Optical Pre-Emphasis by Cascaded Graphene Electro Absorption Modulators

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Abstract—A simple optical circuit made by a cascade of two graphene-on-silicon electro absorption modulators (EAMs) of different length is used for the optical pre-emphasis of 10 Gb/s non-return-to-zero (NRZ) signals by delay-inverse-weight compensation. Transmission up to 100 km on single mode fiber (SMF) without dispersion compensation is reported, showing also the large performance advantage (6 dB in back-to-back and around 5 dB in transmission) in respect of the conventional single EAM transmitter configuration.

Index Terms—Electro absorption modulators, graphene photonics, optical pre-emphasis, dispersion compensation.

I. INTRODUCTION

GRAPHENE is nowadays extensively studied for a large range of applications including its use in photonic integrated circuits (PICs) [1]. In PICs, graphene is expected to improve device performance simplifying, at the same time, the fabrication technology [2]. In particular, graphene-based photodetectors do not need Ge epitaxy (currently used for Si photonics photodetectors), and also work on much larger spectral regions. Moreover, they can be extremely fast, and work at zero dark current when operated in voltage-detection mode [3], [4]. Similarly, graphene-based electro-optic modulators have a number of advantages over Si-based modulators. They are capable of efficient and broadband electro-absorption or phase modulation and are compatible with complementary metal oxide semiconductor (CMOS) processing with simplified post-processing fabrication on various substrates. Indeed, graphene modulators do not strictly require Si or Ge doping, hence, Si, SiN, SiO2 or other materials can be used as waveguides [2] and short devices (of the order of 50-150 microns length), driven in lumped mode, can be realized.

Recently, broadband electro-absorption [5] and pure phase modulation [6] have been reported on a Si platform using short single layer graphene-based modulators. Graphene electro absorption modulators (EAMs), in particular, have been reported working at 10 Gb/s [7], and very recently, at 20 Gb/s [8], using a single layer configuration, being mainly bandwidth limited by the graphene-metal electrical contact resistance value. Additionally, graphene EAMs show significant positive linear chirp associated to the Fermi level electrical gating responsible for the absorption changes [9].

In this letter, we show that signals generated by graphene EAMs can be significantly improved by optical pre-emphasis using a simple compact circuit made cascading two short graphene EAMs driven by two proper complementary electrical signals. This paper is an extended version of a recently presented conference paper [10], and reports 10 Gb/s back-to-back and transmission results obtained with the double EAM modulator, also performing a comparison with the single modulator case.

II. DEVICE DESCRIPTION

The fabricated device is made by cascading two single layer Graphene (SLG) on Si waveguide EAMs similar to the one recently reported in [7], [9]. As shown in Fig. 1, it is made by input/output vertical coupling gratings and the cascade of a 100 and a 50 μm-long EAM.

The modulators are made by Si photonic waveguides with SLG transferred on top of the Si waveguide core. The Si photonic part was realized within the IMEC iSiPP25G silicon on insulator (SOI) platform [11]. The Si ridge waveguide is designed to support a single transverse electric (TE) in-plane polarized optical mode with a core cross-section of 480 nm x 220 nm and 60 nm slab. The waveguide is boron doped to reduce the Si electrode resistance and allow high-speed operation. The waveguide SiO2 top cladding is thinned down to 10 nm on the top of the waveguide core. SLG is grown

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Fig. 1. Top part, mask design of the cascaded graphene EAMs. Lower part, microscope picture of a fabricated sample.

by chemical vapor deposition (CVD) on copper foil [12], and then transferred on the waveguide by standard wet transfer [13]. Graphene was shaped through optical lithography and oxygen ashing. Metal contacts were placed by metal lift-off on the SLG and Si with separate processes: Palladium (Pd) is used for the SLG, while Si is contacted with a stack of Titanium (Ti)/Platinum (Pt)/Gold (Au). The 10 nm-thick layer of SiO₂ insulates Graphene from the Si waveguide core and forms a Silicon-Insulator-Graphene (SIG) capacitor [14]. Fermi Level on Graphene may be changed by applying a voltage across the SIG capacitor. Standard single polarization grating couplers having 5 dB insertion loss at 1550 nm are also included in the device design for input and output vertical fiber coupling.

As recently reported in [9], the 100 μm graphene EAM has a 5 GHz 3-dB electrooptic bandwidth, a modulation efficiency of 1dB/V, a maximum attainable extinction ratio of 4.5 dB. In addition, it shows an opposite optical transmissivity and refractive index change dependence with respect to the applied voltage. This gives, in a certain range of Fermi levels, an instantaneous and linear frequency chirp on the carved optical signal as shown in Fig. 2a. The figure reports the signal chirp in GHz measured by a complex spectrum analyzer in correspondence of an isolated signal pulse. Moreover, it results that the amount of linear chirp depends on the applied driving voltage as reported in Fig. 2b.

This modulator pre-chirping can be used for fiber chromatic dispersion compensation through the time lens effect and, thanks to this effect, 100 km transmission on SMF at 10 Gb/s has been reported [9] demonstrating a self-focusing distance (transmission distance for which there is the same signal sensitivity as in back-to-back) of 60 km (at a driving voltage of 2.5 Vpp).

The setup for the transmission experiment is reported in Fig. 4. An optical continuous wave (CW) signal generated by an external cavity laser (ECL) at 1550 nm was coupled into the chip through a TE vertical grating coupler. The two EAMs were driven by 10 Gb/s data and inverted data through two Bias Tees. A $2^{31}−1$ long non-return-to-zero (NRZ) pseudo random bit sequence (PRBS) with a peak-to-peak voltage of 2.5 Vpp was sent to the first EAM and the same delayed and inverted sequence with a peak-to-peak voltage of 0.8 V to the second one. Signal time delay between the two electrical
The effect of the optical pre-emphasis by the cascaded EAMs can be clearly seen starting from the back-to-back eye diagrams reported in Fig. 5. On the right top part, the best attainable eye diagram with the single EAM, on the lower part, the best one by the cascaded EAMs.

The comparison is made using a 100 μm long single EAM, like the one reported in [9], and the 100 μm plus the 50 μm long modulator driven like reported in Fig. 3, i.e., with the same sequence with opposite sign, after attenuation and proper delay. The main modulating device is still the 100 μm long EAM with the same absorption length, series resistance, capacitance, and insertion loss, the second device contributes with the slight over-modulation needed to compensate for the slower part of the modulator response, at the expense of an extra loss.

In both cases the extinction ratio is 2.5 dB, but, the cascaded eye diagram is significantly more clear and open with a net reduction of the pattern sequence dependence. This is due to the enhanced digital transitions by high pass optical filtering of the modulator cascade.

Overall, this gives a Q-factor improvement, measured by the electrical sampling scope, of around 2, from 3.4 to 5.3.
significantly lower than the conventional Reed-Solomon forward error correction (RS-FEC) threshold of $10^{-3}$ is clearly possible.

In order to compare these results with the single EAM, sample eye diagrams and BER curves of cascaded and single EAM (100 μm-long) are reported in Fig. 7, together with the corresponding BER curves for the cases 40, 60 and 100 km.

The eye opening gain at the transmitter, reported in Fig. 5, gives an improved transmitted signal at every distance so that the 6 dB OSNR advantage in back-to-back is still more than 5 dB at 40 and 60 km and also removes the BER floor at $10^{-6}$ at 100 km. The signal improvement for every of the transmission distances can be clearly envisioned by comparing the recorded eye diagrams for the two cases reported in the right part of Fig. 7.

IV. CONCLUSION

A novel silicon-graphene circuit which implements the optical pre-emphasis for NRZ signals, made by the cascade of a 100 and a 50 μm long EAM, has been fabricated and reported, showing a significant improved sensitivity in back-to-back (6 dB) and in fiber transmission up to 100 km, in respect of the single graphene EAM. The delay inverse weight high pass filtering optical pre-processing is obtained by driving the second shorter modulator with a delayed inverted and attenuated copy of the modulating electrical signal. Despite 10 Gb/s operation has been reported in this letter with a 5 GHz bandwidth modulator, this is a very promising technique for obtaining much faster operation when larger bandwidth graphene EAM modulators are used.

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