5 × 25 Gbit/s WDM transmitters based on passivated graphene–silicon electro-absorption modulators

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Today, one of the key challenges of graphene devices is establishing fabrication processes that can ensure performance stability and repeatability and that can eventually enable production in high volumes. In this paper, we use up-scalable fabrication processes to demonstrate three five-channel wavelength-division multiplexing (WDM) transmitters, each based on five graphene–silicon electro-absorption modulators. A passivation-first approach is used to encapsulate graphene, which results in hysteresis-free and uniform performance across the five channels of each WDM transmitter, for a total of 15 modulators. Open-eye diagrams are obtained at 25 Gb/s using 2.5 Vpp, thus demonstrating potential for multi-channel data transmission at 5 × 25 Gb/s on each of the three WDM transmitters.

1. INTRODUCTION

As cloud computing, big data applications, and social networking are expected to keep growing exponentially, the amount of annual global data center traffic is set to surpass 20 ZB by 2021 [1]. To meet this demand, it is estimated that data center operators will have to upgrade their networks to 1.6 Tb/s by 2022 [2]. Advanced multiplexing technologies represent an effective solution to achieve a network infrastructure that can carry more data more efficiently [3,4]. Wavelength-division multiplexing (WDM) uses different channels to carry signals at different wavelengths in a single optical fiber or waveguide simultaneously [5,6]. Next to WDM, other multiplexing solutions are space-division multiplexing (SDM) [7], based on multi-core waveguides; mode-division multiplexing (MDM) [8], with multiple guided modes; and polarization-division multiplexing (PDM), using two orthogonal polarizations together. These approaches have independent degrees of freedom and can be combined to form hybrid multiplexing systems with capacity up to Pbit/s [4]. Among these, WDM links, enabled by low loss, broadband, and low power consumption modulators, are one of the most successful technologies. WDM allows to exploit the full bandwidth of existing optical fibers, leading to a reduced construction cost. In addition, it is simple to implement, as channels can be flexibly added or removed, and the active optical equipment is shared by the different channels.

Graphene has attracted interest in recent years due to its characteristic broadband absorption, which ranges from visible to infrared. Graphene’s absorption can be easily tuned through capacitive charging by applying an electric field [9], and has therefore the potential to enable active optoelectronic functionality onto passive optical waveguides, such as Si or SiN waveguides [10,11]. These properties, together with high carrier mobility, make graphene an attractive material for high-speed photonic devices [12,13], such as modulators [10,14–21] and photodetectors [22–25]. Graphene-based modulators can therefore be implemented in WDM systems to modulate the signal on different channels. Graphene integration in photonics has already been demonstrated for Mach–Zehnder modulators (MZMs) [18], microring modulators (MRMs) [10], and electro-absorption modulators (EAMs) [14–17,19,21]. Compared to graphene MZMs and MRMs, graphene EAMs offer some advantages. Graphene MZMs have a wide optical bandwidth and high extinction ratio (ER), but suffer from high insertion loss (IL), high power consumption, and large device footprint [18]. On the other hand, graphene MRMs offer lower power consumption and smaller device footprint, but fail to exploit graphene’s characteristic broadband absorption due to the resonant nature of the microring [10]. In addition, MRMs suffer from tight fabrication tolerance, and therefore thermal stabilization is necessary to match the resonant wavelength of
Table 1. Waveguide Width ($W_{wg}$) and Device Length ($L_{device}$) Values Used to Fabricate the Three WDM Transmitters

| Transmitter | $W_{wg}$ (nm) | $L_{device}$ (µm) |
|-------------|---------------|-------------------|
| WDM1        | 500           | 100               |
| WDM2        | 600           | 100               |
| WDM3        | 600           | 150               |

*Increasing $W_{wg}$ and $L_{device}$ is expected to increase the extinction ratio but also the device capacitance, and therefore to reduce the 3 dB bandwidth.

the ring to the incoming wavelength. Graphene-based EAMs offer a very wide optical bandwidth (up to 180 nm in the C-band) [17], potentially low power consumption, and low IL [15,16].

So far, the demonstration of graphene modulators has been focused on individual components, due to challenges in processing, transfer, and integration of high-quality graphene at large scale [26]. In this work, we demonstrate for the first time the integration of multiple graphene EAMs with functional silicon photonics circuits. We use three five-channel WDM transmitters, each based on five graphene-Si EAMs designed for TE-polarized light (see Table 1) and Si-based second-order microring resonators (MRRs) for wavelength multiplexing, to demonstrate uniform and hysteresis-free performance across 15 graphene EAMs. To achieve this, we employ up-scalable fabrication processes and a passivation-first approach to encapsulate the graphene layer. The three WDM transmitters are fabricated varying the waveguide width and the device length of the EAMs. For the first and second WDM transmitters, we report 5.5 dB and 5.6 dB ER across 10 nm bandwidth for five identical 100-µm-long devices with 500-nm- and 600-nm-wide waveguides, respectively. On the third transmitter, with 150-µm-long EAMs, we achieve 8.1 dB ER. Open-eye diagrams are measured at 25 Gb/s using $2.5 V_{pp}$ on each of the five channels of the three WDM transmitters, thus demonstrating potential for data transmission at 25 Gb/s using 2.5 V.

Open-eye diagrams for WDM1, WDM2, and WDM3 transmitters are shown in Fig. 1, demonstrating potential for data transmission at 25 Gb/s using 2.5 V.

| Transmitter | $W_{wg}$ (nm) | $L_{device}$ (µm) |
|-------------|---------------|-------------------|
| WDM1        | 500           | 100               |
| WDM2        | 600           | 100               |
| WDM3        | 600           | 150               |

*Increasing $W_{wg}$ and $L_{device}$ is expected to increase the extinction ratio but also the device capacitance, and therefore to reduce the 3 dB bandwidth.

The rings have a racetrack shape and are implemented with 450-nm-wide waveguides, 9 µm coupling length, 5 µm radius, and 190 nm bus-ring gap [5]. To reduce fabrication complexity and power consumption, no temperature control is used; therefore, variations in IL, resonant wavelength, and crosstalk are expected due to local non-uniformities, as shown in Ref. [5]. The first transmitter (WDM1) is made of graphene EAMs with 500-nm-wide waveguides and 100-µm-long graphene. The second (WDM2) and third (WDM3) transmitters are made of graphene EAMs with 600-nm-wide waveguides and 100-µm- and 150-µm-long waveguides, respectively. The MRRs are connected to the EAMs using tapers. Increasing the waveguide width ($W_{wg}$) and the device length ($L_{device}$) is expected to increase the ER but also the device capacitance, and therefore to reduce the 3 dB bandwidth.

Fig. 1. Top-view microscope image showing the three WDM transmitters, each based on five graphene-Si EAMs and five second-order MRRs.

Fig. 2. Main steps of the process flow used to fabricate the graphene-Si EAMs: (a) graphene shaping, (b) Si(0.5 nm)/Al$_2$O$_3$ (10 nm) deposition, (c) graphene contact, and (d) Si contact. The passivation layer on graphene helps in obtaining uniform and hysteresis-free performance. The Si waveguide is connected to a TE-mode fiber grating coupler.

2. DESIGN AND FABRICATION

We fabricated three WDM transmitters consisting of five graphene EAMs and five second-order MRRs each, as shown in Fig. 1. Each transmitted wavelength goes through the graphene EAMs before being added to the bus waveguide of the MRRs. The channel spacing of the MRRs, acting as multiplexer (MUX), is designed to fit a grid spacing of 300 GHz (2.4 nm) and a free-spectral range (FSR) of 12 nm. The rings have a racetrack shape and are implemented with 450-nm-wide waveguides, 9 µm coupling length, 5 µm radius, and 190 nm bus-ring gap [5]. To reduce fabrication complexity and power consumption, no temperature control is used; therefore, variations in IL, resonant wavelength, and crosstalk are expected due to local non-uniformities, as shown in Ref. [5]. The first transmitter (WDM1) is made of graphene EAMs with 500-nm-wide waveguides and 100-µm-long graphene. The second (WDM2) and third (WDM3) transmitters are made of graphene EAMs with 600-nm-wide waveguides and 100-µm- and 150-µm-long waveguides, respectively. The MRRs are connected to the EAMs using tapers. Increasing the waveguide width ($W_{wg}$) and the device length ($L_{device}$) is expected to increase the ER but also the device capacitance, and therefore to reduce the 3 dB bandwidth.

After oxide chemical–mechanical planarization (CMP), the processing is continued at coupon level in a lab environment, and graphene grown by chemical vapor deposition (CVD), commercially available from Graphenea, is transferred onto the substrate. Graphene-based devices show high sensitivity to environmental factors, such as ambient air, organic solvents, and...
the WDM transmitters is dominated by the IL of the graphene modulators.

The electro-optical response of the graphene EAMs was characterized by sweeping the wavelength from 1510 nm to 1600 nm on each channel, while applying voltage bias ranging from $-4 \, \text{V}$ to $4 \, \text{V}$. The optical power was measured at the output of the transmitters (bus waveguide). An example of this measurement performed on WDM2 is shown in Fig. 3(b) (with reduced wavelength range from $1552.5 \, \text{nm}$ to $1562.5 \, \text{nm}$ for clarity). The ER at $8 \, \text{V}_{\text{pp}}$ was obtained by extracting the transmission as a function of the voltage at the peak transmission wavelength of each channel [example for WDM2 in Fig. 3(c)]. The ER was consistent across all channels, with average values of $5.5 \pm 0.1 \, \text{dB}$ for WDM1, $5.6 \pm 0.1 \, \text{dB}$ for WDM2, and $8.1 \pm 0.7 \, \text{dB}$ for WDM3 (Table 2). The higher ER in WDM3 is due to the longer device length, which ensures a longer interaction between the graphene layer and the evanescent field of the light traveling through the waveguide. The electro-optical switching in transmission occurs around $0 \, \text{V}$, because of p-doping in graphene. The p-doping characteristic is ideal for electro-optical modulation, because it allows to operate the device at low voltage DC bias. The carrier mobility of graphene is estimated to be $\sim 800 \, \text{cm}^2/(\text{Vs})$ from measurements performed on electrical test structures fabricated on the same sample. The static power consumption at $-1 \, \text{V}$ is calculated to be $< 2 \times 10^{-8} \, \text{mW}$, due to the $< 20 \, \text{pA}$ measured leakage current.

In order to study the effect of the Al$_2$O$_3$ passivation layer on the hysteretic behavior of the EAMs, we performed double-sweep electro-optical measurements at 1560 nm wavelength on a standalone 25-$\mu$m-long graphene EAM fabricated simultaneously on the same chip. We compared these results with the ones obtained on an unpassivated 25-$\mu$m-long graphene EAM fabricated under the same processing conditions (Fig. 4). The unpassivated EAM shows hysteretic behavior, with a difference in transmission at $0 \, \text{V}$ between the forward and backward voltage sweeps of $\Delta T = 0.35 \, \text{dB}$. This behavior is not present in the passivated EAM, where $\Delta T$ is only $0.02 \, \text{dB}$, thus showing that the Al$_2$O$_3$ passivation layer allows to obtain hysteresis-free electro-optical response, while at the same time preserving the p-doping characteristic of unpassivated graphene. The same measurement repeated on the passivated EAM after two months shows no significant degradation in the response of the device ($\Delta T = 0.16 \, \text{dB}$). Two parameters could be optimized to further improve stability over time. The first is the thickness of the Al$_2$O$_3$, as it has been shown to affect the performance stability of graphene field-effect devices [33]. In addition, a thick SiO$_2$ layer ($\sim 1 \, \mu\text{m}$) could be deposited on top of the Al$_2$O$_3$ to increase further the thickness of the dielectric stack. The second is the

| Table 2. Insertion Loss (IL) and Extinction Ratio (ER) at 8 $V_{\text{pp}}$ |
|-----------------|-----------------|-----------------|
|                 | $L_{\text{device}}$ (µm) | IL (dB)         | ER (dB) |
| WDM1            | 100              | $3.8 \pm 1.0$   | $5.5 \pm 0.1$ |
| WDM2            | 100              | $2.9 \pm 0.7$   | $5.6 \pm 0.1$ |
| WDM3            | 150              | $4.0 \pm 0.5$   | $8.1 \pm 0.7$ |

The values are averaged over five channels. WDM3 exhibits higher IL and ER due to the longer $L_{\text{device}}$. |
Fig. 3. (a) Transmission spectra, normalized to a reference waveguide, measured on a WDM filter without graphene, showing the insertion loss of the second-order MRRs. (b) Transmission spectra on WDM2, normalized to a reference waveguide without graphene. The voltage is varied from $-4 \text{ V}$ to $4 \text{ V}$ on each graphene EAM, resulting in the tuning of the transmission on each channel. (c) Normalized transmission as a function of DC voltage bias, measured on WDM2. The transmission is extracted at the peak wavelength of each channel. The modulation is uniform on the five channels.

Fig. 4. Comparison of transmission curves, measured with a double-voltage sweep right after fabrication, between an unpassivated (yellow) and a passivated (blue) 25-$\mu\text{m}$-long graphene EAM. The unpassivated EAM shows hysteretic behavior, which is not present in the passivated EAM. The same measurement is repeated on the passivated EAM after two months (red), showing a small hysteresis that remains less pronounced compared to the unpassivated device.

Eye diagrams were measured at the peak wavelength of each channel using $2^{7}-1$ pseudorandom binary sequence (PRBS) at $2.5 \text{ V}_{pp}$ with a 50 $\Omega$ terminated probe. The applied DC bias is different for each channel because of small variations in graphene doping, with an average value of $-1.2 \pm 0.2 \text{ V}$. Open- and symmetrical-eye diagrams were generated from 5 Gb/s to 25 Gb/s for all channels, thus allowing to transmit data up to $5 \times 25 \text{ Gb/s}$ on each WDM transmitter. Eye diagrams measured on the five channels of WDM2 are shown in Fig. 6. The dynamic ER and signal-to-noise ratio (SNR) of the five channels on each WDM transmitter are reported in Fig. 7 as a function of bit rate. The SNR is higher than 3.0 up to 25 Gbit/s for all the WDM transmitters. WDM3 exhibits a 45% higher ER, due to the longer graphene waveguide coverage, thus allowing to obtain open-eye diagrams up to 30 Gb/s with an SNR of 2.9 and a dynamic ER of 1.2 dB (Fig. 8). This shows that the primary limiting factor of these devices is the ER, followed by the frequency response. The dynamic energy consumption ($E_{\text{bit}} = C V^2/4$) of a single graphene EAM at $-1 \text{ V}$ is estimated to be $\sim 163 \text{ fJ}$ for WDM1, $\sim 195 \text{ fJ}$ for WDM2, and $\sim 308 \text{ fJ}$ for WDM3. These values are, to the best of our knowledge, the lowest reported for graphene-based modulators.

To further improve the performance of these devices, the thickness of the oxide between graphene and Si can be increased.
Fig. 5. (a) Electro-optical $S_{21}$ (inset: $S_{11}$) frequency response measured at 0 V DC bias on WDM2. The response is uniform across the five channels. (b) GOS capacitance and 3 dB bandwidth of WDM1 as a function of DC bias. The GOS capacitance increases at forward bias, causing a drop in 3 dB bandwidth. The ideal operating region is therefore at 0 V or low reverse bias.

Table 3. Total Resistance ($R_{\text{tot}}$) and GOS Capacitance ($C_{\text{GOS}}$) Extracted from $S_{11}$ Parameter Fitting, Simulated (from the Fitted Parameters in Columns 1 and 2) and Measured $f_{3\text{db}}$ at 0 V

| Device | $L_{\text{device}}$ (µm) | $R_{\text{tot}}$ (Ω) | $C_{\text{GOS}}$ (fF) | $f_{3\text{db}}$ (GHz) at 0 V |
|--------|----------------|----------------|----------------|-----------------|
| WDM1   | 100           | 78 ± 5          | 112.6 ± 0.5    | 10.1 ± 0.5      | 9.5 ± 0.7 |
| WDM2   | 100           | 65 ± 5          | 134.7 ± 0.5    | 9.5 ± 0.5       | 9.3 ± 0.1 |
| WDM3   | 150           | 49 ± 5          | 206.6 ± 0.5    | 7.0 ± 0.5       | 7.1 ± 0.3 |

The values are averaged over five channels. Due to the longer $L_{\text{device}}$, WDM3 exhibits higher $RC$ constant, and therefore lower $f_{3\text{db}}$.

to reduce the device capacitance and therefore the RC constant. However, this leads to a lower modulation efficiency, due to the increased DC bias and $V_{pp}$ necessary to operate the device. Therefore, we suggest a different approach. The Si doping in the waveguide can be optimized to reduce the Si capacitance and resistance contributions in the operating region. For example, an improvement of $\sim$42% in 3 dB frequency response can be achieved by p-doping instead of n-doping the Si waveguide without affecting the modulation efficiency, because the device can be operated in depletion mode instead of accumulation mode [37]. A two-fold improvement in ER can be attained by designing graphene-based WDM transmitters for TM- instead of TE-polarized light [15]. Furthermore, an improvement in graphene quality, and therefore in the carrier mobility of graphene, will allow to increase the ER for fixed $V_{pp}$, reduce graphene resistance, and reduce the IL of the graphene EAMs.
4. CONCLUSION
We demonstrated three graphene-based five-channel WDM transmitters, fabricated with an up-scalable fabrication process and with passivated graphene, to ensure uniform and hysteresis-free device performance. On each channel, the TE-polarized light was modulated using broadband graphene EAMs, for a total of 15 working devices. On the first and second transmitters, with 100-µm-long graphene EAMs, we achieved average static ERs of 5.5 ± 0.1 dB and 5.6 ± 0.1 dB, respectively. On the third transmitter, with 150-µm-long graphene EAMs, we achieved 8.1 ± 0.7 dB average static ER. Open-eye diagrams were measured in the C-band at 2.5 V_{pp} on three WDM transmitters, thus demonstrating potential for data transmission at 5 × 25 Gb/s.

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