laser operating at nearly 1 μm. The stable mode locking is achieved under the pump power up to 5.73 W. The demonstrated pulse width is 5.0 ps with a repetition rate of 100 MHz. The central wavelength of the laser spectrum is 1043.2 nm. When the pump power reaches 8.16 W, the passively mode-locked laser pulses at 1036.3 nm and 1043.5 nm are simultaneously observed. The calculated beat frequency of the two wavelength peaks is 2.00 THz. The maximum output power of the mode-locked laser is 181 mW. To the best of our knowledge, this is the first graphene oxide absorber based mode-locked laser operating at dual-wavelength. Such a laser source could potentially be used to generate the laser in the THz range.

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