Graphene Q-switched mode-locked waveguide laser operating at 1535 nm

Amol Choudhary,[1*] Shonali Dhingra,[2] Brian D'Urso,[2] Pradeesh Kannan,[1] and David P. Shepherd[1]
[1]*Optoelectronics Research Centre, University of Southampton, Southampton, SO17 1BJ, United Kingdom*
[2]*Department of Physics and Astronomy, University of Pittsburgh, Pennsylvania 15260, USA*
**Author e-mail address:* a.choudhary@soton.ac.uk

Abstract: A diode-pumped Er,Yb:glass waveguide laser, Q-switched mode-locked using a graphene saturable absorber is presented. Mode-locked pulses at a repetition rate of 6.8 GHz are achieved at an output power of 27 mW and a wavelength of 1535 nm.
OCIS codes: (140.4050) Mode-locked lasers; (230.7380) Waveguides, channeled; (140.3480) Lasers, diode-pumped; (140.3500) Lasers, erbium

1. Introduction

Ultrafast lasers with multi-GHz repetition rates can have applications in medicine, optical frequency metrology, optical sampling and in the calibration of astronomical spectrographs. However, development of such high-repetition-rate lasers poses a technological challenge owing to the reduction in the optical length of the cavity. Solid-state waveguide lasers with integrated saturable absorber elements are suitable candidates to realize such GHz laser systems because of the possibility of having very small and compact systems. Additionally, such devices have the advantage of ease of fabrication and mass-production using standard photonic foundry techniques. Other advantages include a low laser and mode-locking threshold owing to the small mode sizes and a thin-slab configuration allowing good thermal management which is advantageous for power scaling. Recently, several mode-locked waveguide laser systems have been demonstrated [1-3] in the 1-1.5 μm spectral window using semiconductor saturable absorber mirrors (SESAMs) with repetition rates as high as 15 GHz [2] being achieved. However, SESAM fabrication can be relatively expensive and the resulting bandwidth of operation of the device is quite limited.

Graphene has recently emerged as an interesting alternative for use as a saturable absorber [4] and has the advantage of having a wide wavelength band of operation and being easy and relatively low-cost to fabricate. Recently, graphene has been used to demonstrate Q-switch mode-locking [5, 6] in waveguide lasers.

In this paper we present, to the best of our knowledge, the first waveguide laser Q-switched and mode-locked by a graphene saturable absorber in the 1.5 μm spectral window. The mode-locked repetition rate was measured to be 6.8 GHz at a wavelength of 1535 nm. The repetition-rate of the Q-switched pulse envelope was found to increase from 344 kHz to 526 kHz on increasing the pump power from 206 mW to 612 mW. A maximum average output power of 27 mW was obtained at maximum pump power.

2. Experimental details

The waveguides were fabricated in an Er^{3+},Yb^{3+}-doped phosphates glass (IOG-1, Schott) using ion-exchange [1] using a mask with channel openings with widths of 1 μm -10 μm in steps of 0.2 μm. Following the fabrication steps [1], the waveguide sample was polished to a length of 14.5 mm.

The graphene film was grown on a 1-inch-diameter, diamond-turned copper substrate using atmospheric pressure chemical vapour deposition (APCVD) [7]. Following which a PMMA layer was spin-coated on the graphene. After etching the copper, the graphene was transferred on to a fused silica substrate [8], which had a dielectric coating with transmission (T)= 95% at the pump wavelength (975 nm) and T=2% at the laser wavelength (1535 nm). Finally, the PMMA was removed from the graphene-coated output coupler (GOC) using acetone. Single-layer graphene growth was confirmed by the location and shape of the 2D and G peaks in the Raman spectrum (Figure 1 (a)). Also, the transmission spectra of the output coupler (OC) and the GOC were measured using a Cary 500 spectrophotometer and are shown in figure 1 (b). There is a decrease of ~2.3% in the transmission of the GOC due to the graphene layer, which is also consistent with single-layer growth [5].

The Er,Yb:glass waveguide was pumped by a fibre-coupled single-mode laser-diode operating at a central wavelength of 975 nm and delivering a maximum power of 750 mW. The pump was collimated by an f=8 mm aspheric objective after which a half-wave plate and a Faraday isolator were installed to stop back-reflections from damaging the laser diode. A f=15.4 mm aspheric lens, forming a spot of radius 6.4 μm at the waveguide facet was used to efficiently launch into the waveguide fabricated using a channel opening of ~7 μm. The output from the waveguide laser was collimated by an f=11 mm aspheric lens and a dichroic mirror separated the pump and laser beams. The laser cavity was formed by directly butting a 200-µm-thick mirror with T=94% at 975 nm and R>99.9% at 1535 nm at the input facet and the GOC, held on a manipulation stage, was butted to the output facet.

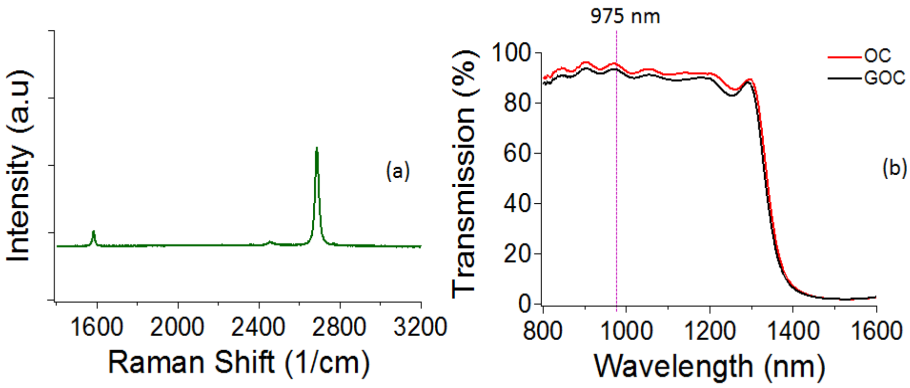

Fig. 1. (a) Raman spectrum measured for GOC at an excitation wavelength of 532 nm, and (b) spectrophotometer traces for the OC and GOC.

3. Results

The GOC was aligned with respect to the Er,Yb:glass waveguide by controlling the separation between the waveguide and the GOC and the tip and tilt. The laser output was focused on a fast detector (12.5 GHz), which was connected to an RF spectrum analyser. The RF spectrum was found to be centred at 6.8 GHz and is shown in figure 2 (a). The peak at 6.8 GHz is broad when compared to a CW mode-locked waveguide laser [3], which is expected for Q-switched mode-locked pulses [5, 9]. The output from the fast detector was then connected to a 50 GHz scope and the measured train of pulses contained within the Q-switched envelope is shown in figure 2 (a). The measured repetition-rate is in good agreement with the 6.8 GHz measured in the RF spectrum. The output spectrum was measured by an optical spectrum analyser and is shown in figure 2 (c). The spectrum is centred on 1535.6 nm and has a bandwidth of 0.44 nm.

The repetition-rate of the Q-switched envelope was measured and was found to increase from 344 kHz to 526 kHz on increasing the pump power from 206 mW to 612 mW. A maximum average output power of 27 mW was obtained at the maximum pump power and the slope efficiency was measured to be 5%. The repetition rate and output power against the incident pump power is shown in figure 3 (a). The measured pulse profile at an incident power of 612 mW is shown in figure 3 (b) and it can be seen that the full width at half maximum (FWHM) pulse duration is 120 ns. The Q-switched pulse train is also shown in the inset, and the repetition rate was measured to be 526 kHz.

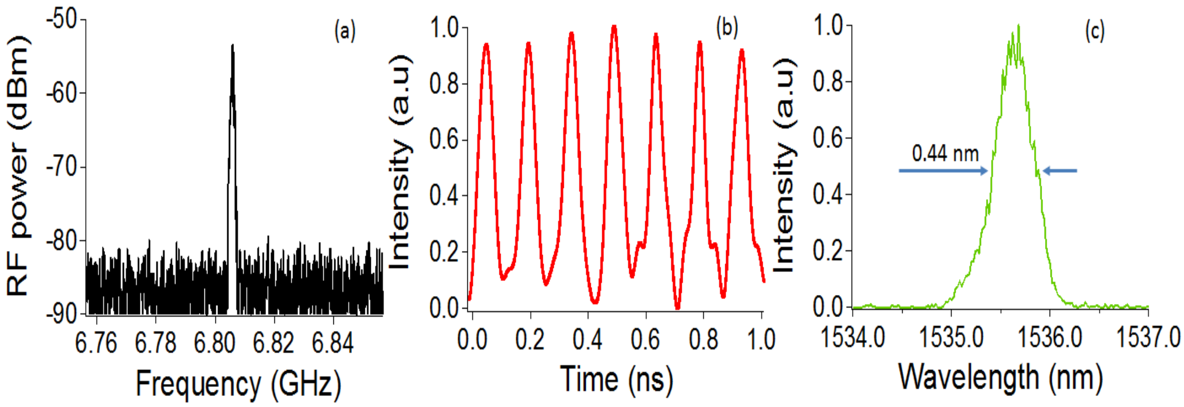

Fig. 2. (a) Radio Frequency spectrum, (b) measured pulse train, and (c) optical spectrum of the waveguide laser.

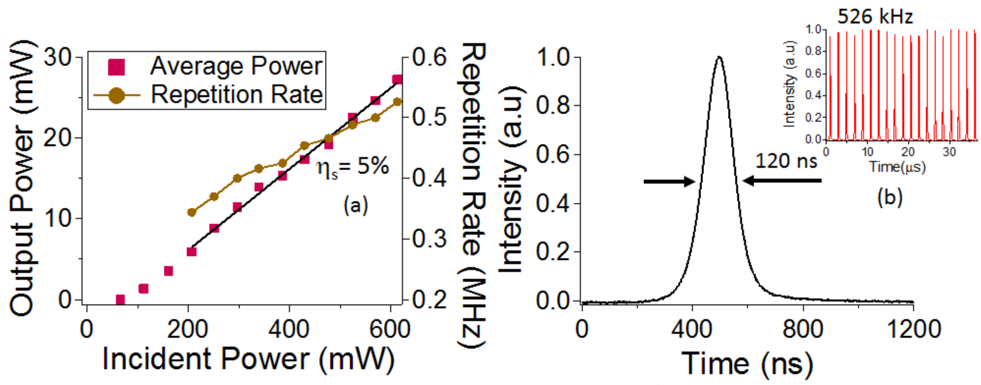

Fig. 3. (a) Output power and Repetition rate vs. Incident power, and (b) measure pulse profile and pulse train (inset) at an incident power of 612 mW.

4. Conclusions

In conclusion, we have demonstrated the first, to the best of our knowledge, 1.5 μm Q-switched mode-locked waveguide laser using a graphene saturable absorber. This is also the first mode-locking result in an ion-exchanged waveguide using graphene. Single-layer graphene was grown using atmospheric pressure chemical vapor deposition on an output coupling mirror. An Er,Yb:phosphate glass waveguide laser was formed by end-butting a thin dielectric mirror on one end and the graphene-coated output coupler mirror on the other. This compact 14.5-mm-long cavity generated mode-locked pulses at a repetition-rate as high as 6.8 GHz. The repetition-rate of the Q-switched envelope was found to increase from 344 kHz to 526 kHz and a maximum output power of 27 mW was obtained at maximum pump power. The Q-switched envelope had a pulse width of 120 ns at maximum pump power. Such compact devices can have various applications ranging from medicine to defense. Future work would include power scaling of these devices using master oscillator power amplifier (MOPA) configurations.

5. References

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