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Efficient and compact Q-switched green laser using graphene oxide as saturable absorber

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ABSTRACT

A new type of graphene oxide (GO) is successfully prepared using an improved modified Hummers method. The Raman shift, X-ray diffraction (XRD), and scanning electron microscope (SEM) measurement techniques are used to characterize the GO. An efficient and compact Q-switched green laser based on Nd:YVO_4/PPLN is demonstrated with a few-layered GO as the saturable absorber. Our experimental results show that such a few-layered GO saturable absorber allows for the generation of a stable Q-switched laser pulse centered at 532.1 nm with a 3 dB spectral bandwidth of 2.78 nm, a repetition rate of 71.4 kHz, and a pulse duration of 98 ns. The maximum average output power of 536 mW is obtained at the absorbed pump power of 5.16 W, corresponding to an optical conversion efficiency of 10.3%.

1. Introduction

Q-switched green lasers in a nanosecond time scale are widely used in many applications, such as information storage, underwater communication, projection display, and medical test and treatment [1,2]. A highly efficient nanosecond green laser can be achieved by second harmonic generation (SHG) with various active or passive Q-switching techniques [3,4]. Compared with active methods involving the use of acousto-optic or electro-optic modulators, passive techniques have attracted much attention because of their advantages of lower cost and less complexity in fabrication and operation. For passive Q-switching, a saturable absorber (SA) is generally required to initiate and sustain the pulsing operation. Thus far, various SAs (e.g., semiconductors [5,6], crystals doped with ions like Cr^{4+}, V^{3+}, and Co^{2+} [7–9], or carbon-based materials [10–13]) have been extensively investigated to generate a high-performance pulse laser. Unfortunately, the energy level structure of traditional saturable absorption materials (e.g., Cr^{4+}:YAG and semiconductor SA mirrors (SESAMs)) makes them effective only in a narrow wavelength range. Graphene can be used as a wavelength-insensitive SA because of their zero band gap structure, making it a hot research topic since its discovery in 2004. However, graphene is still expensive because of the complex production procedures [14–17]. Carbon nanotube (CNT) is another excellent SA, which has highly environmental stability and is independent of the polarizations of pulses [18–20]. By tuning the nanotube diameters and its structures, the laser operating wavelength can cover a wide spectral range. Recently, a CNT-based tunable distributed ultrafast fiber laser is reported based on a linearly chirped fiber Bragg grating, where the total cavity length is linearly changeable with the pulse wavelength [21]. Recent research results suggest that graphene oxide (GO) exhibits a similar favorable optical performance as graphene and may be produced using several simple methods [22,23]. Furthermore, the prepared GO is made to contain a high hydroxyl content, which is beneficial for film formation on the substrate to fabricate the Q-switching element, by improving the traditional modified Hummers method (MHM). This new kind of GO is believed to be a promising SA for passive Q-switching operations.

For the green laser generation, the frequency doubling of the laser diode (LD)-pumped Q-switched laser using nonlinear crystals, such as KTP, LBO, and PPLN, is a convenient method of extending the wavelength to the green range. The PPLN crystal is widely used in efficient frequency conversions because of their advantages of quasi-phase matching at arbitrary wavelength, large nonlinear coefficient, and wide transparent window [24,25]. Specifically, as for the SHG, the extra-cavity frequency doubling has merits of simple construction, good polarization property, and high stability. However, the volume and cost of the whole laser system increase because of the separate fundamental laser and a longer nonlinear crystal required [26]. In contrast, the intra-cavity frequency

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doubling is a better solution for achieving a high optical conversion efficiency while keeping the system compactness.

In this study, a compact and efficient LD end-pumped intracavity frequency doubled Nd:YVO_4/PPLN green pulse laser is demonstrated by using a new kind of GO as the SA. The laser is based on a simple plane–plane resonator formed by two high-reflection coatings on the Nd:YVO_4 and PPLN crystals without any additional optical mirrors. A 536 mW pulsed green laser at 531.2 nm is generated at a repetition of 71.4 kHz with a pulse duration of 98 ns.

2. Fabrication of graphene oxide saturable absorber and laser setup

The new type of GO was prepared according to the improved MHM [27]. Accordingly, 1 mg GO was added into 100 mL absolute ethyl alcohol to create a suspension. The suspension was dispersed for 3 h using an ultrasonic apparatus. Subsequently, a drop (0.4 mL) of the dispersed suspension was spin coated on a square quartz substrate (2.5 cm × 2.5 cm). The quartz coated with GO was dried on a heating platform for 5 min at 80 °C in a clean room. Finally, the Raman shift spectrum, X-ray diffraction (XRD) analysis, and scanning electron microscope (SEM) image were measured to characterize the prepared GO SA. Fig. 1(a) shows the Raman spectrum of the GO SA. The two main peaks observed in the spectrum (i.e., D and G peaks) were typical to that of GO. The D peak was located at ~1350 cm^{-1}, while the G peak was located at ~1590 cm^{-1} with FWHM bandwidths of ~90 cm^{-1} and ~60 cm^{-1}, respectively. The broad 2D band was located at ~2750 cm^{-1}, indicating that the GO film consisted of ~10 layers [28]. The GO structure was studied through an XRD analysis with an intensive characteristic diffraction peak at $2\theta = 10.3°$ (Fig. 1(b)). An inter-layer distance of GO was calculated as 0.85 nm according to Bragg's equation. The peak of graphite located at $2\theta = 26.6°$ disappeared after being oxidized. This result suggested that graphite was already oxidized to form GO [29]. The GO SA was also tested by SEM. Fig. 1(c) shows a large area of the gauze structure, which indicated that the GO sheets had a smooth surface and a relatively large diameter.

Fig. 2 presents the schematic of the Q-switched green laser based on the GO SA. As a gain material, the Nd:YVO_4 crystal with an Nd^{3+} concentration of 0.5 at.% was cut along its a-direction having dimensions of $3 \times 3 \times 5$ mm^3. The Nd:YVO_4 crystal was pumped by a fiber-coupled LD with a central wavelength of 808 nm. The fiber pigtail had a core diameter of 400 μm and a numerical aperture of 0.22. The output laser beam of the LD was focused into the laser crystal with a beam radius of 200 μm using a 1:1 coupling system. The Nd:YVO_4 crystal was wrapped with indium foil and tightly mounted in a water-cooled copper block to reduce the thermal effects while pumping. The circulating water temperature for the experiment was set at 25 °C. The PPLN crystal had dimensions of $2.2 \times 0.5 \times 1.3$ mm^3 (width × height × length) with a grating period of 7 μm. The PPLN crystal temperature was controlled by a high-accuracy thermal electronic cooler with a precision of ±0.1 °C. The left side of the Nd:YVO_4 crystal (M1) acted as the input mirror and was anti-reflection (AR)-coated at the pump wavelength (808 nm) and high-reflection (HR)-coated at the fundamental wavelength (1064 nm). The other side of the Nd:YVO_4 crystal was AR-coated at 1064 nm. Meanwhile, the right surface of the PPLN crystal (M2) served as the output mirror and was HR- and AR-coated at 1064 nm and 532 nm, respectively. The left surface of the PPLN crystal (M3) was AR- and HR-coated at

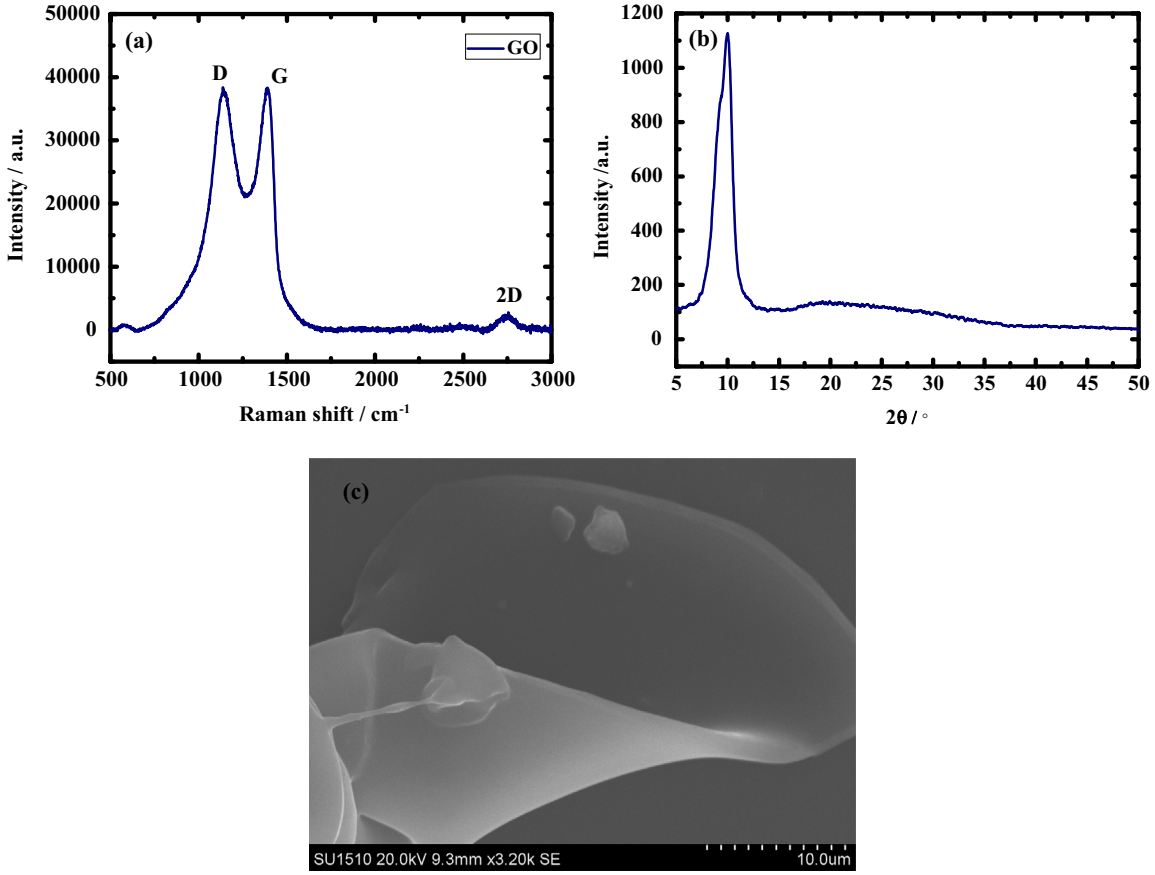

Fig. 1. Characterization of the GO SA. (a) Raman spectrum; (b) XRD; (c) SEM image.