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# Q-switched Nd:YAG channel waveguide laser through evanescent field interaction with surface coated graphene

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We demonstrate a compact passively Q-switched channel waveguide laser based on the interaction of the evanescent-field and the graphene coated surface. The graphene layer is transferred onto the surface of a femtosecond laser inscribed Nd:YAG surface waveguide for a simple integration of the saturable absorber and waveguide structure. The passive Q-switching configuration is based on the evanescent-field interaction with graphene. A 1064 nm pulsed waveguide laser with a maximum repetition rate of 10.4 MHz has been achieved, reaching an output power of 48 mW. The shortest pulse duration of the channel waveguide laser is 52 ns. © *2014 AIP Publishing LLC*.
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The two-dimensional structure of graphene has exhibited a wide range of applications in many attractive fields owing to their rich electronic and optical properties.[1] In photonics, among other applications, graphene has been used for the development of ultrafast lasers since its first demonstration as an efficient saturable absorber (SA) in 2009.[1–4] Compared with semiconductor saturable absorber mirrors (SESAMs) and carbon nanotube saturable absorbers (CNT-SAs), graphene has a larger intrinsic wideband operation extending from the ultraviolet to the far-infrared region. It has been used to generate short pulses with wavelengths ranging from 0.8 $\mu$m to 2.9 $\mu$m in both bulk and fiber laser systems.[5–9] More recently, graphene also showed potential as a key component to achieve a number of integrated optical devices, such as pulsed waveguide lasers, waveguide polarizers, and optoelectronic modulators, due to the polarization dependent absorption and nanometer-scale thickness of graphene.[10–12]

Waveguide lasers possess the advantage of integration with other micro-optic elements, which enable the realization of multi-functional photonic circuits.[13–15] A waveguide structure allows high degree of beam confinement, which in turn results in high irradiances inside the cavity with relatively low powers. Low lasing thresholds are therefore possible, providing the prospect of higher efficiencies compared with the corresponding bulk material laser systems. Several techniques have been applied to produce waveguides in laser gain media,[16–18] width femtosecond (fs) laser inscription emerging as a powerful method to fabricate waveguides with diverse geometries in a wide range of optical materials. The ability to perform three dimensional micromachining, combined with material flexibility of the technology enables high-quality, versatile waveguide production in a wide range of substrates. In crystalline materials, typically, damage tracks passing through the material are fabricated by the fs-laser inscription process, which has a lower refractive index compared to the non-inscribed region. Surrounded by these lower refractive index tracks, the region within the tracks forms the waveguide core. Recently, depressed cladding waveguides produced by fs-laser inscription have attracted considerable interest. In such a configuration, the waveguide core is typically surrounded by a number of fs-laser induced damage tracks with a reduced refractive index.[19–21] Advantages of these cladding structures include the flexibility in the shape of the cladding-core cross-section as well as efficient coupling of waveguide modes and incident light field. In addition, unlike the normal "dual line" waveguides that are buried in the bulk, cladding waveguides could be either surface or buried structures. To date, continuous wave (cw) waveguide lasers have been realized in fs-laser written cladding waveguides in a few laser materials.[6,16,17] By using graphene mirror as SA, mode-locking of fs-laser inscribed glass waveguide lasers has been achieved.[10] Nevertheless, in such a design, since the SAs are inserted between the active waveguide and the resonator mirrors,[11,12] additional intracavity loss is generated through the direct interaction with the SA, which further affects the laser efficiency. Recently, a design for passively Q-switched planar waveguide lasers based on the evanescent-field interaction of surface coated single-wall CNT-SAs was demonstrated, in which a low intracavity loss was introduced.[22–24] In this letter, we propose a graphene-SA based design to realize passive Q-switching of an Nd:YAG channel waveguide laser by evanescent field interaction with surface coated graphene instead of end-face located graphene mirror. Due to the selective absorption of graphene layer on transverse magnetic (TM) polarized light, there are polarization-dependent features with high modulation depth of the pulsed waveguide lasers. Compared with planar waveguides, channel waveguides support 2D confinement of light, which is more suitable for the design of compact integrated photonic devices.

The Nd:YAG (doped by 1 at. % $Nd^{3+}$ ions) crystal was cut into dimensions of $10 \times 10 \times 2\,mm^3$ and optically

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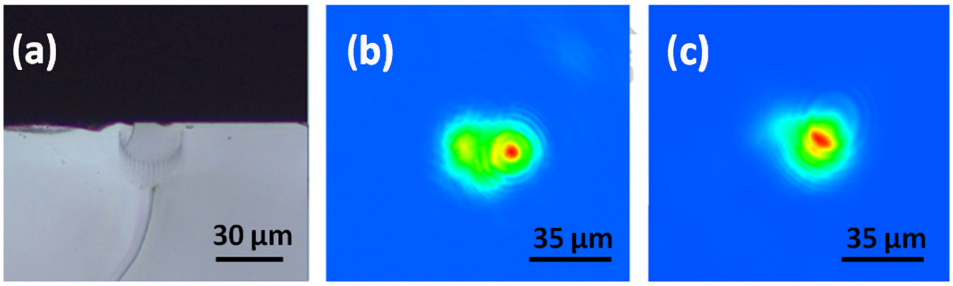


FIG. 1. (a) Optical transmission microscope image of the surface cladding waveguide. Modal profiles of the propagation mode in the waveguide at wavelength of (b) 810 nm and (c) 1064 nm, respectively.

polished. A surface cladding waveguide with a semicircle cross-sectional geometry was produced by fs-laser inscription. The inscription laser was a fiber laser master oscillator power amplifier system (IMRA MicroJewel D400) which provided 460 fs pulses at a repetition rate of 500 kHz. Waveguides were inscribed using a circularly polarized beam. Pulse energies of 160–260 nJ were investigated for the optimization of inscription parameters. The sample was translated through the inscription beam at velocities of 2, 3, and 4 mm/s at each pulse energy resulting in a total of 33 investigated parameter sets. The cross section of the channel waveguide is depicted in Fig. 1(a). Surrounded by a number of low-index tracks, a semi-cladding structure was observed near the surface with the diameter of 30 $\mu$m. The damage tracks form a low-index barrier wall, combined with the substrate-air boundary so that the light was confined in the waveguide near the surface. The mode properties of the channel waveguide structure were studied at the intended pump wavelength of 810 nm. The propagation modes of the waveguide are depicted in Figs. 1(b) and 1(c) at the pump and emission wavelengths of 810 and 1060 nm, respectively. As one can see, this waveguide enabled the guidance of a single mode in the range of near infrared wavelength. At the pump wavelength, the propagation mode was found to be multimode with a propagation loss of 1 dB.cm$^{-1}$ measured by the method mentioned in Ref. 25. For the wavelength of 1064 nm, a single mode operation was observed with a propagation loss of 0.8 dB.cm$^{-1}$. The supported modes were asymmetric due to the semi-circular shape of the waveguide and the strong asymmetry section provided by the substrate-air boundary.

By chemical vapor deposition (CVD) method, graphene layers were manufactured on copper and nickel disks, then transferred onto the surface of the planar waveguide. The Raman spectrum of the graphene layers is shown in Fig. 2(a). As depicted in the Raman spectrum, the G peak and 2D peak can be observed and the intensity ratio of G peak to 2D peak is around 0.82. From Refs. 26 and 27, the thickness of the graphene film is assumed to be 2–4 atom layers. Through the overlap of the graphene layers and the evanescent field of the laser along the waveguide surface, the intensity of the output laser can be modulated.

Figure 2(b) shows the experimental scheme for the passively Q-switched waveguide laser by evanescent-field interaction of light with graphene. The Fabry-Perot resonator cavity consists of the channel waveguide with the cavity mirrors (input and output mirrors) adhered to the end-facets of the waveguide. The input mirror has a high reflectivity at 1064 nm (>99.9%), while the transmission of the output mirror at 1064 nm is ~95%. Both mirrors have a high transmission (>99%) at the pump wavelength at 810 nm. The pump laser was a Ti:Sapphire cw laser (Coherent MBR PE) at 810 nm, which was coupled into the channel waveguide through a lens by the end-coupling method.

Figure 2(c) shows the laser oscillation spectra of the pulsed laser. The evolution of the average laser output as a function of the incident pump power is plotted in Fig. 3(a). The laser has a threshold ~15 mW after which the laser output increased linearly with pump power. For an incident pump power of 476 mW, a maximum output power of 47.2 mW was achieved, leading to a laser slope efficiency of 10%. According to the measured average output power and the repetition rate, the maximum pulse energy within a Q-switched pulse was calculated to be 4.5 nJ.

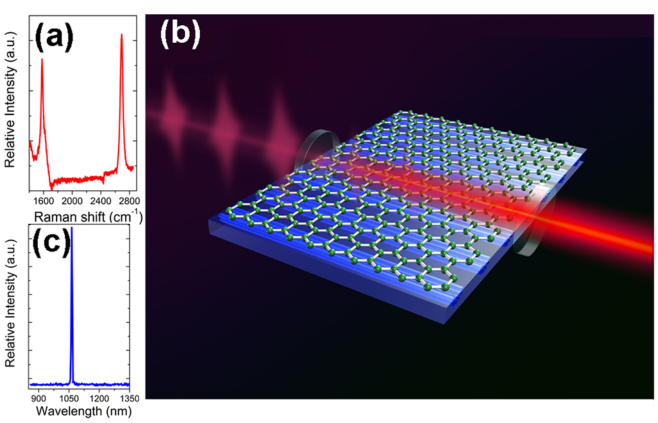


FIG. 2. (a) Raman spectrum of graphene coated on the surface of the waveguide, (b) the experiment setup for the indirect interaction graphene Q-switched waveguide laser generation, and (c) the optical spectra of the graphene Q-switched waveguide laser.

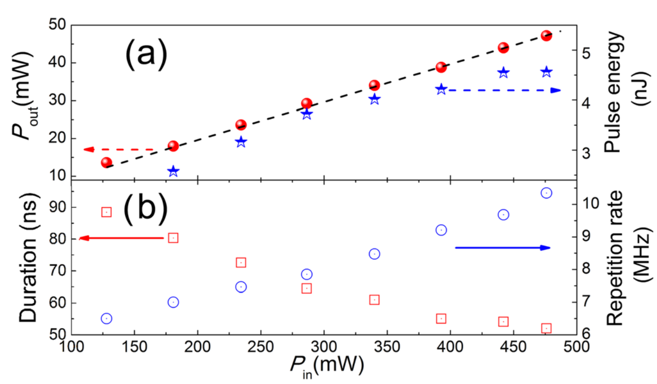


FIG. 3. (a) The average output power and pulse energy vs. launched pump power and (b) pulse width and repetition rate vs. incident pump power.

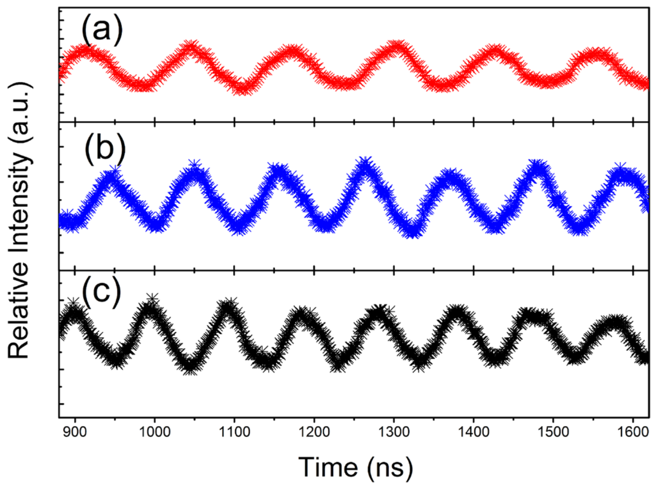


FIG. 4. Pulse profiles of the waveguide laser for pump powers of (a) 289.5 mW, (b) 392.8 mW, and (c) 476 mW, respectively.

The typical oscilloscope trace of the Q-switched laser pulse is shown in Fig. 4 at pump powers of 289.5 mW, 392.8 mW, and 476 mW, respectively. As one can see, the repetition rate increased with increasing pump power and no mode-locking was observed. The variation of the pulse duration and repetition rate for the Q-switched laser are shown in Fig. 3(b). With increasing pump powers, the pulse width decreased with a corresponding increase in the repetition rate, which is typical for a passively Q-switched laser.[28] The shortest pulse duration of the Q-switched pulse laser was found to be 55 ns. For the available range of pump powers, the repetition rate of the pulses increased from 6.5 MHz to 10.3 MHz.

It should be noted that the pulse width is far shorter than typical fiber and bulk Q-switched laser systems (microsecond scale),[29] which could be explained by the following expression:

$$t = \frac{3.54 T_R}{\Delta T}, \tag{1}$$

where $t$ is the pulse width, $T_R$ is the cavity round-trip time, and $\Delta T$ is the modulation depth. In our case, the length of the waveguide is 9 mm, corresponding to $T_R \approx 0.06$ ns. The value of $T_R$ is smaller than most fiber and bulk lasers (more than 1 ns) by several orders of magnitude. Hence it is much easier to obtain shorter laser pulses. Besides, the repetition rate of the Q-switched waveguide laser is much larger—several MHz. The favorable properties demonstrated such as the high repetition rate, short pulse duration, and a compact laser cavity show promise for improvement in the development of future ultrafast laser inscribed waveguide lasers.

In conclusion, Q-switched laser oscillation was demonstrated in a surface channel waveguide based on the evanescent-field interaction of light with graphene SA. The graphene layers were coated directly on the top of the waveguide. The 9-mm-long waveguide laser generated Q-switched pulses with the maximum output power of 48 mW corresponding to a repetition rate of 10.4 MHz and pulse energy of 4.6 nJ.

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