456 mW graphene Q-switched Yb:yttria waveguide laser by evanescent-field interaction

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In this paper we present a passively Q-switched Yb:Y_2O_3 waveguide laser using evanescent-field interaction with an atmospheric-pressure-chemical-vapour deposited graphene saturable absorber. The waveguide, pumped by a broad area diode laser, produced an average output power of 456 mW at an absorbed power of 4.1 W. The corresponding pulse energy and peak power were 330 nJ and 2 W, respectively. No graphene damage was observed, demonstrating the suitability of top-deposited graphene for high-power operation.

Pulsed laser systems are beneficial for applications in areas such as non-linear frequency conversion [1], material processing [2] and medicine [3]. Waveguide lasers offer interesting advantages for such systems including monolithic integrated structures with a natural compatibility with the geometry of high-power diode pump lasers allowing compact devices [4, 5]. Additionally, if propagation losses can be kept low, optical confinement can lead to low laser thresholds, high efficiencies, and low power requirements for passive Q-switching [4-7] or mode-locking [8, 9] via saturable absorbers (SAs).

Pulsed laser deposition (PLD) is a technique that has been used to demonstrate low-loss waveguides for lasing applications [10]. In PLD a pulse from an ultraviolet laser is incident on a target, made of the material to be grown, inside a vacuum chamber. The generated plume of the target material is deposited on a heated substrate allowing epitaxial growth of high-quality films. Recently, PLD has been used to fabricate active waveguides based on thulium [11] and ytterbium (Yb) [12] doped yttria (Y_2O_3). Rare-earth-doped sesquioxide materials, such as yttria, possess physical and spectroscopic properties that make them very interesting for high-power solid-state lasers [13].

We recently reported the Q-switched operation of a PLD-grown Yb:Y_2O_3 waveguide using a graphene-covered output coupler acting as a SA [14]. However, the output power of this laser was limited by damage to the graphene layer, which was in the path of the laser beam. Nevertheless, waveguides also offer the opportunity of coupling the laser beam to the SA via evanescent field coupling [15-17] and this in turn offers the possibility of high-power pulsed operation. Since the adoption of graphene for photonics applications, it has been employed in various fields including ultrafast optics as an SA [18]. It is a very versatile material that is easy to produce and transfer onto a variety of substrates and has a zero bandgap [19]. Such properties allow graphene to be used as an SA [20] for a broad range of wavelengths. Using an Nd:YAG waveguide with evanescent-field coupling to a graphene upper layer, low contrast pulses, with the optical power reducing to ~50% of its peak value between pulses, were observed [21]. These pulses were of ~10 μs duration at repetition rates of tens of kilohertz. More recently, higher contrast pulses have been produced from an Yb:KYW planar waveguide laser with evanescent-field coupling to a graphene layer, delivering 349 ns pulses at an average power of 34 mW [22].

In this paper we present a diode-pumped Q-switched planar waveguide laser, exploiting evanescent-field interaction with a graphene SA, to deliver an average output power of ~0.5 W, giving pulse-durations of 158 ns at a 1470 kHz repetition rate. This was achieved at an absorbed pump power of 4.1 W using a Yb:Y_2O_3 planar waveguide, without damage to the graphene SA as previously encountered with an in-line graphene SA [14].

The fabrication and characterization of the PLD-grown Yb:Y_2O_3 waveguide is similar to that described in [12]. In this case however, the doped-film was grown directly on an yttrium aluminum garnet (YAG) substrate and did not have un-doped cladding layers, and therefore allowed direct access to the laser core from the top surface. The final 8-mm-long, end-polished Yb:Y_2O_3 waveguide had the structure shown in figure 1 and is calculated to support 14 modes with a fundamental mode diameter of 9 μm at the expected lasing wavelength of 1030 nm. The propagation loss of the waveguide was estimated from continuous wave laser experiments before the deposition of the graphene layer at ~1.1 dB/cm.

Graphene grown using atmospheric pressure chemical vapor deposition [23] was used as the SA on the PLD waveguide. The graphene was initially grown on an ultra-flat large-domain copper substrate at 1050°C. A piece of the desired size was then transferred onto the target waveguide using ~300 nm thick poly-(methyl methacrylate) (PMMA) as the support layer, after etching away the underlying copper. After transfer, the waveguide was heated above the glass transition temperature of PMMA to remove any additional stress in the graphene and to flatten it out on the waveguide. The

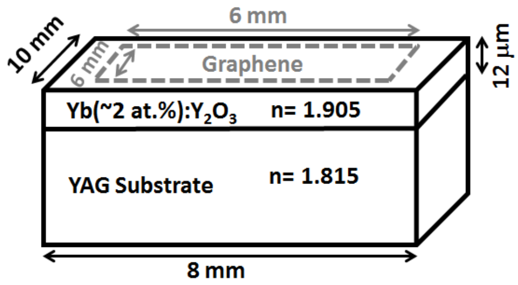

Fig. 1. (Color online) Schematic diagram of the graphene-covered waveguide.

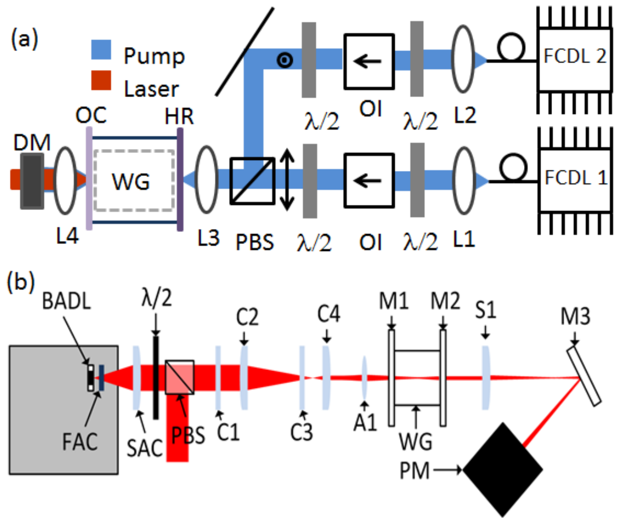

Fig. 2. (Color online) (a) Setup for configuration 1: FCDL- fiber-coupled diode lasers, L1, L2, L3, L4- aspheric lenses, OI-optical isolator, $\lambda/2$- half wave plate, PBS- polarisation beam splitter, HR- high reflectivity mirror, WG- graphene covered waveguide, OC-output coupling mirror, DM-dichroic mirror, (b) Setup for configuration 2: BADL- broad area diode laser, FAC- fast axis collimator, $\lambda/2$- half wave plate, SAC- slow axis collimator, PBS-polarisation beam splitter, C1, C2, C3, and C4- cylindrical lenses, A1- aspheric lens, M1 and M2- thin dielectric mirrors, WG- graphene covered waveguide, S1- spherical lens, M3-dichroic mirror, PM-power meter.

PMMA was then removed by submerging the waveguide in acetone for 10-12 hours. This left graphene covering an area of ~6×6 mm on top of the waveguide, as shown schematically in figure 1.

The graphene-covered waveguide was pumped using two configurations for different average power regimes: using, (1) polarized fiber-coupled single-transverse-mode diodes lasers (FCDLs) with a combined power of 1.1 W and (2) a broad-area diode laser (BADL) delivering up to 6 W incident power. In the first configuration (shown in figure 2 (a)), two FCDLs from 3S Photonics, delivering a maximum output power of 750 mW each at a wavelength of 975 nm, were polarization multiplexed. The output from each fiber was collimated by an f= 8 mm aspheric lens and a combination of a $\lambda/2$-plate and an isolator protected the laser diode from any back-reflections. The output beams from each diode laser were combined by a polarizing beam splitter (PBS) and coupled into the waveguide using an f = 15.3 mm aspheric lens. The laser cavity was formed by end-butting thin (200-µm-thick) mirrors on the end-facets of the waveguide using a fluorinated liquid (Fluorinert FC-70). A high reflectivity (HR) mirror with R>99.9% at the laser wavelength was butted on the input facet and output coupling (OC) mirrors with T=12% and 19.5% were attached to the other end-facet. The output from the waveguide was collimated by an f = 11 mm aspheric lens and the pump and laser beams separated by a dichroic filter.

In configuration 2, shown in figure 2, a BADL (with a 90 µm emitter width) with a central wavelength of 976.5 nm and bandwidth of 4.1 nm was used as the pump source. The BADL was attached to a water-cooled heat sink kept at 25°C and driven at a current of 12 A. The waveguide was adhered to a water cooled copper heat sink held at 19°C using silver paint. Fast- and slow-axis cylindrical lenses were used to collimate the output of the BADL, followed by a half-wave plate and PBS to form a variable attenuator. C1 was a vertically orientated cylindrical f = 25 mm lens, which focused the fast axis and formed an afocal telescope with C3 (f = 130 mm), giving a magnification of 5.2×. For the slow axis, C2 (f = 70 mm) and C4 (f = 10 mm) were cylindrical lenses forming a near afocal telescope reducing the beam size by ~7×. A1 was an f = 15 mm aspheric lens focusing the fast axis to a 4σ diameter of 10 µm and the slow axis to a 4σ diameter of 190 µm. The position of the slow axis focus relative to the fast axis focus was adjusted by tuning the spacing of lenses C2 and C4. The spacing was selected such that the slow axis beam waist was positioned 2 mm after the fast axis waist in free space corresponding to a slow axis focus at approximately the longitudinal centre of the waveguide. S1 was a spherical lens of f = 25 mm and M3 was a dichroic mirror with high transmission (HT) for <1000 nm and HR for 1020-1050 nm (at an angle of 30°) rejecting unabsorbed pump, and PM was a thermal power meter. M1 and M2 were similar dielectric mirrors to those used in configuration 1, with M1 being the HR mirror and M2 being the OC mirror. The laser output was incident on a DET-10 detector (Thor Labs) and the Q-switched operation was observed on a 1 GHz digital oscilloscope (Agilent MSO6104A).

For configuration 1, the combined pump beam was focused to a $1/e^2$ diameter of 12.6 µm at the input facet of the waveguide. Using the 12% OC, a maximum output power of 85 mW was obtained at an absorbed pump power of 1052 mW and the slope efficiency was determined to be 16.2%. Figure 3 shows the average output power, repetition rate, pulse energy and duration versus absorbed power for both of the output couplers. The Q-switched pulse repetition-rate increased from 912 kHz to 1282 kHz on increasing the pump power from 778 mW to 1052 mW and the pulse duration decreased from 235 ns to 121 ns. The pulse profile and the pulse train at maximum power are shown in figure 4. The pulse to pulse power had a standard deviation of 6%. The calculated pulse energies were found to increase from 43 nJ to 63 nJ on increasing the pump power. Replacing the 12% OC with a 19.5% mirror, Q-switched operation was observed at a pump power of 778 mW and an output

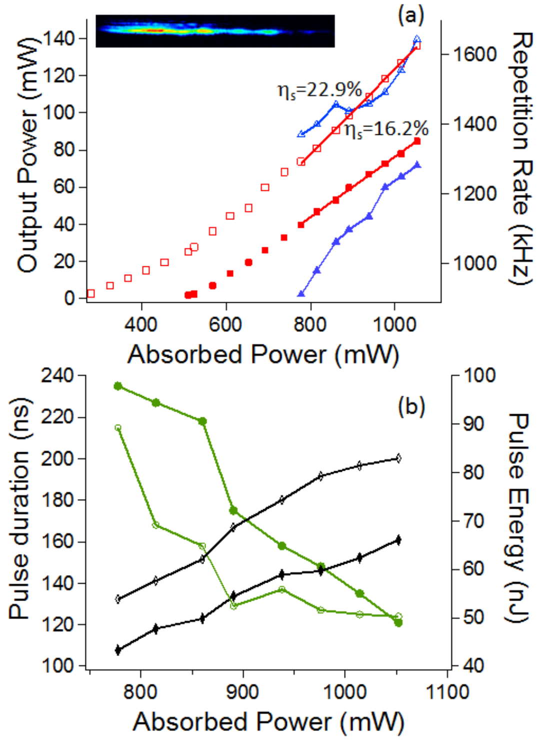

Fig. 3. (Color online) (a) Output power (square) and repetition rate (triangle) vs. incident power and (b) pulse duration (circle) and pulse energy (diamond) vs. incident power for the graphene-covered WG in configuration 1. Solid markers- 12% OC, open markers- 19.5% OC. Inset: measured mode profile.

power of 136 mW was obtained at the maximum pump power. The laser emitted preferentially in the TM polarisation. The slope efficiency was 22.9%, which was considerably higher than with the 12% OC, highlighting the relatively high cavity losses of the device. The repetition-rate increased from 1370 kHz to 1640 kHz and the pulse duration decreased from 215 ns to 124 ns on increasing the pump power. The pulse energies were found to increase from 54 nJ to 83 nJ. When compared to a Yb:Y_2O_3 waveguide laser [14] which was Q-switched with graphene end-butted on the waveguide and pumped by one single-mode diode, the pulse energy is found to have increased by more than 6 times, demonstrating the advantage of the evanescent-coupled graphene-covered waveguides for higher power operation. Also, due to the quasi-monolithic cavity configuration, there was no decrease in the performance due to misalignment of the mirror or the waveguide [24] as was observed in [14]. The measured mode profile is shown in the inset of figure 3 (a) and the 4σ mode diameter was found to be 9 µm in the guided direction.

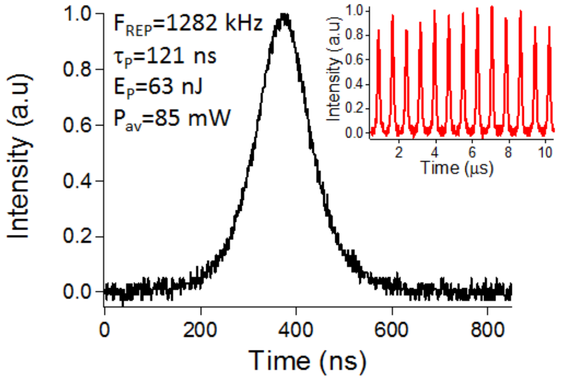

Fig. 4. (Color online) (a) Measured pulse profile and (inset) the corresponding pulse train at an output power of 85 mW using the 12% OC.

With the same cavity consisting of the HR mirror and the 12% OC end-butted on the waveguide using Fluorinert FC-70 and using configuration 2, the output power increased and the repetition-rate reduced slightly, as can be seen in figure 5 (a). The lasing threshold was found to be at an absorbed power of 1.33 W. On increasing the pump power to 2.8 W, the output power increased to 123 mW and Q-switched operation was observed to start. The pulse duration was measured to be 270 ns and the corresponding repetition-rate was 934 kHz. An output power of 261 mW was obtained at the maximum absorbed pump power of 4.1 W, and the slope efficiency was found to be 12.6%. The slightly decreased slope efficiency compared to configuration 1 may be attributed to the larger mode-size in the unguided plane, which sampled more of the structural variation in the waveguide [12]. Essentially this is expected to increase the total loss encountered by the mode. The repetition-rate increased to 1149 kHz at the maximum pump power and the lowest pulse duration observed for this configuration was 160 ns. The pulse energies were found to increase from 132 nJ to 227 nJ on increasing the pump power from 1.33 W to 4 W. The pulse duration and pulse energy as a function of

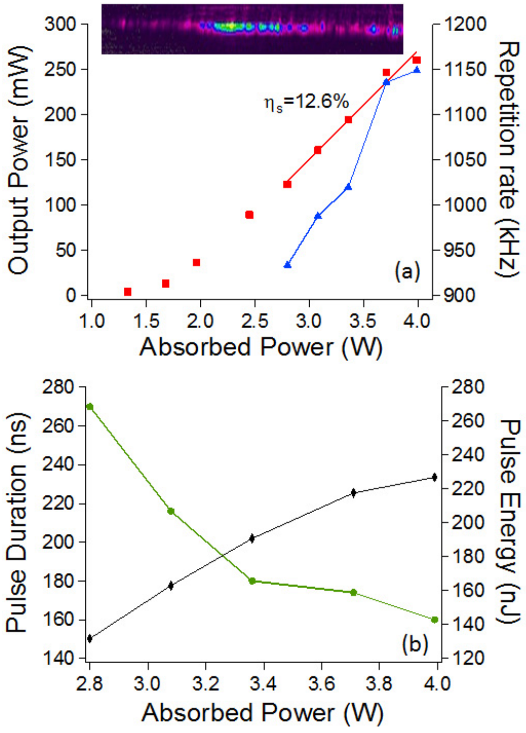

Fig. 5. (Color online) (a) Output power (square) and repetition rate (triangle) vs. incident power and (b) pulse duration (circle) and pulse energy (diamond) vs. incident power for the graphene-covered WG in configuration 2. Inset: measured mode profile.

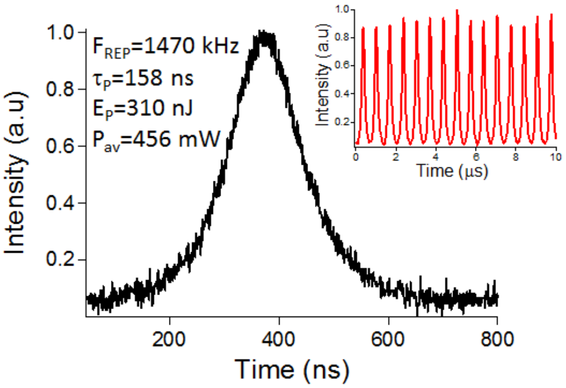

Fig. 6. (Color online) (a) Measured pulse profile and (inset) the corresponding pulse train at an output power of 456 mW using the 19.5% OC.

absorbed power are shown in figure 5 (b). The absorption was calculated from the balance of incident and transmitted power measured at laser threshold, determined to be 70%. This was as expected owing to the broad emission spectrum of the BADL in comparison to the absorption bandwidth of the zero-phonon line of $Yb:Y_2O_3$. The measured mode profile is shown in the inset of figure 5 (a) and the 4σ mode diameter was found to be 10 μm in the guided direction. The mode is not uniform in the un-guided direction due to the striations in the $Yb:Y_2O_3$ film as discussed in [12].

When the 12% OC was replaced by the 19.5% OC, the output power increased to 456 mW at the maximum pump power. Q-switched operation was observed with pulse duration of 158 ns at a repetition-rate of 1470 kHz as seen from figure 6. The pulse to pulse power had a standard deviation of 4%. The peak power was calculated to be 1.96 W and the pulse energy 310 nJ. On reducing the pump power, Q-switching was only observed by realigning the cavity, which was most likely due to thermal effects. Better heat removal from the waveguide should allow stabilized operation at different power levels. No damage to the graphene was observed at such high pump powers and an improvement of more than 25 times in average power and pulse energy was observed when compared to previous work using end-butted graphene [14] demonstrating the capability of evanescent-field interaction with graphene for high-power operation.

In conclusion, we have demonstrated a high-power Q-switched $Yb:Y_2O_3$ planar waveguide laser using evanescent-field interaction with graphene. Using single-mode pump diodes, an output power of 136 mW and pulse energy of up to 83 nJ was obtained in pulses of 120 ns duration, with a slope efficiency of 23% with respect to absorbed power. On pumping with higher-power broad area diode lasers, an average output power of 456 mW and pulse energy of 310 nJ was obtained in 160 ns pulses, which is the highest power and pulse energy to be obtained from any graphene Q-switched waveguide laser. No damage to the graphene at these powers was observed, paving the way for the realisation of multi-Watt, multi-μJ systems using higher-power pump diodes.

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