Broadband 20 Gbit/s Graphene-Si Electro-Absorption Modulator

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Abstract *We demonstrate a 20Gbit/s single-layer graphene EAM based on p-doped graphene on p-doped waveguide with 4.4dB extinction ratio and >15.7GHz 3dB bandwidth at 0V DC bias across 70nm wavelength range.*

Introduction

Single-layer graphene modulators have attracted great interest in recent years due to the characteristic broadband absorption, from visible to infrared, that is tuneable by applying a voltage bias between the silicon waveguide and graphene. In addition, CVD grown graphene can be transferred onto any substrate and has the potential to enable active optoelectronic functionality onto passive optical waveguides. These advantages, together with the high carrier mobility, make graphene an attractive material for high-speed electro-absorption modulators (EAM).

Many graphene modulators have already been demonstrated[1,2]. The highest reported 3dB bandwidth of 30GHz with an open eye at 22Gbit/s at 2.5 peak-to-peak drive voltage (V_{pp}) was achieved decreasing the capacitance of a ring modulator by using a 65nm thick Al_2O_3. However, this comes at the expense of -30V DC bias and limited device bandwidth[1]. A broadband graphene EAM operating at a lower DC bias of 1.75V has also been demonstrated using an n-doped silicon waveguide, achieving a 3dB bandwidth of 5.9GHz and an open eye at 10Gbit/s at $2.5V_{pp}$[2].

In this paper, we demonstrate a broadband graphene-Si EAM, by transferring p-doped graphene on a p-doped silicon waveguide, with 4.4dB extinction ratio, 7.7dB insertion loss and 15.7GHz 3dB bandwidth at 0V DC bias at 1560 nm. The graphene EAM maintains >15.7GHz 3dB bandwidth across 70nm wavelength range. Eye diagrams are obtained up to 25Gbit/s at $2.5V_{pp}$ using 2V DC bias at 1560 nm.

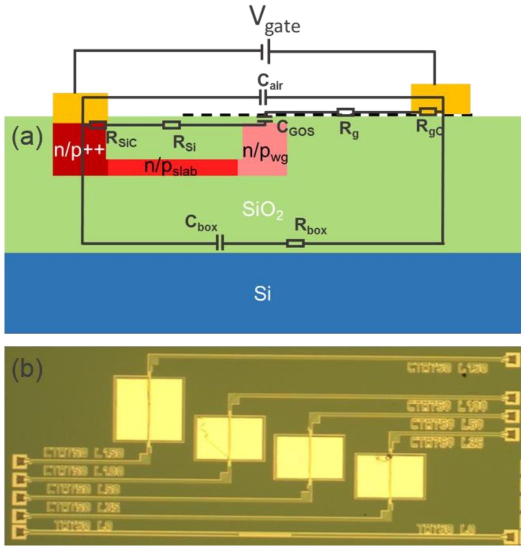

Fig. 1: (a) Schematic cross section of the graphene EAM indicating the equivalent electrical model. **(b)** Top-view microscope image showing the graphene EAMs.

Device design

The single-layer graphene EAM is based on a graphene-oxide-silicon structure (GOS), on top of a planarised doped silicon waveguide embedded in SiO_2, fabricated in a CMOS semiconductor fab (Fig. 1a). After planarisation, CVD graphene is transferred and patterned on the silicon waveguides. Contacts are made on graphene and on the doped silicon based on a standard lift-off lab process. The oxide separating the graphene from

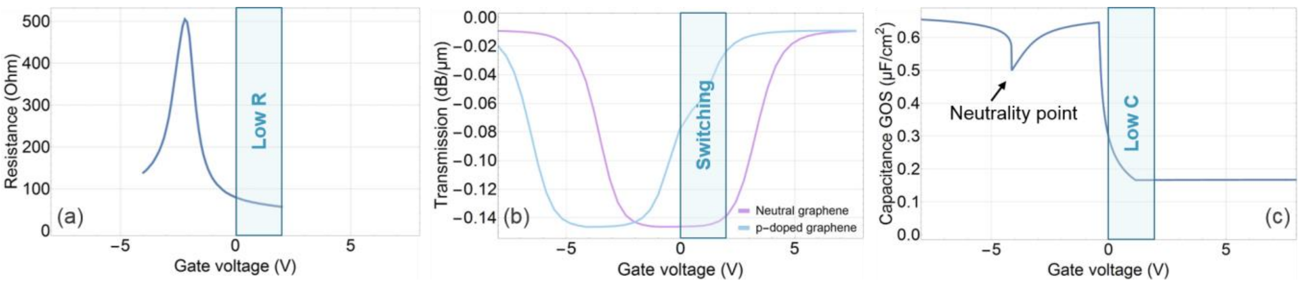

Fig. 2: (a) Measured resistance (R_{sheet} + $R_{contact}$) of a p-doped graphene layer. The neutrality point is at negative bias, allowing to have low resistance at positive bias. **(b)** Modelled TM optical transmission as a function of gate voltage of a graphene EAM with 5nm oxide, 750nm waveguide width and p_{wg} = 5.6e17cm^{-3}, for neutral (n_0 = 0cm^{-2}) and p-doped (n_0 = 12cm^{-2}) graphene. **(c)** Analytically calculated C-V of a GOS capacitor, showing low capacitance at positive voltage bias.

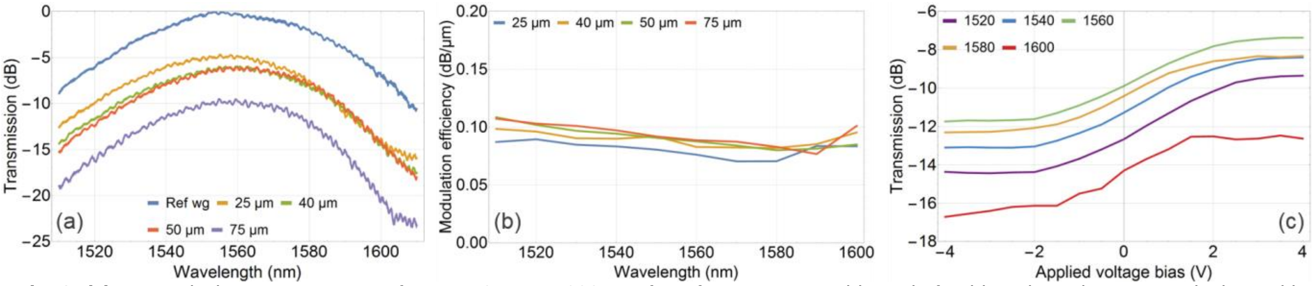

Fig. 3: (a) Transmission measurements from 1510nm to 1600nm of a reference waveguide and of unbiased graphene EAM devices with lengths of 25µm, 40µm, 50µm and 75µm, normalised to the peak of the reference waveguide. **(b)** Modulation efficiency (ER/L) of four graphene EAM, obtained by measuring the transmission spectrum from 1510nm to 1600nm at -4V ~ 4V voltage bias. **(c)** Transmission, normalised to the reference waveguide, as a function of voltage measured on a 50µm long graphene EAM at wavelengths ranging from 1520nm to 1600nm.

the Si waveguide is 5nm thick. The Pd contact to graphene and Ti contact to Si are used to apply an electric field across the GOS. Due to the electric field, charges are accumulated or depleted in the graphene layer, which allow to tune the graphene Fermi level and therefore the graphene absorption. The contacts are placed 2µm away from the waveguide and therefore have no impact on transmission loss.

Unpassivated graphene is typically highly p-doped due to environment and polymer contamination while processing[3] and dangling oxygen bonds in the SiO_2 below. Consequently, when an electric field is applied across the GOS capacitor by contacting graphene and Si as shown in Fig.1a, the graphene neutrality point is shifted towards negative voltage bias, leading to low resistance at low positive bias (Fig. 2a). The presence of p-doping on graphene presents an advantage also from an electro-optical point of view. In p-doped graphene the minimum of light transmission is shifted towards negative bias. As a result, the switching between on and off state occurs in the range of around 0V to low positive bias (~2V), instead of high forward or reverse bias. This behaviour is shown in the modelled transmission versus gate voltage graph in Fig.2b.

In order to minimise the graphene EAM capacitance at low forward bias, a p-doped Si waveguide can be used. The modelled capacitance as a function of voltage of such a GOS capacitor is plotted in Fig. 2c. The GOS capacitor operates in accumulation at negative DC bias and switches to depletion at low forward DC bias, resulting in lower capacitance in the operating region of the graphene EAM. For our devices we used p_{wg} = 5.6e17cm^{-3}.

Device static performance

Transmission measurements of a reference waveguide without graphene and of unbiased graphene EAM devices with lengths of 25µm, 40µm, 50µm, 75µm were performed from 1510nm to 1610nm on waveguides optimised for TM polarised light, with waveguide width w_{wg} = 750nm (Fig.3a). The Gaussian shape of the spectrum is due to the wavelength dependence of the fiber grating coupler response, which limits the wavelength range of the measurement. The transmission scales linearly with the device length and the graphene absorption is 0.12 dB/µm. The modulation efficiency (ME = ER/L_{device}) of the four devices, obtained by measuring the transmission spectrum from 1510nm to 1600nm at voltage bias ranging from -4V to 4V, is shown in Fig.3b. Values are consistent throughout the whole spectrum, ranging from 0.07dB/µm to 0.11dB/µm. Fig. 3c shows the normalised transmission versus applied voltage measured at different wavelengths for the 50µm long device. The insertion loss at 1560nm is 7.7dB and the extinction ratio is 4.4±0.3dB from 1520nm to 1600nm. The electro-optical switching in transmission occurs around 0V due to the p-doping in graphene.

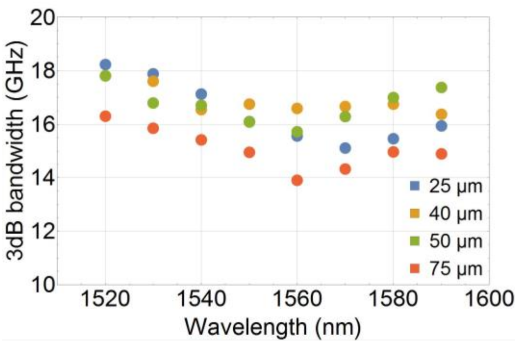

Fig. 4: 3dB bandwidth measured at 0V DC bias from 1520nm to 1600nm on graphene EAM devices with lengths of 25µm, 40µm, 50µm and 75µm.

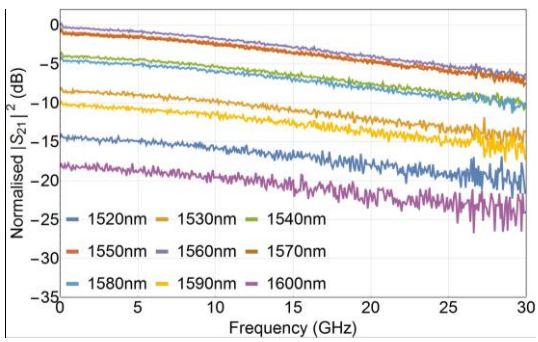

Fig. 5: S_{21} frequency response measured at 0V DC bias on a 50µm graphene EAM device from 1520nm to 1600nm, normalised to the maximum at 1560nm.

Tab. 1: Values of series resistance (R_s) and GOS capacitance (C_{GOS}) extracted from S_{11} parameters fitting, simulated f_{3dB} (from values in columns 1 and 2) and measured f_{3dB} at 1560nm and at 0V, 1V, 2V for a 50µm graphene EAM.

	R_s (Ω)	C_{GOS} (fF)	Simulated f_{3dB} (GHz)	Measured f_{3dB} (GHz)
0 V	185 ± 5	47.8 ± 1.0	13.2 ± 2.0	15.7
1 V	187 ± 5	51.2 ± 1.0	12.2 ± 2.0	10.4
2 V	187 ± 5	56.9 ± 1.0	11.0 ± 2.0	9.7

Device high speed performance

The electro-optical S_{21} frequency response was measured on the four devices at 0V DC bias from 1520nm to 1590nm with a step of 10nm at 12dBm input power (Fig. 4). Fig. 5 shows an example of the measurement performed on the 50µm long device. The 3dB frequency response variation with wavelength is <2.5GHz for all the devices measured across the whole wavelength range. The limitation to measure the graphene EAM S_{21} response across a larger wavelength range is coming from the grating couplers, that are optimised to have a transmission peak at 1560nm. Average 3dB bandwidth of 16.4±1.0GHz, 16.9±0.5GHz, 16.7±0.6GHz and 15.7±0.9GHz are reported respectively for the 25µm, 40µm, 50µm and 75µm graphene EAM devices across 70nm wavelength range.

S_{21} measurements at 1V and 2V were performed on the 50µm device. With increasing DC bias, the 3dB bandwidth decreases due to a slow increase in the capacitance of the device, caused by the graphene quantum capacitance. This is reflected by the values of GOS capacitance extracted from fitting to the electrical S_{11} measurements, using the equivalent electrical circuit shown in Fig.1a. Values of 47.8fF at 0V, 51.2fF at 1V and 56.9fF at 2V were extracted for the GOS capacitance. The extracted series resistance is 185±5Ω, and remains constant at different DC bias within the error bar.

Eye diagrams were measured at 1560nm using 8dBm laser power, 2^7-1 PRBS at 2.5V_{pp} and 2V DC bias with an unterminated probe. Open eye diagrams were generated up to 20Gbit/s with 1.8dB extinction ratio and an SNR of 3.3 (Fig. 6). By increasing the laser power to 12dBm, eye diagrams were generated at 25Gbit/s (Fig.7), showing a 1.7dB extinction ratio and an SNR of 2.9. Using a terminated probe and higher drive voltages (e.g. 4V_{pp}) is expected to improve the eye openings in future measurements.

Conclusions

We demonstrated a graphene-Si electro-absorption modulator based on p-doped graphene on a p-doped Si waveguide, that has 4.4dB extinction ratio and 16GHz 3dB bandwidth across a wavelength range of 70nm (1520nm–1590nm). The device operates at 20Gbit/s demonstrating 1.8dB dynamic extinction ratio using 2.5V_{pp}.

Further improvement of the device is possible by optimising the doping level of the Si waveguide and of the contact slab, in order to optimise the trade-off between resistance and capacitance, and maximise the RC constant.

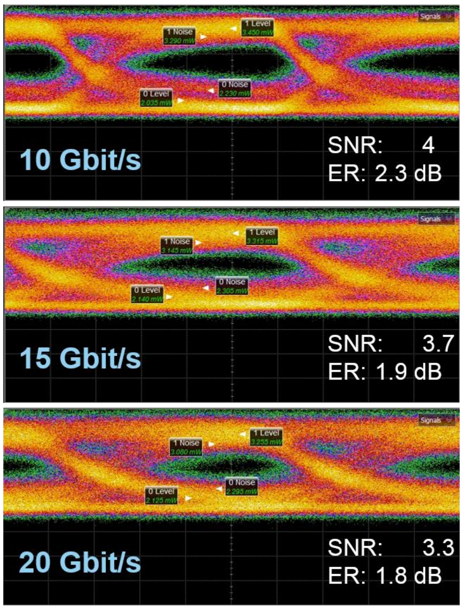

Fig. 6: Optical 2^7-1 PRBS eye diagrams measured at 1560nm at 8dBm laser power, with a drive voltage of 2.5V_{pp} and a DC bias of 2V, at 10Gbit/s, 15Gbit/s and 20Gbit./s.

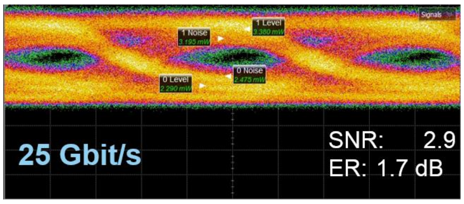

Fig. 7: Optical 2^7-1 PRBS eye diagrams measured at 1560nm at 12dBm laser power, with a drive voltage of 2.5V_{pp} and a voltage bias of 2V, at 25Gbit/s.

Acknowledgements

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References

[1] C. T. Phare et al., "Graphene Electro-Optic Modulator with 30 GHz Bandwidth," Nat. Photonics, Vol. **9**, no. 8, p.511 (2015).

[2] Y. Hu et al., "Broadband 10 Gb/s Operation of Graphene Electro-Absorption Modulator on Silicon," Laser Photonics Rev., Vol. **10**, no. 2, p.307 (2016).

[3] C. J. Shih et al., "Understanding Surfactant/graphene Interactions Using a Graphene Field Effect Transistor: Relating Molecular Structure to Hysteresis and Carrier Mobility," Langmuir, Vol. **28**, no. 22, p.8579 (2012).