4-Channel C-Band WDM Transmitter Based on 10 GHz Graphene-Silicon Electro-Absorption Modulators

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Abstract: We demonstrate three 4-channel WDM transmitters, each based on four graphene-silicon electro-absorption modulators with passivated graphene, achieving ∼2.6dB insertion loss, ∼5.5dB extinction ratio for 8V voltage swing and ∼10GHz 3dB-bandwidth at 0V DC bias.

OCIS codes: 060.1810, 160.2100, 250.5300.

1. Introduction

The forecast for IP traffic in data centers estimates that data traffic will reach 20.6 ZB/year by 2021 [1]. This data rate is far higher than what can be handled by single optoelectronic transmitters and receivers. Wavelength division multiplexing (WDM) is a way to increase the bandwidth by combining multiple data streams, transferred at different wavelengths, on a single optical fiber.

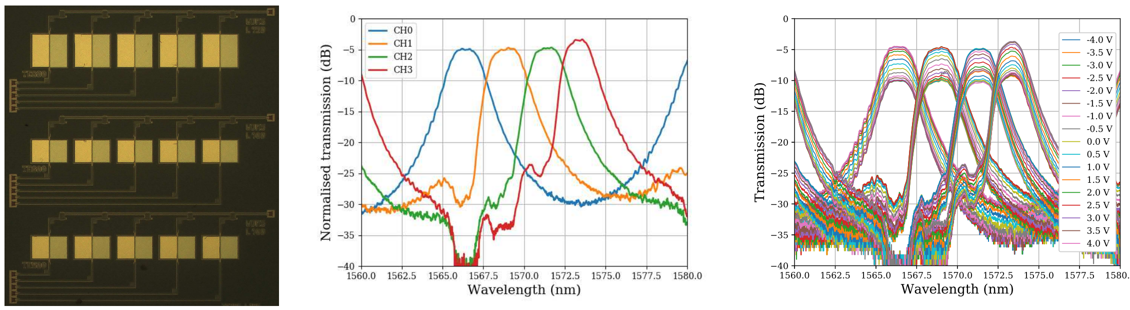
Single-layer graphene devices have attracted interest in recent years due to graphene's characteristic broadband absorption, from visible to infrared. Graphene's absorption can be easily tuned by applying an electric field [2]. In addition, CVD grown graphene can be transferred onto any substrate and 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 photonic devices.

Graphene integration in photonics has already been demonstrated for both modulators [3] and photodetectors [4]. Due to graphene's broadband absorption, devices operating at different wavelengths can be built simultaneously using the same technology. Graphene-based transceivers offer some advantages compared to their silicon counterpart. In graphene based devices, the signal is enabled by suppressing the absorption in the graphene layer (and viceversa), therefore removing the tight fabrication requirements, such as those needed for Si ring-based modulators. Another advantage is that in graphene-based devices the loss variation is obtained by capacitive charging. As a consequence, there is no power consumption in normal state, when the capacitor is discharged, achieving in this way low-power transceivers. However, to date, graphene device demonstration has been limited to individual components and no WDM transmitter has yet been demonstrated.

In [3] we showed a 20 Gbit/s graphene-silicon electro-absorption modulator (EAM). Using the same technology, we now demonstrate three TE-polarised 4-channel WDM transmitters, each based on four graphene-silicon electro-absorption modulators with passivated graphene, achieving ∼2.6 dB insertion loss, ∼5.5 dB extinction ratio and ∼10 GHz 3dB-bandwidth at 0 V DC bias when using a 500nm-wide waveguide and 100μm-long devices.

2. Device design and fabrication

We fabricated three WDM transmitters consisting of four second order micro-ring resonators (MRR), as shown in Fig.1a [5]. The first transmitter (WDM1) is made of a 500nm-wide waveguide and 100 μm-long devices. The second (WDM2) and third (WDM3) transmitters are made of a 600nm-wide waveguide and 100 μm- and 150 μm-long devices respectively. Each device is based on a planarised n-doped silicon waveguide on SOI, which is embedded in SiO_2, fabricated in a CMOS semiconductor fab. After planarisation, CVD graphene is transferred, passivated with



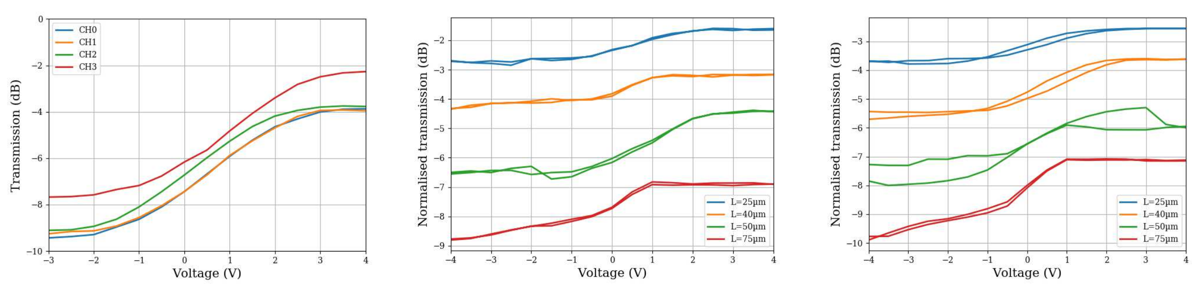
(a) (b) (c)

Fig. 1: : (a) Top view microscope image showing the three WDM transmitters, each based on four graphene-silicon electro-absorption modulators. (b) Transmission measurements, normalised to a reference waveguide without graphene, from 1510 nm to 1600 nm of a 4-channel WDM transmitter with a 500nm-wide waveguide and 100μm-long devices; (c) 600nm-wide waveguide and 150μm-long devices.

Si(0.5nm)/Al_2O_3(10nm) and patterned to cover part of the silicon waveguide. Contacts are made to graphene (Pd) and to the doped silicon (Ti) with a standard lift-off process. They are placed 2 μm away from the waveguide and therefore have no impact on transmission loss. Graphene and the silicon waveguide are separated by a SiO_2 layer of 5 nm, thus forming a graphene-oxide-silicon (GOS) capacitor. The metal contacts are used to apply an electric field across the GOS capacitor. Due to the electric field, charges are accumulated or depleted in the graphene layer, and consequently the graphene absorption is tuned as a function of the applied voltage bias [2]. To fabricate these devices we used a passivation-first approach, which allows to protect the graphene layer since the beginning of the fabrication process from polymer contamination and from the environment. The Al_2O_3 passivation layer allows to obtain hysteresis-free electro-optical response, but at the same time it preserves the p-doping characteristic of unpassivated graphene, due to which the switching in the electro-optical behaviour takes place around 0 V DC bias.

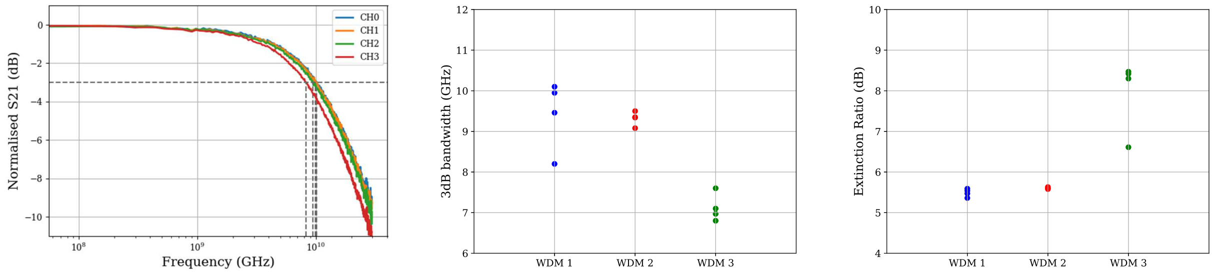
3. Device static performance

We performed unbiased transmission measurements of the three WDM transmitters, each composed of four channels (Fig.1b). All the devices are designed to transmit TE-polarised light in the C-band. The channel spacing is designed to fit a grid spacing of 300 GHz (2.4 nm) and a free-spectral range (FSR) of 12 nm. The insertion loss is as low as 2.6 dB, 2.8 dB and 3.4 dB for WDM1, WDM2 and WDM3 respectively. The extinction ratio was obtained by measuring the spectrum from 1510 nm to 1600 nm on each channel at voltage bias ranging from -4 V to 4V (Fig.1c). Fig.2a shows the extracted transmission of the 4 channels as a function of voltage bias for the WDM transmitter WDM1. The modulation is consistent across all the channels (Fig.3c), with an extinction ratio (8 V_{pp}) of 5.5 $\pm$ 0.1 dB for



(a) (b) (c)

Fig. 2: (a) Transmission, normalised to a reference waveguide without graphene, as a function of applied voltage bias measured on a 4-channel WDM transmitter based on 100μm-long devices with a 500nm-wide waveguide. (b) Transmission, normalised a reference waveguide without graphene, as a function of applied voltage bias measured on four graphene EAMs with a double voltage sweep; no hysteresis is present thanks to the Al_2O_3 passivation layer. (c) Same as (b), but measured after two months time; no degradation in the passivation layer is observed.



(a) (b) (c)

Fig. 3: (a) S_{21} frequency response measured at 0 V DC bias on a 4-channel WDM with a 500nm-wide waveguide and 100μm-long devices. (b) 3dB bandwidth at 0 V of the 4 channels of the three WDM transmitters. (c) Extinction ratio of the 4 channels of the three WDM transmitters, measured with 8 V voltage sweep.

WDM1, 5.6 $\pm$ 0.1 dB for WDM2 and 7.9 $\pm$ 0.7 dB for WDM3. The electro-optical switching in transmission occurs around 0 V due to the p-doping in graphene. Double sweep electro-optical measurements, performed at 1560 nm on four graphene electro-absorption modulators (EAM) fabricated simultaneously on the same chip, show that graphene is hysteresis-free due to the presence of the passivation layer (Fig.2b). The same measurement is repeated a second time after two months time and no degradation in the passivation layer is observed, meaning that the fabricated devices are stable (Fig.2c).

4. Device high speed performance

The electro-optical S_{21} frequency response was measured on all three 4-channel WDM transmitters at 0 V DC bias (Fig.3a). The 3dB frequency response is consistent across the different channels for the three WDM transmitters (Fig.3b). Average 3dB-bandwidths of 9.4 $\pm$ 0.7 GHz, 9.3 $\pm$ 0.2 GHz and 7.1 $\pm$ 0.3 GHz are reported respectively for WDM1, WDM2 and WDM3.

5. Conclusions

We demonstrated three 4-channel WDM transmitters, using graphene-silicon EAMs and passivated graphene for the first time. Graphene passivation improves the device stability and repeatability. We achieved $\sim$2.6 dB insertion loss, $\sim$5.5 dB extinction ratio and $\sim$10 GHz 3dB-bandwidth at 0 V DC bias for the 4-channel WDM transmitter with 100μm-long graphene-silicon EAMs.

The authors acknowledge imec's industrial affiliation Optical I/O program and the Graphene Flagship for this work.

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