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Transmitter made up of a Silicon Photonic IC and its Flip-Chipped CMOS IC Driver
Targeting implementation in FDMA-PON

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Abstract - We report on the design, fabrication and characterization of a reflective transmitter targeting implementation in Passive Optical Networks (PON) with Frequency Division Multiplexed Access (FDMA). It is made up of a Silicon Photonic Integrated Circuit (Si-PIC) comprising a Reflective Mach Zehnder Modulator (R-MZM) and its flip-chipped CMOS Electronic Integrated Circuit (EIC) driver, the two ICs being interconnected by means of high density and low parasitic copper micro pillars. Several transmissions, in an FDMA PON context, are successfully demonstrated using 500MHzbaud QPSK and 16-QAM modulated subcarriers, achieving Bit Error Rate (BER) below 2.10⁻³. For QPSK-modulated subcarriers (respectively 16-QAM), the available access frequency bandwidth is measured to be [1-7GHz] (respectively [2-4GHz]) with an available loss budget of 9dB (respectively 5dB). Improvements of the Si-PIC are further identified to achieve compliancy with 31dB ODN loss.

Index Terms—PON, FDM/FDMA, Silicon Photonics, CMOS electronics, 3D stacking, micro-pillars, Reflective MZM, QAM modulation, Faraday Rotator Mirror effect.

I. INTRODUCTION

Frequency Division Multiple Access (FDMA) was proven to be an efficient architecture compliant with ITU-T class N2, as defined in the XG-Passive Optical Network (PON) standard (up to 40km and a 31 dB loss budget for the Optical Distribution Network-ODN) [1][2]. The upstream transmissions from the users’ Optical Network Units (ONUs) to the Central Office (CO) receiver were made using off-the-shelf LiNbO₃ modulators and Semiconductor Optical Amplifiers (SOAs) as the ONUs’ transmitters. In order to meet the challenges of the mass market PON application, the ONU must be manufactured in very large scale and at low cost. In [3], we proposed to implement the ONU transmitter and receiver using Si-Photonics and CMOS electronics. We report here on the design, fabrication and experimental demonstration of such an ONU transmitter. Thanks to the latter, an upstream transmission can be established from the ONU to the CO, where single polarization homodyne coherent detection is implemented.

II. UP-LINK FROM THE ONU TO THE CO

The overall architecture of the uplink transmission, from a user ONU to the CO, is reminded in Fig. 1. The Si-PIC operation was previously described in [4], highlighting the Faraday Rotator Mirror (FRM) effect it enables.

The continuous wave seeding light of an External Cavity Laser (ECL) with output power $P_s$ is sent to the Si-PIC at the ONU. The Si-PIC comprises a 2D-surface Grating Coupler (2D-GC) which splits the light into two Transverse Elective (TE) waveguide modes, $TE_{CW}$ and $TE_{CCW}$, propagating, respectively Clock Wise (CW) and Counter Clock Wise (CCW) towards the Si-MZM. As the input state of polarization is unknown the splitting ratio is also random. The electrical signal $u(t)$ (defined below) is applied on the phase modulation sections of each arm of the Si-MZM, in opposite directions, $u_{CW}(t)$ and $u_{CCW}(t)$, co-propagating in the same direction respectively as $TE_{CW}$ and $TE_{CCW}$, and modulating them.

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Afterwards $TE_{CW}$ and $TE_{ECW}$ recombine in the 2D-GC, the splitting of the input signal is thus reversed. The recombined signal is transmitted back to the CO, carrying the upstream data of the user. If the two MZM arms have a π phase difference, the reflected modulated light has a polarization orthogonal to that of the seeding light when arriving at the CO [4], independently of the state of polarization at the input of the device. The resulting homodyne detection signal is shown to be proportional to:

$$\sqrt{P_c} \cdot \text{Loss}_{\text{Fiber}} \cdot \text{Loss}_{\text{R-MZM}} \cdot \epsilon_{co} \cdot \left[1 - \frac{\epsilon_{\text{counter}}}{\epsilon_{co}}\right] \cdot u(t) \quad (1)$$

where $\epsilon_{co}$ (respectively $\epsilon_{\text{counter}}$) are the phase-modulation efficiencies in case of a co-propagating with the optical wave (respectively counter-propagating). $\text{Loss}_{\text{Fiber}}$ and $\text{Loss}_{\text{R-MZM}}$ are respectively the losses of the fiber from the CO to the ONU, and the round trip losses through the Si-R-MZM. Although this is beyond the scope of this paper, it is worth noting that the coherent receiver could also be fabricated using Silicon Photonics technology [5] [6].

The electrical signal applied to the R-MZM arms ($u(t) = \cos(2\pi f_{RF} \cdot t) \cdot s(t)$) is an individual 16-QAM-modulated subcarrier whose frequency $f_{RF}$ (allocated to one user-ONU) and bandwidth, $B_{RF}$, are reminded in Table 1 [1]. In [1], a 32 Gbps upstream capacity was demonstrated, with 32 users being allocated each a different subcarrier frequency $f_{RF}$ comprised in the [1-12] GHz frequency range. Each user having a 330MHz $B_{RF}$ bandwidth, was able to transmit 16-QAM signals at a Baud rate of 300Mbaud over a 31dB loss ODN.

<table>
<thead>
<tr>
<th>$f_{RF}$ &amp; $B_{RF}$</th>
<th>Up Stream capacity (FDMA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>32 users with $1 &lt; f_{RF} &lt; 12$GHz $B_{RF} = 330$MHz</td>
<td>32 users x 1Gbs/user Per user : 16QAM x 300Mbaud x 0.8 (FEC overhead)</td>
</tr>
</tbody>
</table>

Table 1 - Modulating signal features at one user ONU.

The signal $u(t)$ can be generated directly by a very high speed DAC (=25 GS/s) or, as indicated by Fig. 2, by a lower speed dual output DAC (=1 GS/s) followed by individual RF up-conversion stages (IQ mixers and Local Oscillators). While the first solution is useful in prototype experiments, the second solution is much more appropriate for a real application in a low-cost ONU scenario.

![Fig. 2 - u(t) Signal generation at the ONU. AAF = Anti-Aliasing Filter.](image)

III. Si-PIC AND EIC DRIVER DESIGN AND PERFORMANCES

A first version of the PIC which does not integrate an SOA was designed and fabricated (Fig. 3-left). This version is intended to verify the R-MZM and its driver operation, as well as its implementation in the upstream coherent transmission, as described in Section 1. This version will not allow to reach the targeted power budget of the ODN. A second version integrating a heterogeneous III-V/Silicon SOA (Fig. 3) is being fabricated according to the fabrication process reported in [7]. With 10dB gain per SOA, an additional power budget of 20dB is expected for this second version.

![Fig. 3 – Schematics of Version 1 and Version 2 of the Silicon PIC, respectively without and with III-V/Silicon heterogeneously integrated SOA.](image)

A segmented MZM structure (which top view is given in Fig. 4) is chosen to overcome the trade-offs of traditional travelling wave electrodes modulators [8][9]. Each arm is segmented into 12 phase modulation sections with length of 500µm each. Considering one single section, no propagation effects have to be taken into account and a simple lumped circuit model can be used. Besides, the required voltage levels along the whole modulator-arm-electrodes can be guaranteed without suffering from the propagation attenuation featured by integrated transmission lines. The circuit is designed so that the EIC driver is flip-chipped on top of the Si-PIC, reducing the path between the output stages of the driver and the modulation sections.

![Fig. 4 - Top view of the Si PIC.](image)

The Si-PIC was fabricated at CEA-Leti. The waveguides are etched in a 220nm-thick silicon layer, on top of a 2µm-thick buried oxide (BOX). A rib structure is used with a 100nm-thick slab for both passive components of the PIC (MII, 2D-GC) and the phase modulation sections of the modulator. The latter are made from PN doped waveguides. A 50µm-long phase tuner is arranged in one arm of the R-MZM, consisting of a passive waveguide section heated up by flowing a current in a TiTIN layer placed on top of the waveguide. It purpose is to precisely set a π phase difference between the two arms of the R-MZM. Fig. 5 gives the cross section of the phase modulation and phase tuning sections.
The components integrated in the R-MZM were characterized separately. Their performances are reported in Table 2. The 2D-GC exhibits -7 dB Insertion Loss ($I_{LM2-GC}$). The 33.5μm-long MMI has Insertion Losses ($I_{LM}$) of -0.25 dB. It is centered at 1550 nm and has a -1 dB BW greater than 100 nm. The Figures of Merit of the phase modulation sections, $V_g, L_{el}$, propagation loss, $P_L$, and E/O bandwidth, BW, are measured to be respectively 4V.cm, 1 dB/mm and 20 GHz when biased at -1 V. The round trip losses through the Si-R-MZM are then written as follows:

$$Loss_{R-MZM} = 2 \times [I_{LM2-GC} + I_{LM}] + \varepsilon \times P_L$$

(2)

where $L_{el}$ is the sum of the active distributed Phase Modulation sections.

<table>
<thead>
<tr>
<th>$I_{LM2-GC}$</th>
<th>$I_{LM}$</th>
<th>Phase modulation section, 500μm-long (PN doped Si-waveguide)</th>
</tr>
</thead>
<tbody>
<tr>
<td>-7 dB</td>
<td>-0.25 dB</td>
<td>$V_g, L_{el} @ -1 V$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$P_L = 4 V \cdot cm$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>BW $@ -1 V$ &gt; 20 GHz</td>
</tr>
</tbody>
</table>


For the R-MZM reported here, only 6 out of 12 modulation sections were made active (i.e. $L_{el}=3 mm$). The reason for having limited the number of active doped sections was to limit the R-MZM losses. At the same time, this limits the signal strength. These trade-offs are further discussed below. The R-MZM round trip losses are therefore estimated to be $Loss_{R-MZM} \approx 17.5$ dB.

The measured efficiency of the phase tuner is $\approx 0.056 \times \pi / mW$ ($\approx 18 mW$ are required for a $\pi$ phase shift). From Equation (1), simulations can be driven in order to assess the trade-offs of the device [10][11]. Maximizing the demodulated signal reflected back from the R-MZM requires to null the counter modulation efficiency $\varepsilon_{counter}$. For that purpose, cumulating more phase modulation sections makes counter propagating RF and optical waves having bigger delay mismatches, and therefore reduces down the counter modulation efficiency $\varepsilon_{counter}$. In addition with reducing down counter-propagation efficiency, this provides higher phase modulation. On the other hand, as more phase modulation sections are cumulated, the Insertion loss of the MMZ increases. Assuming a 1.6Vpp modulating voltage provided by the CMOS driver, one can quantify these trade-offs. Fig. 6 plots the R-MZM contribution to the homodyne detection signal level

$$\sqrt{Loss_{R-MZM} \times [\varepsilon_{co} - \varepsilon_{counter}]} dB$$

against frequency, for two lengths $L_{el}$ (3 mm and 6 mm) of phase modulation sections and two types of such sections (with different $P_L$ and $V_g, L_{el}$).

$\varepsilon_{counter}$ is evaluated by computing the phase mismatch between the optical and RF waves along the MZM arm length [10][11]. As described in [11], at low RF frequencies ($f_{RF} < 2$ GHz), the counter-propagating modulation efficiency stays high and equal to the co-propagating efficiency ($\varepsilon_{counter} = \varepsilon_{co}$). This is because the RF wavelength is several 10 times longer than $L_{el}$.

![Fig. 5 – Cross section of the phase modulation and phase tuning sections.](image)

![Fig. 6. Contribution of the R-MZM to the homodyne detection signal.](image)
output of driving stage #1, 10.3GHz at the output of driving stage #12.

![Fig. 7](image)

**Fig. 7** – Measured small signal transfer function of the EIC driver elements

The measured large signal transfer function at an input signal of 340mVpp is compared with simulations in **Fig. 8**. Less than 0.2dB gain mismatch per driver stage is observed. The Total Harmonic Distortion is measured to be better than -15dB.

![Fig. 8](image)

**Fig. 8**. Large signal transfer function of the EIC driver elements

In the measurements reported below, only the first 6 stages of the driver are switched ON. For the E/O chip, the achievable modulation voltage is expected to be $V_{mod}=\pm0.8V$, corresponding to a modulation depth of $\pm0.06\sqrt{\pi}$.  

**IV. PACKAGING OF THE SILICON ONU**

The EIC driver was flip-chip mounted on the Si-PIC using 20µm diameter (40µm pitch) copper pillars which were deposited on the EIC wafer [12][13]. These copper pillars were capped with a SnAgCu eutectic solder layer. The corresponding bond pads on the Si-PIC consisted of Al with a Ti/Ni/Au Under Bump Metallization (UBM). Solder reflow was used as the flip-chip bonding method. With this approach, both the chip-alignment and solder-joints were much improved over the results from the thermo-compression bonding. Moreover, this solder reflow is more attractive than thermo-compression as the standard flip-chip bonding process for the mass reflow in industry, due to cost-effectiveness. The quality of the flip-chip bond was checked using cross-sectional grinding and die peeling-off tests, along with electrical tests. All individual copper/solder pillar bumps were found to be well connected. Fig. 9 shows a cross section and top view of the EIC/PIC stacking.

![Fig. 9](image)

**Fig. 9**. Cross-section of the flip-chip bonded EIC and PIC, showing the Cu-Solder pillars between the two chips. Microscope images of the Cu-Solder pillars after cross-sectional grinding.

Using the software modelling tool SolidWorks, a complete virtual mock-up of the full-module was designed, including the flip-chip bonded EIC/PIC, heat-spreader, Peltier-cooler, Al base-plate, PCB, and fibre-array. The test PCBs were designed and fabricated, consisting of three layers with a Rogers-4350B interposer for wire-bonding to the PIC, and containing MSMP-connectors for the RF signals, with surface-mounted electrical components to handle the DC signals. The EIC/PIC assembly is attached to the PCB using Au wire-bonding (Fig. 10 top-left), together with the Al heat-spreader and a Thermo Electric Cooler (TEC). An 8-channel fibre-array was aligned and bonded to the grating-couplers on the Si-PIC (Fig. 10 top-right). Fibre-to-PIC alignment is achieved using active optical feedback through 1D shunt GCs (Fig. 4). The fibre-to-fibre transmission was -11dB, indicating a coupling insertion loss of -5.5dB for each 1D-GC.

![Fig. 10](image)

**Fig. 10** – Overview of the EIC/PIC packaged mockup.
In order to design a thermally optimized package structure, a good working knowledge of the thermal characteristics of the EIC/PIC stacking is important, not only because the stability of filters and SOAs of the Si-PIC are strongly temperature sensitive, but also because it helps determine the appropriate thermal-management solution, which contributes to the overall power consumption- of the device. With this motivation, the temperature increase of the EIC and Si-PIC were measured with the EIC drivers fully switched ON (1.5 Watt-input power). Without TEC control, the temperature increase of the EIC and Si-PIC were +24°C and +17°C respectively. Although the PIC temperature can be stabilized to 20°C±0.01°C using the TEC, no active cooling was implemented for the reported transmission experiments.

V. TRANSMISSION EXPERIMENTS

Referring to Fig. 1, an Arbitrary Waveform Generator (AWG) with 340mVpp-output voltage feeds the input of the EIC driver for generating the modulating signal $\mu(t)$ (with QPSK or 16QAM). A high speed oscilloscope is used after the Photo Detector (PD) array to compute the Error Vector Magnitude (EVM) of the transmitted signal. While the phase difference between the two MZM arms is biased and locked at $\pi$ and $B_{RF}$ is set to 500 MHz, several measurements are performed. Fig. 11 reports the measured EVM as a function of the frequency $f_{RF}$ (which is allocated to the ONU) as the light polarization is randomly rotated over 100 states on the way to the ONU in order to demonstrate the insensitivity to input polarizations. The optical power $P_c$ of the seeding light is set to +11.5dBm and the VOA loss is set such that the optical input power, $P_{IN}$, feeding the R-MZM equals +7.5dBm. The low dispersion of the EVM confirms the polarization insensitivity of the device thanks to the FRM effect. The EVM is kept below -15.9dB (respectively -9.1dB) over a frequency range of [2-4] GHz (respectively [1-7] GHz) which is below the maximum EVM required for achieving a $2.10^{-3}$BER with 16-QAM modulation (respectively QPSK) [14]. This represents a ~2Gbps (respectively 1Gbps) bit rate per user.

Fig. 12 reports the measured EVM as a function of $P_{IN}$ when $f_{RF}$ is set to 3GHz. $P_c$ is set to +11.5dBm and measurements are made by tuning the VOA losses and using 0 and 10km-fiber-length $L_{Fiber}$. A minimum power $P_{IN}$ of -6.5dBm (respectively 2.5dBm) is required for achieving a 16-QAM transmission (respectively QPSK), leading to an available loss budget, ($P_c - P_{IN}$), of 5dB (respectively 9dB). No fiber transmission penalty is observed.

In order to increase the available power budget for the ODN, we increased the optical power $P_c$ of the seeding light, from 11.5dBm to 15.5 dBm. Fig. 13 reports the measured EVM as a function of $P_{IN}$ when $f_{RF}$ is set to 3GHz. Measurements are made by tuning the VOA losses and using 0 km-fiber-length. A noise degradation is clearly brought by the increased EDFA noise at the CO. Besides we suspect that increasing $P_c$ leads to increased Brillouin back scattering, even though over very small fiber length.
VI. DISCUSSION AND CONCLUSION

We demonstrated a novel reflective transmitter targeting implementation in Passive Optical Networks (PON) with Frequency Division Multiplexed Access (FDMA). It is made up of a Silicon Photonic Integrated Circuit (Si-PIC) comprising a Reflective Mach Zehnder Modulator (R-MZM) and its flip chipped CMOS Electronic Integrated Circuit (EIC) driver. Transmissions are successfully demonstrated using 500Mbaud QPSK and 16-QAM modulated subcarriers, achieving Bit Error Rate (BER) below $2 \times 10^{-3}$ with an available loss budget of 9dB (respectively 5dB).

Table 3

<table>
<thead>
<tr>
<th>PIC versions</th>
<th>First version (this work) measured performances</th>
<th>Second version (future work) expected improvement in performances</th>
</tr>
</thead>
<tbody>
<tr>
<td>Round trip -2D-GC loss:</td>
<td>-14 dB (-2 x 7 dB)</td>
<td>Round trip -2D-GC loss reduction: -7 dB (-2 x 3.5 dB)</td>
</tr>
<tr>
<td></td>
<td>$= 14$ dB</td>
<td>Addition of SOA gain: +20 dB (+2 x 10 dB)</td>
</tr>
<tr>
<td></td>
<td>$= +5$ dB (16-QAM)</td>
<td>Expected Improved power budget: +5 dB +27 dB (16-QAM)</td>
</tr>
</tbody>
</table>

Table 3 – PIC versions: Version 1 (this work): measured performances, Version 2 (future work): expected performances comparison

VII. ACKNOWLEDGMENT

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REFERENCES

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