An experimental demonstration of a passively mode-locked laser using an integrated graphene saturable absorber.

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Abstract

Graphene has many promising properties for use as a saturable absorber in mode-locked lasers, such as a low saturation power, a broad optical bandwidth and a fast carrier recombination time. Passively mode-locked lasers using graphene saturable absorbers have been demonstrated, but the graphene integration methods used require complex manufacturing steps and do not support mass-production of these devices. In this paper we demonstrate experimentally that an integrated graphene saturable absorber on a silicon waveguide can passively mode-lock a hybrid laser. This integrated graphene saturable absorber was manufactured on wafer-scale, demonstrating that this graphene integration approach is a reliable and scalable method for manufacturing graphene saturable absorber assemblies for both integrated and fibre based passively mode-locked lasers.

I. Introduction

Mode-locked lasers generate optical pulse-trains which produce a large number of equally spaced laser lines locked together in phase and frequency. This type of laser is beneficial for many applications such as for telecom systems, gas spectroscopy and biomedical applications [1]–[3]. Optical pulses inside the cavity are formed through loss and/or gain modulation inside a laser cavity at an integer multiple of the roundtrip time [4]. This can be achieved either through active mode-locking, in which the loss or gain is electrically modulated resulting in pulses forming inside the cavity, or by using a passive mode-locking regime in which a saturable absorber (SA) modulates the loss inside the cavity.

Saturable absorption is a nonlinear effect where the optical transmission of a SA increases with an increase in optical power. A pulse passing through a SA saturates its absorption resulting in a short window where the loss inside the cavity is reduced, which in turn favours the pulse's propagation. There are various approaches to making saturable absorbers. The most common SA assemblies used in passively mode-locked lasers at the time of writing are based on semiconductor devices, with free-space, fibre and VCSEL mode-locked lasers often using semiconductor saturable absorber mirror assemblies (SESAM) [5] and integrated photonic circuits often using a reverse biased electrically isolated section of a III/V semiconductor amplifier [6]–[8]. These semiconductor based saturable absorbers have a limited optical operating bandwidth however, and reverse biased amplifiers have been reported having recovery times exceeding 2.5 ps which has been theorised to limit the achievable pulsewidth of mode-locked lasers [8][9]. This has motivated research to find new saturable absorber materials, one of which is graphene.

Since the exfoliation of graphene in 2004 [10], it was found that graphene has many promising properties for use as a saturable absorber, such as a broadband operating region (covering full IR and NIR bands), low saturation intensity, fast recovery times (around 200 fs) and a tunable modulation depth [11][12]. Initial experimental demonstrations of passively mode-locked lasers using graphene-based saturable absorbers used chemical vapour deposition (CVD) grown single- and few-layer graphene flakes on a fibre ferrule [11], and later single- and few-layer graphene-oxide flake composites [13]. A downside of these graphene integration methods is that light interacts with the graphene at a normal incidence, which due to the atomic thickness of graphene (0.7 nm) significantly limits the saturable modulation depth due to the short optical interaction length. This modulation depth can be increased by placing the graphene sheet in the evanescent tail and along the propagation direction of a propagating mode. This has been demonstrated through D-shaped and micro-fibres [14]–[16].

Graphene integrated on semiconductor waveguides works through the same principle, which is that a graphene sheet placed on top of an integrated waveguide interacts with the evanescent tail of the propagating mode. Using this approach integrated electro-absorption modulators (EAM) and photo-detectors have been demonstrated [17][18]. Advantages of the integration of graphene onto semiconductor waveguides are the scalability and manufacturing reproducibility as was demonstrated in the 300 mm fab at imec [19].

Graphene integrated on semiconductor waveguides has been experimentally demonstrated to have saturable absorption effects in both TE, TM and slot waveguides [20]–[23]. By adding a gate the chemical potential of graphene can be controlled resulting in control over the insertion loss and saturable absorption depth [24][25]. However, to our knowledge, actual demonstrations of active or passive mode-locking using an integrated graphene saturable absorber have not yet been reported.

In this report, we experimentally demonstrate that an integrated single-layer graphene modulator can be used to passively mode-lock a hybrid laser. This graphene SA integration approach shows potential for reliable production of the SA devices on a wafer scale and the compatibility for use in fully integrated mode-locked lasers.

II. Graphene Assembly and Experimental Setup

The saturable absorber assembly used in our experiment was manufactured using imec's 220 nm thick silicon on 2 μm BOX silicon photonics platform and the graphene integration was performed in a 300 mm fab using standard CMOS production tools. A schematic cross-section of the single-layer graphene saturable-absorber is shown in Figure 1a. The optical mode is confined in a planarised 500 nm wide socket waveguide and this silicon waveguide is used as a gate to electrically control the chemical potential of graphene. Three separate ion doping implantation steps were used to reduce the electrical resistance of this gate while keeping optical losses to a minimum. The graphene was electrically isolated from the gate by a 5nm thick SiOx layer. Graphene was CVD grown on a 6 inch wafer and transferred onto the patterned 300 mm silicon wafer by Graphenea, after which the graphene was encapsulated with a 30 nm thick ALD-AlOx layer. This graphene and AlOx stack was patterned by dry-etching using a SiOx hardmask. In order to contact the doped silicon and graphene, a 600 nm thick pre-metal dielectric was deposited in which via's were etched. A Ti/TiN/W stack was deposited followed by a Tungsten chemical mechanical polishing step. Finally the final metal layer was deposited through a Cu-oxidation step.
A microscope photo showing the top of the silicon device is shown in Figure 1b. Coupling to and from a 50 μm long SLG device is achieved through TE-optimised grating couplers, which are connected to the device through a total of 800 μm long 450 nm wide silicon strip waveguides. More information on the manufacturing steps, EAM performance and wafer reliability can be found in ref. [19].

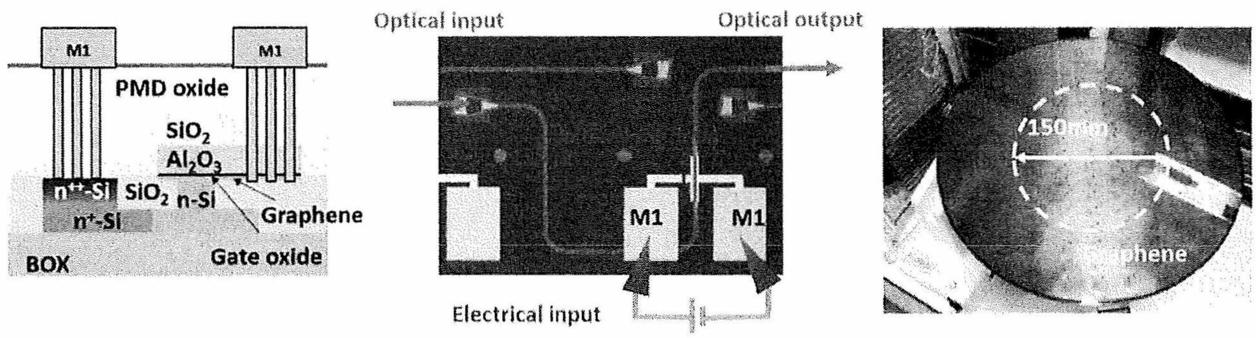


Fig. 1: The graphene saturable absorber assembly used for passive mode-locking [19]. Figure a) shows the schematic cross-section of the graphene modulator, Figure b) shows a top-down photograph of the device used as a saturable absorber. And Figure c) shows the 300mm patterned silicon wafer on which a 6 inch graphene sheet is placed.

A schematic setup of the mode-locked laser cavity used is shown in Figure 2. The cavity consists of an Opto-Link C-band EDFA having approximately 28 m of internal fibre with 27 dB of small-signal gain and an integrated internal isolator. After the EDFA an optical splitter is used to couple 10% of the light out of the cavity after which 90% is passed to a polarisation controller to couple light to the integrated silicon waveguides through a grating coupler having a 45 nm 3 dB bandwidth centered at 1560 nm. The graphene modulator is biased using a Keithley source measurement unit. The output of the integrated graphene modulator is passed back to the input of the EDFA completing the laser cavity.
The output optical signal is measured on an Alphalas 25 GHz photodetector of which the electrical signal is split using a 3 dB splitter to simultaneously measure the electrical spectrum on an R&S electrical spectrum analyser (ESA) and the temporal response on a Keysight oscilloscope. The optical spectrum is measured with a Yokogawa AQ6310 optical spectrum analyser. In order to measure the optical pulsewidth the output from the laser is amplified by a second Opto-link CW-EDFA, after which the optical signal is measured using an APE autocorrelator.

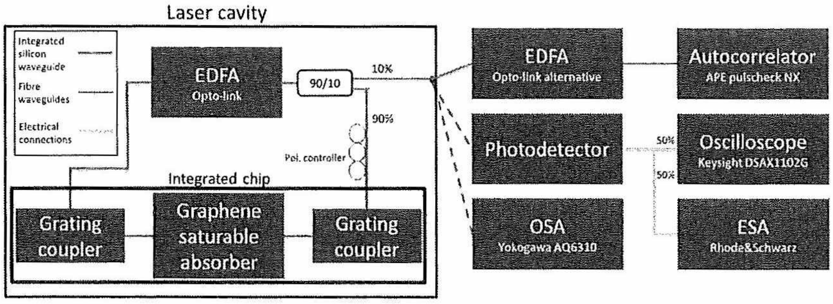
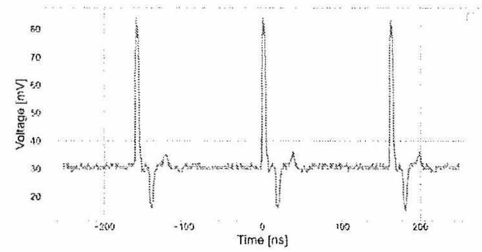
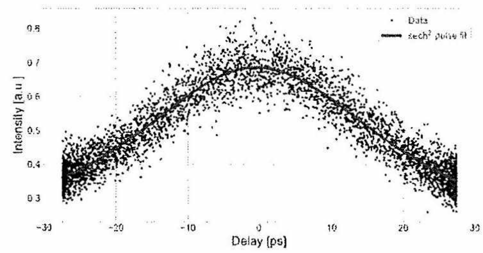


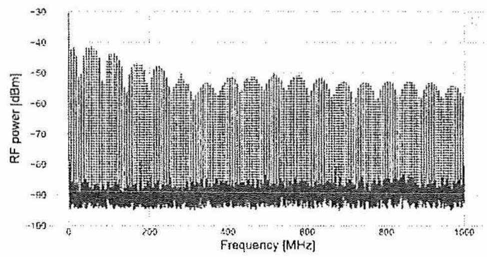
Fig. 2: Schematic of the experimental setup. The section in the black box indicates the laser cavity, and the section on the right the measurement equipment used



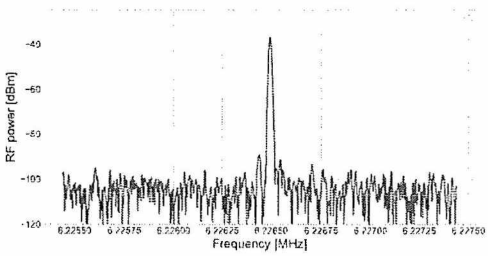
(a) Temporal pulsetrain measured using an oscilloscope



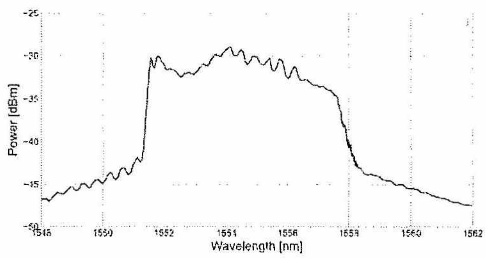
(b) Autocorrelation trace of the optical pulse after passing through an EDFA. The $sech^2$ fit gives a FWHM pulsewidth of 26ps.



(c) RF spectrum of the ESA at a 10kHz BW.



(d) RF spectrum of the first harmonic, measured with a 10Hz bandwidth. The image shows a side-mode suppression ratio of 52dB.



(e) Optical spectrum of the mode-locked laser.

Fig. 3: Measurement results of the passive mode-locked laser result.

III. RESULTS

The mode-locked laser described in section II passively mode-locks with a repetition rate of 6.23 MHz, which is consistent with the cavity length dominated by 28 m of fibre inside the EDFA. The temporal signal coming from the photo-detector measured using an oscilloscope is shown in Figure 3a, which shows a stable pulse-train. The electrical spectrum measured using the ESA is shown in Figure 3c, which shows RF comb lines spaced by 6.23 MHz combined with an approximate 100 MHz intensity modulation. The fundamental RF peak is shown in Figure 3d and has >50 dB signal-to-noise ratio indicating stable mode-locking. The optical pulse-width measured using the auto-correlator was fitted with a $sech^2$ pulse, which is shown in Figure 3b showing a 26 ps wide optical pulse, where it should be noted that this pulse is broadened due to the amplification of a second CW-type EDFA at the output. The optical spectrum of the output signal is shown in Figure 3e, which shows a 6 nm wide optical bandwidth centered at 1554 nm, which is expected to be limited by the bandwidth of the grating-couplers.

IV. Conclusion

Passive spontaneous mode-locking was demonstrated in a hybrid laser cavity using an integrated graphene electro-absorption modulator manufactured using standard CMOS tools. These results demonstrate that integrated graphene modulators can be used as a saturable absorber in fibre lasers. Furthermore by further integrating an amplifier and a passive extended cavity onto a semiconductor platform a fully integrated actively and passively mode-locked laser using graphene saturable absorbers should be able to be realised.

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