# Graphene Q-switched Mode-locked and Q-Switched Ion-exchanged Waveguide Lasers

Amol Choudhary, Shonali Dhingra, Brian D'Urso, Pradeesh Kannan, and David P. Shepherd

*Abstract*— **In this paper, we present the use of mono-layer graphene saturable absorbers to produce Q-switched and Q-switched mode-locked operation of Yb and Yb:Er-doped phosphate glass waveguide lasers, respectively. For the 1535-nm-wavelength Yb:Er laser, the Q-switched pulses have repetition rates up to 526 kHz and contain mode-locked pulses at a repetition frequency of 6.8 GHz. The measured 0.44 nm bandwidth should allow pulses as short as ~6ps to be generated. Maximum average output powers of 27 mW are obtained at a slope efficiency of 5% in this mode of operation. For the 1057-nm-wavelength Yb laser, Q-switched pulses are obtained with a repetition rate of up to 833 kHz and a maximum average output power of 21 mW. The pulse duration is found to decrease from 292 ns to 140 ns and the pulse energy increase from 17 nJ to 27 nJ as the incident pump power increases from 220 to 652 mW.**

*Index Terms*—**Erbium, femtosecond pulse, high repetition rate, solid-statelaser, optical pulses,optical waveguides,ytterbium.**

## I. INTRODUCTION

PULSED laser systems can have numerous applications in medicine [1], industrial material processing [2], optical frequency metrology [3], astronomy [4] and optical telecommunications [5]. Sources have been developed with pulse durations in the femtosecond and picosecond regimes using mode-locking techniques and with pulses in the nanosecond and microsecond regime using Q-switching. Saturable absorbers are one of the most common elements used to generate optical pulses. They can cause a modulation in the loss in the laser cavity that creates a short window where the gain is greater than the loss leading to the formation of a pulse. Semiconductor saturable absorber mirrors (SESAMs) [6] are one of the most widely used saturable absorbers and consist of a semiconductor saturable absorber layer combined with a semiconductor Bragg structure, which forms the mirror. However, the fabrication of SESAMs requires the use of molecular beam epitaxy and the wavelength range of operation is limited by the semiconductor bandgap. In contrast, fabrication of graphene saturable absorbers is relatively low-cost and simple and they can operate over a broad range of wavelengths making them promising candidates for use as saturable absorbers [7].

Diode-pumped solid-state waveguide lasers have several key features [8] that make them good candidates for pulsed laser systems such as a low laser threshold, and high slope efficiency (as long as the passive losses are kept low), good thermal management allowing high average power operation, reduced mode-locking threshold owing to the reduced mode-sizes in the gain media and on the saturable absorber, compactness and integration, and possibility of mass-production using photonic clean-room techniques. Indeed, mode-locked waveguide lasers have been demonstrated using SESAMs [9-12], obtaining a repetition rate as high as 15 GHz [10] from an integrated ion-exchanged waveguide laser. Ion-exchange is a versatile technique for producing low-loss waveguides and is compatible with photonic mass-production techniques. Q-switched waveguide lasers have been demonstrated using a variety of saturable absorbers [13-17] including graphene [17]. However, there have been limited reports of graphene mode-locked waveguide lasers, with femtosecond-written waveguide lasers generating Q-switched mode-locked pulses [18, 19]. In this paper we demonstrate the first, to the best of our knowledge, Q-switched mode-locked integrated waveguide laser operating in the 1.5 μm spectral window with a repetition-rate of 6.8 GHz. A Q-switched Yb-doped ion-exchanged glass waveguide laser is also demonstrated and together these are the first pulsed waveguide laser results based on the widely used ion-exchange waveguide-fabrication technique using graphene as a saturable absorber.

## II. FABRICATION DETAILS

The channel waveguides were fabricated via standard photolithographic techniques in commercially available Schott IOG-1 phosphate glasses using ion-exchange as outlined in detail in [9]. For the 1.5 μm experiments the glass was doped with 1.16 wt.% erbium (Er) and 4.77 wt.% ytterbium (Yb) and for the 1 μm experiments the glass was doped with 12 wt. % ytterbium (Yb). The samples were kept in the ion-exchange furnace at a temperature of 325°C for 10 minutes for the $Yb^{3+}$-doped glass and for 30 minutes for the $Er^{3+}$, $Yb^{3+}$-doped glass to form single-mode waveguides at the lasing wavelength. During the ion-exchange the $Na^+$ ions within the glass matrix were exchanged with the $K^+$ and $Ag^+$ ions in the melt, which caused a local increase in the refractive index (.0066 and .0051 for the Yb:IOG-1 and Er.Yb:IOG-1, respectively) allowing waveguiding. The $Er^{3+}$, $Yb^{3+}$-doped glass was

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polished to a length of 14.5 mm and the $Yb^{3+}$-doped glass was polished to a length of 17.8 mm. These relatively long lengths allow almost complete absorption of the pump light and restrict the mode-locking repetition frequency to <10 GHz such that a relatively low mode-locking threshold may be achieved [20]. The single-layer graphene was grown by atmospheric pressure chemical vapor deposition (APCVD) on 1-inch-diameter ultra-flat diamond-turned large-domain copper substrates at 1050°C [21], following which the graphene layer was transferred onto 1-mm-thick substrates [22]. The two substrates used for graphene transfer were fused-silica with dielectric coatings, with both having a high transmission (T) at the pump wavelength (975 nm) and one having T=2% at 1057 nm and the other having T=2% at 1535 nm. The versatility of graphene is demonstrated by the fact that the same graphene layer was transferred onto desired mirrors for operation at 1 μm and 1.5 μm reducing complexity and fabrication cost of the saturable absorber. The measured Raman spectra at 532 nm for both the graphene-coated output couplers (GOC) are shown in figure 1 (a). Two distinct peaks can be discerned from the figure: the 2D peak at 2687 $cm^{-1}$ and the G peak at 1584 $cm^{-1}$. The position of the peaks and the Lorentzian shape of the 2D peak indicate presence of single-layer graphene on the GOCs [23]. The transmission spectra of the GOCs and non-graphene-coated output couplers (OCs) measured using a Cary 500 spectrophotometer (Varian Ltd, UK) are shown in figure 1 (b). A ~2.3% decrease in transmission due to the graphene layer can be seen at 975 nm, consistent with the existence of a single-layer graphene [18]. It can also be seen that the transmission at 532 nm is 5% and 50% for the 1.5 micron GOC and 1 micron GOC, respectively. This results in an increase in the excitation of the graphene by the 532 Raman pump for the 1.5 micron GOC thus resulting in a better signal to noise ratio when compared to the 1 micron GOC as is evident from figure 1 (a).

## III. EXPERIMENTAL SETUP

For both the laser experiments, the glass waveguides were pumped by a single-transverse-mode, fibre-coupled laser diode with a maximum output power of 750 mW at a central wavelength of 975 nm (3S photonics). The pump output was collimated by an aspheric lens with a focal length, f = 8 mm and was efficiently launched into the waveguide using an aspheric lens with f = 11 mm for pumping the $Yb^{3+}$-doped glass waveguide and f = 15.4 mm for the $Er^{3+}$, $Yb^{3+}$-doped glass waveguide, making waist radii of 4.4 μm and 6.4 μm, respectively. A half-wave plate and an optical isolator were introduced after the collimating lens to prevent feedback into the laser diode. The laser cavity was formed by end-butting a 200-μm-thick high reflectivity (HR) mirror on the input facet of the waveguide with R>99.9% at 1057 nm and T>99.9% at 975 nm for the 1 μm experiments, and R>99.9% at 1535 nm and T=94% at 975 nm for the 1.5 μm experiments. The waveguides were mounted on a Peltier-cooled copper block kept at a temperature of ~16°C. The respective OCs or GOCs were end-butted on the waveguide using a fluorinated liquid (Fluorinert FC-70, 3M) in order to construct the waveguide laser cavity for continuous wave (CW) and pulsed operation. The output from the waveguide laser was collimated by an aspheric lens with f = 11 mm and a dichroic mirror was used to separate the laser and the pump beams.

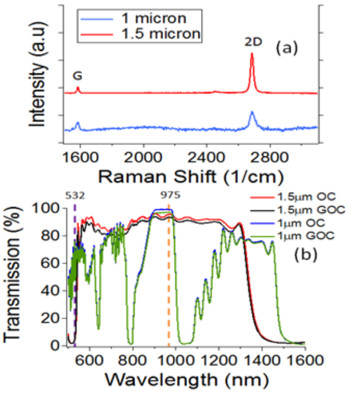

Fig. 1.(a). Raman spectra for the GOCs. Red- 1.5 μm GOC, Blue- 1 μm GOC. The spectrum measured for the 1 μm GOC has been magnified to show more detail, and (b) the measured transmission spectra for the 1.5 μm OC (red), 1.5 μm GOC (black), 1 μm OC (blue) and 1 μm GOC (green).

## IV. CW CHARACTERIZATION

The CW operation of the Er, Yb-doped glass waveguide fabricated with a mask opening width of ~7 μm was characterized for laser resonators with 200-μm-thick OC mirrors with T=2% and T=4%. The diffusion depth was measured to be 6.9 μm for the Yb:IOG-1 waveguide and 14.6 μm for the Er,Yb:IOG-1 glass. The incident power was measured just before the waveguide and the slope efficiencies are reported with respect to the incident powers. With the 2% OC, a maximum output power of 55 mW was obtained at a slope efficiency of 9.7%. With the 4% OC, the maximum output power was found to increase to 74 mW and the slope efficiency was measured to be 13.2%. 200-μm-thick OCs with T=2% and T=5% were used to characterize CW performance of the Yb-doped glass waveguide fabricated with an ion-exchange mask opening width of ~5 μm. Maximum output powers of 86 mW and 183 mW were obtained for the 2% OC and 5% OC, respectively, with corresponding slope efficiencies of 15.8% and 29.5%. The output power against incident power for both the waveguides using different OCs is shown in figure 2. From the measured slope efficiencies the losses are estimated to be <0.5 dB/cm in agreement with previously fabricated ion-exchanged waveguides [9-11].

## V. MODE-LOCKING AT 1.5 MICRON

After the CW characterization of the Er,Yb-phosphate glass waveguide, the OC was replaced by the 1.5 μm GOC, which was held on a 3-axis mount with tip and tilt control for the mode-locking experiments. The GOC was aligned with respect to the waveguide by controlling the gap and the tip and tilt in order to allow efficient laser operation. A fluorinated liquid (Fluorinert FC-70) was used between the waveguide facets and the mirrors. The output from the waveguide laser was focused on a 12.5 GHz detector (818-BB-35 from

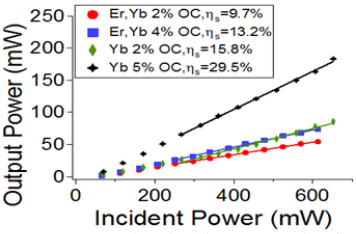

Fig. 2.Average output power against incident power for the Er,Yb:phosphate glass waveguide laser and Yb:phosphate glass waveguide laser for different OCs during CW operation.

Newport), which was connected to an RF spectrum analyzer. The measured RF spectrum, centered on 6.8 GHz, is shown in figure 3 (a). It can be seen that the peak is relatively broad in comparison to a CW mode-locked waveguide laser [10], which is consistent with Q-switched mode-locked pulses [18, 24]. The output from the detector was then connected to a 50 GHz oscilloscope and the measured pulse train is shown in figure 3 (b). It can be seen that the pulses have a repetition rate in agreement with that measured in the RF spectrum. The slightly distorted pulse shape can be attributed to electronic ringing effects of the detector. The Q-switched envelope was also measured and the repetition rate was found to increase from 344 kHz to 526 kHz on increasing the pump power from 206 mW to 612 mW as seen from figure 4 (a). A maximum output power of 27 mW was obtained at a pump power of 612 mW and the slope efficiency was measured to be 5%. The output spectrum is centered at a wavelength of 1535 nm and has a bandwidth of 0.44 nm as seen from figure 4 (b). We were unable to obtain an autocorrelation of these pulses but if they are transform limited, as found in previous SESAM mode-locking experiments [12], we would expect pulses of around 6 ps duration.

## VI. Q-SWITCHING AT 1 MICRON

For the Yb-phosphate glass waveguide pulsed laser experiments, the OCs were replaced by the 1 µm GOC. The output from the waveguide was incident on a DET-10 photodiode (Thor Labs), which was connected to an oscilloscope. On increasing the pump power to 70 mW, CW operation was initially observed, followed by Q-switched operation at an incident power of 220 mW. The average output power at the threshold for Q-switching was 7 mW, and the measured repetition rate was 392 kHz, from which the pulse energy was calculated to be 17 nJ. The full width at half maximum (FWHM) pulse duration was measured to be 292 ns. The plots of output power and repetition rate against incident power are shown in figure 5 (a). It can be seen that at the maximum pump power of 652 mW, the average output power was found to be 21 mW and the slope efficiency was measured to be 3.2%. The wavelength of operation was 1057 nm. The maximum repetition rate was observed at a pump power of 606 mW and was measured to be 833 kHz. The shortest pulses were measured to be 140 ns and the highest pulse energy was measured to be 27 nJ at a pump power of 652 mW as seen from figure 5 (b). The evolution of the repetition rate and the pulse duration were as expected [16]. The Q-switched pulse and the corresponding pulse train measured at the maximum pump power are shown in figure 6. The power was found to vary by 6% over time, as there was no active stabilisation in the cavity.

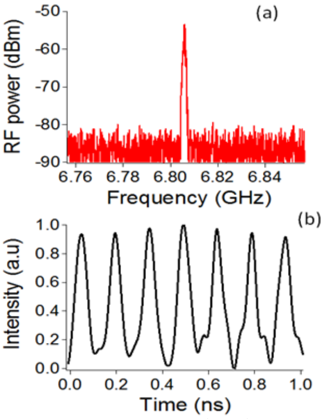

Fig. 3.(a) Radio Frequency spectrum for the Q-switched mode-locked waveguide laser centered on 6.8 GHz, and (b) the mode-locked pulse train measured using a fast oscilloscope corresponding to a repetition frequency of 6.8 GHz.

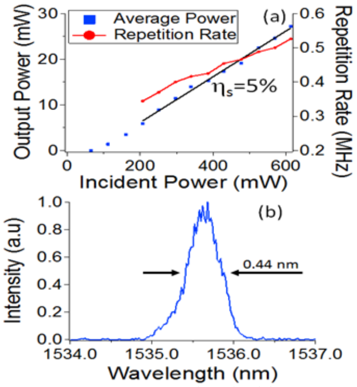

Fig. 4.(a) The average output power against incident power and measured Q-switched repetition rate, and (b) measured optical spectrum during Q-switched mode-locked operation.

We were unable to demonstrate mode-locked behavior in this system, which we believe is due to the lower output power of the Yb-phosphate glass waveguide laser, and hence lower power on the saturable absorber, in comparison to the Er,Yb-phosphate glass laser and possibly due to higher non-saturable losses for the 1 micron GOC. The reduced slope efficiency in comparison to the CW operation can be attributed to the added losses due to 1) the non-saturable losses of the graphene layer and, more significantly, due to 2) the misalignment between the waveguide and the GOC [25].

## VII. CONCLUSION

In conclusion, we have demonstrated for the first time, to the best of our knowledge, a Q-switched mode-locked waveguide laser using a graphene saturable absorber in the 1.5 µm spectral regime. Waveguides were fabricated using ion-exchange in a commercially available Er,Yb-doped phosphate glass and a very compact laser cavity was formed resulting in the generation of mode-locked pulses at a repetition-rate of 6.8 GHz. A maximum average power of 27 mW was obtained and the Q-switched envelope had a maximum repetition rate of 526 kHz. The intra-cavity intensity was not enough to support continuous wave mode-locking owing to the high repetition-rate, which is more than an order of magnitude higher than the sub-100 MHz observed in bulk laser cavities. Such devices can have

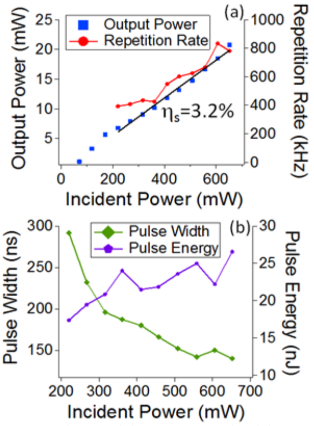

Fig. 5.(a) Output power and repetition rate vs. incident power, and (b) Pulse width and pulse energy vs. incident power for the 1057 nm Q-switched waveguide laser.

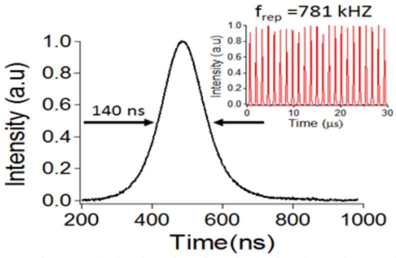

Fig. 6.The measured Q-switched pulse for the Yb:Phosphate glass waveguide laser at maximum pump power. Inset: the measured pulse train.

various applications in non-linear frequency conversion and micromachining. Using ion-exchange, a waveguide was also fabricated in an Yb-doped phosphate glass waveguide, which was Q-switched using a graphene coated output coupler at a wavelength of 1057 nm. Pulses as short as 140 ns were obtained at an average output power of 21 mW at a repetition rate of 781 kHz resulting in a maximum pulse energy of 27 nJ. We believe these to be the first pulsed ion-exchanged waveguide lasers using graphene saturable absorbers. Future work would include power-scaling using master oscillator power amplifier configurations.

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