5G integrated Fiber-Wireless networks exploiting existing photonic technologies for high-density SDN programmable network architectures

## Deliverable D4.4
Final report on optical technologies and devices for 5G network functions

<table>
<thead>
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<th>Programme:</th>
<th>H2020-ICT-2016-2</th>
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<tbody>
<tr>
<td>Project number:</td>
<td>761989</td>
</tr>
<tr>
<td>Project acronym:</td>
<td>5G-PHOS</td>
</tr>
<tr>
<td>Start/End date:</td>
<td>01/09/2017 – 31/08/2020</td>
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<tr>
<th>Deliverable type:</th>
<th>Report</th>
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<tbody>
<tr>
<td>Deliverable reference number:</td>
<td>761989/ D4.4/ Final</td>
</tr>
<tr>
<td>Deliverable title:</td>
<td>Final report on optical technologies and devices for 5G network functions</td>
</tr>
<tr>
<td>WP contributing to the deliverable:</td>
<td>WP4</td>
</tr>
<tr>
<td>Responsible Editor:</td>
<td>LioniX</td>
</tr>
<tr>
<td>Due date:</td>
<td>30/12/2020</td>
</tr>
<tr>
<td>Actual submission date:</td>
<td>10/02/2020</td>
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<tr>
<th>Dissemination level:</th>
<th>Public</th>
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<td>Revision:</td>
<td>Final</td>
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**Abstract:** The deliverable presents documentation of 5G-PHOS project and the progress that has been achieved towards developing the photonic technologies and mainly reports the outcomes of: i) the InP PICs, including the EMLs, EAMs and SOA and PD by III-V lab, that were targeted for the Tx and Rx optical interfaces of the FlexBox and RRH at Section 2, ii) the low-loss TriPleX PICs, including OBFNs and ROADMs by LioniX International at Section 3, that were targeted for the RRH Tx and Rx version, iii) Back-up options that were implemented for the Demonstrators and automated assembly techniques at Section 4 and iv) a summary of a series of Fiber Wireless mmWave transmissions at Section 5.

**Keywords:** Fifth Generation (5G), Remote Radio Head (RRH), 5G-PHOS, Fiber-Wireless, Optical Technologies, Integrated Photonic Technologies, Silicon Nitride, III-V technologies, InP platform, Optical Beamforming Networks, Reconfigurable Optical Add Drop Multiplexer
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Abbreviations

AC         Alternating current
ADC        Analog to Digital Conversion
ADS        Asymmetric Double Stripe
AMZI       asymmetric Mach Zehnder Interferometer
APD        avalanche photodiode
AR         anti-reflection
A-RoF      Analog Radio over Fiber
AWG        Arbitrary Waveform Generator
BBU        Base Band Unit
BtB        Back to Back
DAC        Digital to Analog Conversion
dc         direct current
DEMUX      demultiplexer
DFB        Distributed Feedback
DSP        Digital Signal Processing
EAM        Electro Absorption Modulator
eMBB       Enhanced Mobile Broadband
EML        externally modulated laser
ER         Extinction Ratio
EVM        Error Vector Magnitude
FH         Fronthaul
FSR        Free Spectral Range
GSG        Ground-Signal-Ground
IF         Intermediate Frequency
IFoF       Intermediate Frequencies over Fiber
IIR        Infinite Impulsive Response
IM/DD      Intensity Modulation Direct Detection
InP        Indium Phosphide
KPI        Key Performance Indicators
MFD        Mode Field Diameter
MIMO       multi input multi output
MRR        Micro Ring Resonator
MUX        multiplexer
MZI        Mach Zehnder Interferometer
NRZ        Non-Return to Zero
<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
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<tbody>
<tr>
<td>OBFN</td>
<td>Optical Beam Forming Network</td>
</tr>
<tr>
<td>OOK</td>
<td>On Off Keying</td>
</tr>
<tr>
<td>ORR</td>
<td>Optical Ring Resonator</td>
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<tr>
<td>OSBF</td>
<td>Optical Side Band Filter</td>
</tr>
<tr>
<td>PCB</td>
<td>printed circuit board</td>
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<tr>
<td>PD</td>
<td>Photodiode</td>
</tr>
<tr>
<td>PDL</td>
<td>Polarization dependence losses</td>
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<tr>
<td>PS</td>
<td>Phase Shifter</td>
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<tr>
<td>QAM</td>
<td>Quadrature Amplitude Modulation</td>
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<tr>
<td>QPSK</td>
<td>Quadrature Phase Shift Keying</td>
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<tr>
<td>RF</td>
<td>Radio Frequency</td>
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<tr>
<td>ROADM</td>
<td>Reconfigurable Optical Add Drop Multiplexer</td>
</tr>
<tr>
<td>RoF</td>
<td>Radio over Fiber</td>
</tr>
<tr>
<td>RX</td>
<td>receive</td>
</tr>
<tr>
<td>Si3N4</td>
<td>Silicon Nitride</td>
</tr>
<tr>
<td>SiO2</td>
<td>Silicon Oxide</td>
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<td>SMF</td>
<td>Single Mode Fiber</td>
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<tr>
<td>SMSR</td>
<td>Side Mode Suppression Ratio</td>
</tr>
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<td>Signal to Noise Ratio</td>
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<td>SOA</td>
<td>Semiconductor Optical Amplifier</td>
</tr>
<tr>
<td>TE00</td>
<td>zeroth order transverse electric mode</td>
</tr>
<tr>
<td>TEC</td>
<td>Temperature Controller</td>
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<tr>
<td>TIA</td>
<td>Trans Impedance Amplifier</td>
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<tr>
<td>TX</td>
<td>Transmit</td>
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1 System overview

The 5G-PHOS project aims to develop and exploit integrated optical technologies towards enhancing Fiber-Wireless (FiWi) convergence and realizing cost-effective and energy-efficient 5G network solutions for high density use cases. Hence the project is developing highly performing, spectrally efficient and low-cost integrated photonics solutions, in order to architect 5G networks for dense, ultra-dense case, supporting multiple parallel Fiber Wireless links, as well as FiWi links with interleaved multi-wavelength reconfigurable optical add/drop multiplexing (ROADM) and optical beamforming functionalities for the hotspot cases as shown in Figure 1.1. The basic PHY components of the envisioned a-RoF FH of the 5G-PHOS project include:

a) InP photonic integration technologies to develop 25 Gb/s transceivers capable of carrying multi-format wireless signals, that can be used at the Flexbox centralized unit, as well as the e-o and o-e modulating part of the RRH.

b) low-loss TriPleX OBFN technologies to develop broadband beam steering functionalities that would be interfaced with the mmWave circuitry of the RRH. The architecture of the RRH MIMO PCB, including the TriPleX OBFN of LioniX with the InP components of III-V lab and the rest of the RF chain are shown in Figure 1.2 for the Rx of the RRH. A similar setup applies for the Tx RRH using PDs as detailed in the next sections

c) low-loss mini-Reconfigurable Optical Add/Drop Multiplexers on TriPleX to build reconfigurable optical transport networks, as e.g. shown in Figure 1.3

---

Figure 1.1: 5G-PHOS use cases and network scenarios of increasing density.

Figure 1.2: Schematic view of Rx RRH
The introduction of mmWave in 5G C-RANs poses a strict challenge to interconnect large wireless traffic capacities in the field with a high bandwidth optical network with dynamic allocation in a cost-effective way. Towards transforming the current fixed PtP fronthaul networks into reconfigurable PtMp network topologies, both tree/bus-based and ring-based WDM topologies are being investigated in the global 5G R&D domain. The former can offer simplicity with even a few ROADM nodes connected in a cascade configuration, e.g. when surrounding small 5G hotspot areas with eMBB applications, yet at the cost of reduced fault-tolerance unless secondary optical links are utilized. On the other hand, the ring topology with several ROADM nodes arranged in a circular fashion can facilitate data communication in both clockwise and counter-clockwise direction, providing a secondary back up link with fault-tracking, e.g. for URLLC services of high-reliability, yet incorporating large rings with multiple interconnected RRHs is expected to increase the node complexity and port-counts. Featuring different distinct advantages, both topologies can play complementary roles in next generation FiWi C-RANs, with ring solutions better favoring backhaul/fronthaul communication closer to the BBU pools and tree-/bus-based solutions fitting closer to the cell sites and RRHs.

As shown in Figure 1.3 by adopting a centralized approach, a centralized analog BBU Box (the FlexBox) can be placed at the operator’s central office premises, e.g. at the backhaul or metro-ring network being connected to a series of RRHs in an optical bus topology of cascaded ROADMs. For C-RANs, a low-loss ROADM provisions for more than one number of cascaded stages in the challenging A-RoF power-budget networks with enhanced reconfigurability, while SiPho platforms cater for low-cost and high-bandwidth aspects.

![Central Office mmWave Small cell with 360° coverage 5G Hotspot (Peak eMBB traffic)](image)

**Figure 1.3: Reconfigurable optical transport network, fronthauling mmWave PAAs to serve dense and hotspot areas, through cascaded ROADMs.**

The development of the above components as described below, including the

- **InP The current section aims to provide a** short summary of the InP transmitter and receiver components that had been foreseen and what has been developed during the project, before describing the designs, fabrication and characterization results for each device.
- Transmitter components (EAM-SOA, EML-SOA, DFB), described in 0, envisioned for the optical Tx side of the FlexBox and the Rx side of the RRH.
- **InP Receiver component (including 10GHz and 60GHz Photodiodes)**, as described in 2.2, envisioned for the optical Rx side of the FlexBox and the RRH Tx.
- **TriPleX OBFN (on low-loss silicon nitride)** with the TriPleX Si3N4 overview of OBFNs described in section 3, envisioned for the optical RRH input/output interface.
- **TriPleX ROADM** fully packaged by LioniX described in ROADM test results.
2 III-V active components

The current section aims to provide a short summary of the InP transmitter and receiver components that had been foreseen and what has been developed during the project, before describing the designs, fabrication and characterization results for each device.

2.1 Transmitter components (EAM-SOA, EML-SOA, DFB)

2.1.1 Table summary

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<th>Bars of 4 Multi-λ EML</th>
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<td>Measured Static Extinction ratio</td>
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<td>10GHz</td>
<td>10GHz</td>
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<tr>
<td>Measured Bandwidth</td>
<td>&gt;20GHz</td>
<td>&gt;20GHz</td>
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Table 2-1: run 1 expected delivery

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<th>Bars of 4 Multi-λ EML</th>
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Table 2-2: run 2 expected delivery
2.1.2 What was initially scheduled

As it can be clearly understood from Section 1 of this document and Figure 1.2 for the Rx of the RRH, the InP transmitter PICs based on different device configurations were targeted and realised to be used for different applications within system architectures proposed in the project, including:

- **Transmitter InP PICs for RRH (OBFN-Rx part):**
  - DFB lasers (see Figure 1.2 and Figure 2.1): the larger number of lasers to emit @ $\lambda_1 = 1532.68\text{nm}$ (195.6THz); a limited amount of lasers, for multi-wavelength configurations, with 4 wavelength channels within the range 1532.68 - 1535.04 (195.6 to 195.3THz), with 100GHz wavelength spacing.
  - EAM-SOA (see Figure 1.2 and Figure 2.1): arrays of transmissive EAM-SOA with 7° tilted input/output configurations.

![Figure 2.1: Schematic view of the optical components of the Rx RRH](image)

- **Transmitter InP PICs for application in the FlexBox:**
  - EML-SOAs (i.e. DFB + EAM + SOA): the same emission wavelength as for DFB lasers in RRH were chosen. Different device configurations were proposed, in order to optimise with respect to output power, speed and coupling efficiency with optical fibre.

2.1.3 Realisation in 5G-PHOS project

For the realisation of InP transmitters (DFBs, EAM-SOAs, EML-SOAs) III-V LAB relied on its SI-BH fabrication platform, enabling the realisation of energy-efficient and high-power emitters, and fully compatible for high speed modulators. Moreover, the proposed technological option, allows to obtain quasi-circular mode shapes, enabling the realisation of efficient output couplers.

Two main technological adaptation were introduced, in order to make it fully compatible with assembly approach chosen, within 5G-PHOS project, for the realisation of the system demonstrators:

- Realisation of flip-chip compatible contact pads for all the electrical terminals on the devices: laser, modulator (G-S-G), heater, monitoring photo-diode, SOA. This also include layer stack modification to have the right distance between top of the metal and the optical waveguide.
- Realisation of spot-size converters to cope with the very low tolerance of the alignment process with the LIONIX passive waveguides.

The initial work plan for the implementation of those technology adaptations underwent significant changes of strategy, mainly due to major and repeated failures on the main
epitaxy reactor involved in the SI-BH process flow. In particular, significant deviations from the standard process flow had to be introduced, in order to finalise fabrication.

**Two fabrication runs** were dedicated to the realisation of two generation of InP transmitters:

1. A first run to obtain a first generation of flip-chip compatible components, with novel configurations for the SSCs.
2. A second run to optimise fabrication of flip-chip pads and to further optimise fabrication of narrow waveguide tapers for spot size conversion.

In both fabrication runs, the following device configurations were chosen for the 3 main classes of transmitter PICs:

- **DFB emitters**: in order to grant an optimal control on emission wavelength, phase-shifter DFB laser cavities were used. A spot-size converter is integrated at the laser output, in order to increase coupling efficiency with the optical fibre and LIONIX passive waveguides. The latter is based on a tapered waveguide; by means of electron-beam lithography (EBL), tapers with 0.5µm output widths were realised. A Ni/Cr heater is integrated next to the DFB laser for fine control of the emission wavelength. The typical device configuration for DFB emitters is shown in Figure 2.2.

![Figure 2.2: Typical DFB laser configurations realized by III-V LAB for application in the RRH.](image)

- **EAM-SOA**: two different device configurations were realised based on 150µm and 100µm long EAM sections, respectively. Spot-size converters, based on 0.5µm and 0.3µm output width, were realized at the input/output of the PIC, in order to improve butt-coupling efficiency with LIONIX waveguides. Some examples of realised EAM-SOA arrays are shown in Figure 2.3.
**EML-SOA:** Arrays of EML-SOA were realised based on 5 different device configurations:

1. DFB(500µm) + EAM(150µm) + SOA(200µm) + SSC (7° tilted output).
2. DFB(500µm) + EAM(100µm) + SOA(200µm) + SSC (7° tilted output).
3. DFB(500µm) + EAM(150µm) + SOA(400µm) + SSC (7° tilted output).
4. DFB(500µm) + EAM(150µm) + SOA(200µm) + SSC (0° straight output).
5. DFB(500µm) + EAM(100µm) + SOA(200µm) + SSC (0° straight output)

The integrated SSC on all the proposed device configurations has an output taper width of 0.5µm, in order to have an efficient coupling with optical fibres. A typical EML-SOA transmitter, with a straight output is shown in Figure 2.4.

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**Figure 2.3: Typical EAM-SOA arrays realised by III-V LAB for the RRH.**

**Figure 2.4 Example of EML-SOA transmitter realized by III-V LAB for application in the FlexBox.**

### 2.1.3.1 InP transmitters from run 1

**DFB laser performance:**

Typical L-I curves and emission spectra, at 25°C operation temperature, for DFB emitters (tested in the DFB + SSC configuration) from run 1 are shown in Figure 2.5. The 4 wavelength channels are indicated in the pictures as lambda 1 – lambda 4.
Typical figures of merits are the following:

- **Threshold current**: mean value = 31mA; standard fluctuation = 12mA.
- **Emission wavelength (λ1)**: mean value = 1531.6nm; standard fluctuation = 0.5nm.
- **Side-mode suppression ratio (SMSR)**: mean value = 44dB; standard fluctuation = 4dB.
- **Output Facet power @ 200mA**: mean value = 11mW; standard fluctuation = 4mW.

![L-I curves and emission spectra for DFB lasers from run 1 @ III-V LAB (T= 25°C).](image)

**Figure 2.5**: L-I curves and emission spectra for DFB lasers from run 1 @ III-V LAB (T= 25°C).

- **EAM performance**:

  The EAM performance was tested for an EML-SOA device. Measurements were performed at T=25°C, on a mounted chip and the results are shown in Figure 2.6.

  Typical figure of merits for the tested configuration are at 25°C are:

  - **Static extinction ratio** = 9.6dB @ -2V bias.
  - **E/O bandwidth** = 21.4 GHz.
Figure 2.6: Static extinction curve and E/O response of 150µm long EAM fabricated in first run (characterisation performed @ 25°C).

- **SSC performance:**
The Far field distribution for a spot-size converter with output taper width of 0.3µm is shown in Figure 2.7. The mode exhibits a circular shape with a mode diameter (@ 1/e2) of about 3µm: horizontal and vertical measured divergence (total divergence @ 1/e2) of 16° and 15°, respectively.

Figure 2.7: Far field distribution of a sport-size converter with an output taper width of 0.3µm.
- **EML-SOA performance**

  The LI curve of an EML-SOA is shown in Figure 2.8. This result was obtained for the following device configuration: DFB(500µm) + EAM(150µm) + SOA(200µm) + SSC (0° straight output). The LI measurement was performed in CW regime at 25°C, with $V_{EAM} = 0V$ and $I_{SOA} = 40mA$.

![LI curve for an EML-SOA](image)

**Figure 2.8** LI curve for an EML-SOA (DFB(500µm)+ EAM(150µm) + SOA(200µm)), measured at 25°C in CW, with $V_{EAM} = 0V$ and $I_{SOA} = 40mA$.

### 2.1.3.2 InP transmitters from run 2 (*initial results*)

For the second fabrication run of SI-BH transmitters the characterisation is still in progress.

- **DFB emitters:**

  LI characteristic curves (measured @ 25°C in pulsed regime) on DFB lasers are shown in Figure 2.9. The estimated laser figures of merits are:
  - Threshold current: mean value = 36mA; std fluctuation = 13mA;
  - Power @ 200mA: mean value = 7mW; std fluctuation = 2mW;

  No real improvement can be observed with respect to DFB lasers from run1.
2.1.4 Main Outputs of the 5G-PHOS on InP Tx Technology and Lessons learned

Both fabrication runs of SI-BH transmitters have been impacted by major problems on the main III-V LAB epitaxy reactor. In order to cope with this important limitation, backup epitaxy solutions have been adopted, with associated relevant modification with respect to standard process flow.

Despite this important complication, two generations of transmitters could be fabricated.

The significant deviation from standard process flow resulted in important degradation of device performance. In particular: a strong impact on DFB lasers was observed for both fabrication runs: high threshold current, low output power and large fluctuation on laser emission wavelength.

The fabricated SSCs, with the optimisation of the taper technology, allow to obtain mode of circular shapes, with a 1/e² diameter > 3µm. This new building block will now be implemented in our next fabrication run as it reduces significantly the coupling losses and improve the coupling tolerances.

The fabricated EAMs from run 1 have an E/O bandwidth > 20GHz, and a static ER > 9dB @ -2V applied bias.

Due to the good performance of the fabricated SSCs, transmissive EAM-SOAs are suitable for butt-coupling with LIONIX passive waveguides (RRH side).

Moreover, the EAM performance (E/O bandwidth, ER) is compatible with the envisaged application.

The performance of the EML-SOAs is strongly limited by the integrated DFB lasers. Despite this major limitation, modulated output power around 4dBm (facet) for standard modulation driving conditions (-1V bias on the EAM) is achievable at 25°C. The scarce control over the emission wavelength produces a very low yield for 4-channel EML-SOA bars. Delivery of single wavelength EML-SOA chips are still possible for application on the FlexBox side.
2.2 Receiver component

2.2.1 Table summary

The following table summarize the initial plan of photodiode delivery and the status of deliveries on the 14/12/2020. Characterization and chip selections are still on going and complementary deliveries will be done upon partners request. Some needs have also be modified (no assembly of 60G PD with OBFN and therefroe no arrays of 4 UTC but single UTC for test at IMEC and arrays of 3 PD for flip chip assembly at IZM). More details on the devices and their performances will be done in the following sections.

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<thead>
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<th>Bars of 4 PD 10G run 2</th>
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<th>Single 60G PD</th>
<th>Bar of 3 60G PD</th>
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<td>16</td>
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</tr>
<tr>
<td>What was delivered</td>
<td>47</td>
<td>4</td>
<td>0</td>
<td>8</td>
<td>4</td>
</tr>
<tr>
<td>Expected bandwidth</td>
<td>&gt;10</td>
<td>&gt;10</td>
<td>60</td>
<td>60</td>
<td></td>
</tr>
<tr>
<td>Measured bandwidth</td>
<td></td>
<td></td>
<td>50</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>Expected responsivity</td>
<td>Not specified</td>
<td>Not specified</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 2-3: summary of photodiodes deliveries

2.2.2 What was initially scheduled

In 5G-PHOS project, III-V lab was in charge of developing arrays of photodiodes for the RRH (Figure 2.10). These photodiodes are specific because they need to be passively aligned via flip chip with LioniX TripleX platform as explain in D4.1 (section 3.2.1).

Figure 2.10: schematic view of the PDs assembled with LioniX OBFN
Two versions of photodiodes were foreseen in the project:

- **The first variant is the 10G photodiodes** that are expected to detect the IF signal to be upconverted in the RRH to 60 GHz. For the project needs, these photodiodes will also be used in the flexbox which is in the operator network as their specification are identical to the ones in the RRH. The purpose was to deliver photodiodes with >10 GHz bandwidth. 44 arrays of these photodiodes was expected in the project (4 for the flexbox and 40 to make the different variants RRH)

- **The second variant of photodiodes are 60G photodiodes** to be used in the RRH for direct conversion of the 60 GHz signal from the optical domain to the radio domain. The expected performances was a responsivity of 0.65A/W with a bandwidth of 60 GHz.

### 2.2.3 What was realized in 5G-PHOS project

**The first run of waveguide** photodiodes arrays targeted the 10G applications. Due to a major failure of our MBE (molecular beam epitaxy) reactor, we use an existing wafer for this first fabrication run. The results were presented in D4.3 (section 4.2.2) and Figure 2.11 remind the responsivity of the photodiode versus the wavelength. We can see that the responsivity is between 0.7 and 0.8 A/W in the whole C-band.

![Figure 2.11: Typical variation of responsivity with the wavelength](image)

The bandwidth of the photodiode was above 10 GHz for all diode size as remind in figure 4-12 of D4.3. We delivered 47 arrays of 4 UTC photodiodes to IZM for assembly with LioniX OBFN for the RRH.

For the flexbox, to compensate for the delay of fabrication and due to the absence of flip chip constraints, we selected and delivered 4 arrays of 2 UTC photodiode on an already processed wafer. Similarly, to help IMEC to validate their 1st generation TIA, we selected and delivered 8 existing UTC photodiode.
Due to the issue on our MBE reactor, we developed MOVPE growth for our UTC photodiode (structure description in section 4.2.3 of D4.3). This development is also beneficial in the perspective of future industrialization due to the larger capacity of MOVPE reactor (6×2 inches wafer instead of 3×2 inches wafer for MBE) and the capacity to do risk mitigation with 2 epitaxy reactor validated for this component.

Fabrication ended in August 2020. Figure 2.12 shows a photograph of the wafer at the end of the process. We can observe on the 2 first line photodiodes for deliveries (here with 4×10 µm² and 5×25 µm² photodiode), the 2 last lines are test photodiodes with on chip biasing circuit and on the right of the picture we can see test structure for deembedding HF measurements.

![Figure 2.12: microscopic observation of the wafer at the end of the process](image)

No issue was observed during the process and we observe a very good fabrication yield as shown in Figure 2.13 where we observe a very low dark current below 10 nA@2V reverse bias for all diodes. Even the largest diodes (6×50 µm²) presents a very low dark current of a few nA.

![Figure 2.13: Dark current of UTC photodiodes measured on 16 diodes](image)

Responsivity measurements for different diode length shows that we obtain good responsivity above 0.6 A/W for diodes longer than 15 µm. A very high 0.8 A/W is reached for 30 and 50 µm long diodes. For very short 10 µm long diode, the result is close to 0.5 A/W.
We then measured the photodiode bandwidth for the different diode size. The measurement was done in the frequency range 0-50 GHz using an heterodyne bench measurement. The 3-dB bandwidth was above 50 GHz for 4x10, 4x15 and 5x15 µm² photodiodes (between 2.5 and 3 dB losses at 50 GHz, see Figure 2.15). Their response was very similar so it seems that the bandwidth for such small diodes is transit time limited. Further analysis (frequency response up to 110 GHz, S parameter measurement up to 110 GHz,...) are scheduled beginning 2021 to analyse more deeply this aspect.

Due to their high bandwidth, these diodes are the best for generation of V-band signal around 60 GHz and due to higher responsivity, 4x15 and 5x15 µm² photodiodes seems to be a better compromise than 4x10 µm² photodiodes. First diodes were sent to IZM and IMEC for first experiment of association with IMEC narrow-band TIAs and we are waiting for their feedback for further deliveries.

When we look at bigger photodiode, 4x20, 4x25 and 5x20 µm² photodiodes present a 3-dB bandwidth between 45 and 50 GHz. It then decrease between 40 and 45 GHz for 5x25, 6x25 and 5x30 µm² photodiodes. Finally, for large diode of 5x50 µm² demonstrated a bandwidth of 29 GHz and 6x50 µm² UTC still presents a large bandwidth of 25 GHz (Figure 2.15), far beyond the minimum requested by the project. First samples of large photodiodes arrays were sent to IZM for assembly with LioniX OBFN.

**2.2.4 Main Outputs of the 5G-PHOS on InP Rx Technology**

Within 5G-PHOS project, III-V lab developed several important technologies for its high speed photodiode activities:
The first one is the development of a new process, more robust, without polymer (BCB, polyimide) planarization and compatible with flip chip assembly. This help us to increase reproducibility and reliability and allow us to work with partners for flip chip assembly which is an important topic for high speed receiver and industrialization aspects. As said previously, we have also validated the growth of high speed UTC photodiode with MOVPE epitaxy which present the following benefits:

- *Securization of the process* via the availability of a second source of epitaxy
- *More compatible with industrialization* due to the larger throughput (6 wafer per run instead of 3).

The developed photodiode present a high bandwidth (>50 GHz) and responsivity. The results are under analysis to have a global model of the photodiode (possible due to the large variation of diode geometry in 5G-PHOS wafer) in order to scale them up to reach >100 GHz bandwidth and also implemented in our photonic integrated circuit like preamplified photodiode, to be used in a follow-up H2020 NEBULA project). The main application area will be High speed PON network above 50 Gbit/s (especially when integrated with an optical preamplifier to have a large optical budget), data center applications and generation of mm-wave for communication and security.

Furthermore, we have validated the realization of on chip biasing circuit (decoupling capacitor+matching resistor) which is very interesting for high speed applications. Preliminary results shows that we have a broad bandwidth above 50 GHz for 5×25 µm² photodiode using this technology (Figure 2.16).

![Figure 2.16: Frequency response of UTC photodiodes](image)
3 TriPleX Si$_3$N$_4$ overview of OBFNs and ROADMs

3.1 OBFN System overview

The RX OBFN requires 8 RF inputs and one fiber-output. The fiber output will go to the FlexBox for further processing. The 8 RF inputs are connected to the antennas’ MIMO PCBs. The schematic block-scheme of the whole system is shown in Figure 3.1.

Figure 3.1: schematic block-scheme of the whole system. The RX part is shaded in blue, the TX part is shaded in green. The InP chips are colored purple, and the TriPleX chips are colored gray.

In this figure, the light from the light source (InP Laser) is split into 8 branches using a TriPleX 1x8 splitter, then light is amplified and modulated in two arrays of 4 InP SOA+EAM devices. After this, light is coupled into the TriPleX RX OBFN and at the end of the beam former, light is coupled into a single optical fiber, travelling towards the ROADM to combine the signals from multiple MIMO PCBs into a single fiber towards the FlexBox.

The RF signals are connected to the OBFN via the EAMs. The reason for applying multiple chips in a row, is that on the InP layer stack for lasers it is nearly impossible to produce a 1x8 splitter. Therefore, the splitting is done on TriPleX, with the disadvantage of chip-to-chip coupling loss. To compensate for this additional chip-to-chip loss, an SOA is added in each optical path.

For the 5G-PHOS project, two chip runs in TriPleX were scheduled. For both Run 1 and Run 2, the same basic schematic designs were planned, with the distinction that the RF frequencies in Run 1 are planned for 5 GHz while Run 2 was planned for 60 GHz with backwards compatibility to 5 GHz. During the course of the project, the 60 GHz modulation was shifted from the optical domain to the RF domain (electrical upconversion at the MIMO PCB). This decision was made after the optical designs for Run 2 were made. Because the optical designs (designed for 60 GHz) were backward compatible with 5 GHz, no designs needed to be changed. If the 60 GHz components were available for full integration after all, they could still be deployed.

During the project, it became clear that, to complete the full optical link as shown in Figure 3.1, all optical components needed to seamlessly work together. Because of difficulties in processing of some of these components, LioniX and the 5G-PHOS consortium made a choice to implement also a backup option that relied fully on existing expertise and readily available components of LioniX. The difference in schematic overview is minute; only for RX, an external laser needs to be used, rather than an integrated laser. This is shown in Figure 3.2. Also, the modulators phase modulated rather than amplitude modulated and are not amplified, as was the case in the original system design.
Figure 3.2: schematic block-scheme of the whole backup system. The RX part is shaded in blue, the TX part is shaded in green. The InP chips are colored purple, and the TriPleX chips are colored gray. In this picture, an external laser is used as light source for the RX part of the system.

### 3.2 TriPleX components and hardware deliverables

The table below presents a summary of the components, while the main specifications, mask-designs and photos of each component are each summarized at a separate table.

<table>
<thead>
<tr>
<th>Description</th>
<th>Run</th>
<th>Required project / committed by LioniX</th>
<th>Number of chips available to the consortium (delivered and on-stock combined)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1x8 OBFN RX (5 GHz)</td>
<td>1</td>
<td>10</td>
<td>35</td>
</tr>
<tr>
<td>1x8 OBFN TX (5 GHz)</td>
<td>1</td>
<td>10</td>
<td>35</td>
</tr>
<tr>
<td>1x8 splitter</td>
<td>1</td>
<td>10</td>
<td>30</td>
</tr>
<tr>
<td>1x4 multi λ OBFN TX</td>
<td>1</td>
<td>4</td>
<td>12</td>
</tr>
<tr>
<td>ROADM (chip)</td>
<td>1</td>
<td>2</td>
<td>12</td>
</tr>
<tr>
<td>ROADM (assembly)</td>
<td>1</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>1x8 OBFN RX (60 GHz, backward compatible to 5 GHz)</td>
<td>2</td>
<td>10</td>
<td>30</td>
</tr>
<tr>
<td>1x8 OBFN TX (60 GHz, backward compatible to 5 GHz)</td>
<td>2</td>
<td>10</td>
<td>40</td>
</tr>
<tr>
<td>1x8 splitter</td>
<td>2</td>
<td>10</td>
<td>40</td>
</tr>
<tr>
<td>1x8 OBFN RX backup (chip)</td>
<td>2</td>
<td>0</td>
<td>40</td>
</tr>
<tr>
<td>Item</td>
<td>Quantity 1</td>
<td>Quantity 2</td>
<td>Quantity 3</td>
</tr>
<tr>
<td>-------------------------------------------</td>
<td>------------</td>
<td>------------</td>
<td>------------</td>
</tr>
<tr>
<td>1x8 OBFN RX backup (assembly)</td>
<td>2</td>
<td>0</td>
<td>2</td>
</tr>
<tr>
<td>1x8 OBFN TX backup (chip)</td>
<td>2</td>
<td>0</td>
<td>40</td>
</tr>
<tr>
<td>1x8 OBFN TX backup (assembly)</td>
<td>2</td>
<td>0</td>
<td>2</td>
</tr>
<tr>
<td>Chips to test assembly procedure</td>
<td>2</td>
<td>0</td>
<td>60</td>
</tr>
<tr>
<td>Sabox test electronics</td>
<td>0</td>
<td>0</td>
<td>3</td>
</tr>
</tbody>
</table>
The 1x8 transmit OBFN is designed to receive light from an EML from a fiber (right hand side), go through a single-side-band filter to prepare the modulated light for single-side-band true time delay, split the light into eight branches and each branch contains ring resonators to provide a unique and required flat-top broad-band delay to the signals. The output of the OBFN (left hand side) is coupled to 8 photodiodes, where the modulated light is converted into an electrical RF signal. By tuning the delay properly between the different branches, beam forming can be achieved. The signal from the eight photodiodes will be fed to the 8 antenna tiles, effectively coupling them together to create a steerable and shape-able RF beam.

| Amount of chips required by project and/or committed by LioniX | 10 |
| Number of chips available to the consortium (delivered and on-stock combined) | 35 |
The 1x8 receive OBFN is designed to receive filter light entering from the left. The light originates from a single DFB laser, that is split into 8 branches. Each of these branches is fed into a modulator and amplified by a SOA. The 8 modulators are connected to an RF signal that originates from the 8 antenna tiles. Then, the light enters the TriPleX chip, the 8 branches contain ring resonators to provide a unique and required flat-top broad-band delay to one of the two side-bands. The light is combined by a 1x8 combiner and fed into a single-side-band filter to make the double-side-band modulated light single-side-modulated light, that can be detected by a photodiode at the end of a fiber (right-hand side).

| Amount of chips required by project and/or committed by LioniX | 10 |
| Number of chips available to the consortium (delivered and on-stock combined) | 35 |
### 1x8 splitter, Receive (Run1)

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>The purpose of the 1x8 splitter is to split the light of the receiver from a single diode laser into 8 branches. The output of the branches will be fed into 8 separate modulators. The reason why we have chosen to have 1 laser split into 8, rather than have 8 lasers is that the OBFN requires coherent combining on the chip. Because the light is now 8x lower per branch, an additional SOA is added to each branch to add more optical power.</td>
<td></td>
</tr>
</tbody>
</table>

| **Amount of chips required by project and/or committed by LionIX** | 10 |
| **Number of chips available to the consortium (delivered and on-stock combined)** | 30 |
The purpose of the mini-ROADM was to split 4 wavelengths plus modulated signal into 4 different channels, so 4 OBFNs can be addressed while only 1 fiber input/output is used. The ROADM simultaneously can combine 4 different wavelengths plus modulated signal into a single fiber. From these 4 wavelengths, 1 up to 4 wavelengths can be chosen to be either switched towards the antenna or directed towards the next antenna further down the line. The ROADM was also packaged by LioniX.

| Amount of chips required by project and/or committed by LioniX | 4 |
| Number of chips available to the consortium (delivered and on-stock combined) | 12 |
| Amount of assemblies required by project and/or committed by LioniX | 2 |
| Number of assemblies available to the consortium (delivered and on-stock combined) | 3 |
1x4 OBFN multi-wavelength, Transmit (Run1)

The purpose of the 1x4 multi-wavelength OBFN was to see if the idea of a processing multiple wavelengths on a single OBFN would decrease the number of OBFNs required in the system. Unfortunately, it turned out that processing multiple wavelengths on the same OBFN structure is not compatible with the coherent processing scheme chosen for this project. Therefore, after the test-structure that was a 1x4 OBFN, this multi-wavelength idea was not elaborated further into the second run of chips.

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Amount of chips required by project and/or committed by LioniX</td>
<td>2</td>
</tr>
<tr>
<td>Number of chips available to the consortium (delivered and on-stock combined)</td>
<td>12</td>
</tr>
</tbody>
</table>
The 1x8 transmit OBFN is designed to receive light from an EML from a fiber (right hand side), go through a single-side-band filter to prepare the modulated light for single-side-band true time delay, split the light into eight branches and each branch contains ring resonators to provide a unique and required flat-top broad-band delay to the signals. The output of the OBFN (left hand side) is coupled to 8 photodiodes, where the modulated light is converted into an electrical RF signal. By tuning the delay properly between the different branches, beam forming can be achieved. The signal from the eight photodiodes will be fed to the 8 antenna tiles, effectively coupling them together to create a steerable and shape-able RF beam. The OBFN is designed, such that it is capable to process light that is modulated at 5 GHz, while also being able to process light modulated at 60 GHz, with only a few heater-settings different.

| **Amount of chips required by project and/or committed by LioniX** | 10 |
| **Number of chips available to the consortium (delivered and on-stock combined)** | 40 |
The 1x8 receive OBFN is designed to receive filter light entering from the left. The light originates from a single DFB laser, that is split into 8 branches. Each of these branches is fed into a modulator and amplified by a SOA. The 8 modulators are connected to an RF signal that originates from the 8 antenna tiles. Then, the light enters the TriPleX chip, the 8 branches contain ring resonators to provide a unique and required flat-top broad-band delay to one of the two side-bands. The light is combined by a 1x8 combiner and fed into a single-side-band filter to make the double-side-band modulated light single-side-modulated light, that can be detected by a photodiode at the end of a fiber (right-hand side). The OBFN is designed, such that it is capable to process light that is modulated at 5 GHz, while also being able to process light modulated at 60 GHz, with only a few heater-settings different.

<table>
<thead>
<tr>
<th>Amount of chips required by project and/or committed by LioniX</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of chips available to the consortium (delivered and on-stock combined)</td>
<td>30</td>
</tr>
</tbody>
</table>
### 1x8 splitter, Receive (Run2)

The purpose of the 1x8 splitter is to split the light of the receiver from a single diode laser into 8 branches. The output of the branches will be fed into 8 separate modulators. The reason why we have chosen to have 1 laser split into 8, rather than have 8 lasers is that the OBFN requires coherent combining on the chip. Because the light is now 8x lower per branch, an additional SOA is added to each branch to add more optical power.

| **Amount of chips required by project and/or committed by LioniX** | 10 |
| **Number of chips available to the consortium (delivered and on-stock combined)** | 40 |
**1x8 OBFN Backup, Transmit (Run2)**

The 1x8 transmit OBFN is designed to receive light from an EML from a fiber (right hand side), go through a single-side-band filter to prepare the modulated light for single-side-band true time delay, split the light into eight branches and each branch contains ring resonators to provide a unique and required flat-top broad-band delay to the signals. The output of the OBFN (left hand side) is coupled to 8 photodiodes, where the modulated light is converted into an electrical RF signal. By tuning the delay properly between the different branches, beam forming can be achieved. The signal from the eight photodiodes will be fed to the 8 antenna tiles, effectively coupling them together to create a steerable and shape-able RF beam. The OBFN is designed, such that it is capable to process light that is modulated at 5 GHz, while also being able to process light modulated at 60 GHz, with only a few heater-settings different. This backup design is also packaged by LioniX.

<table>
<thead>
<tr>
<th>Amount of chips required by project and/or committed by LioniX</th>
<th>0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of chips available to the consortium (delivered and on-stock combined)</td>
<td>40</td>
</tr>
<tr>
<td>Amount of assemblies required by project and/or committed by LioniX</td>
<td>0</td>
</tr>
<tr>
<td>Number of assemblies available to the consortium (delivered and on-stock combined)</td>
<td>2</td>
</tr>
</tbody>
</table>
The 1x8 receive OBFN is designed to receive filter light entering from the left. The light originates from a single external fiber coupled DFB laser, that is split into 8 branches by the TriPleX chip. Each of these branches is fed into a phase modulator. The 8 modulators are connected to an RF signal that originates from the 8 antenna tiles. Then, the light enters the TriPleX chip again, the 8 branches contain ring resonators to provide a unique and required flat-top broad-band delay to one of the two side-bands. The light is combined by a 1x8 combiner and fed into a single-side-band filter to make the double-side-band phase-modulated light into single-side-band amplitude modulated light, that can be detected by a photodiode at the end of a fiber (right-hand side). The OBFN is designed, such that it is capable to process light that is modulated at 5 GHz, while also being able to process 60GHz modulated light, with only a few heater-settings different.
The purpose of this chip is to assess the accuracy in which IZM can place optical chips with their passive alignment method. Two of these chips will be coupled to each other to assess the straight waveguide coupling. The advantage of this test chip is that it is 100% certain that the waveguides are at exactly the same height, because they are from the same wafer.

<table>
<thead>
<tr>
<th>Amount of chips required by project and/or committed by LioniX</th>
<th>0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of chips available to the consortium (delivered and on-stock combined)</td>
<td>30</td>
</tr>
</tbody>
</table>
## Chips to test assembly procedure (run 2)

The purpose of this chip is to assess the accuracy in which IZM can place optical chips with their passive alignment method. Two of these chips will be coupled to each other to assess angled waveguide coupling. The advantage of this test chip is that it is 100% certain that the waveguides are at exactly the same height, because they are from the same wafer.

<table>
<thead>
<tr>
<th>Amount of chips required by project and/or committed by LioniX</th>
<th>0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of chips available to the consortium (delivered and on-stock combined)</td>
<td>30</td>
</tr>
</tbody>
</table>
The SaboX is a piece of electronics, in-house designed and build by LioniX International, to drive optical chips, such as OBFNs. The SaboX has the capacity to drive chips with up-to 320 heaters simultaneously. This means 320 voltage sources 0-24V, all controlled by computer. In the original proposal, no driving electronics was taken into account. However, since the chips are very complex to control, LioniX offered to provide 3 one SaboX for the ROADM, one SaboX for the RX OBFN and one SaboX for the TX OBFN.

| Amount of SaboX required by project and/or committed by LioniX | 0 |
| Number of SaboX available to the consortium (delivered and on-stock combined) | 3 |
3.3 Characterization - Test results on TriPleX components

Here, we describe the results that were obtained from the ROADM and from the initial testing of the backup OBFNs.

3.3.1 ROADM test results

The ROADM results have been elaborately described in Deliverable D4.3. here we repeat the most important aspects.

-The ROADM was designed to operate at 4 specific wavelengths on the ITU grid: 1536.61 nm, 1537.40 nm, 1538.19 nm, 1538.98 nm (each spaced 100 GHz apart)

-The ROADM was designed to have a flat-top passband of at least 12 GHz, to pass the carrier and both 2 GHz wide signal bands (double side-band modulation) at a 5 GHz modulation frequency, as schematically depicted in Figure 3.3.

Figure 3.3: schematic representation of the carrier, signal bands and channel spacing.

The ROADM was designed to have roughly 0.5 dB propagation loss (on-chip) and about 1 dB fiber-chip coupling per facet. This means a total expected insertion loss of 2.5dB. The actually fabricated device showed performance close to calculated and designed values. This is shown in Figure 3.4 and Figure 3.5. In-band suppression is as low as -30dB.

Figure 3.4: calculated results for dropping all 4 wavelengths. Figure 3.5: measured results for dropping all 4 wavelengths.
3.3.2 TX backup OBFN, initial results

The TX backup OBFN has been characterized by LioniX, before it was shipped to AUTH for integration into the complete system.

![Figure 3.6](image)

**Figure 3.6:** photograph of the TX OBFN backup option, with the eight photodiode connectors indicated. Light enters the chip from the left-hand side through a fiber.

For setting the filter, we have chosen to modulate a laser wavelength of 1531.22 nm, because a laser was available in our labs at this wavelength. Since the filter is fully controllable and shifts in wavelength with changing chip temperature, the ITU wavelengths of 1536.61 nm, 1537.40 nm, 1538.19 nm, 1538.98 nm (for which the ROADM was designed) will also be easily aligned to the filter. The Single Side Band filter measured response is shown in Figure 3.7. Here, the filter is aligned such that a laser at ITU grid wavelength 1536.61 nm is in the pass-band of the filter. Also, a single side band (indicated by B) will be filtered out, so only a single side band (indicated by C) will be transmitted into the OBFN. This is chosen, because the true-time delay from the OBFN only works with single-side band modulated signals. The filter can be set to any of the above mentioned wavelengths of the ITU grid, to make double-sided modulated signals into single sided modulated signals. This filter curve was measured by means of an optical spectrum analyzer.
Figure 3.7: measured SSBF response, with ITU grid wavelength 1536.61 nm drawn in (indicated at A), and the both side-bands that will occur when this wavelength is modulated at 5 GHz with a bandwidth of 2 GHz are indicated by the blue bands B and C.

Figure 3.8: same as Figure 3.7, but now with the calculated filter response drawn in (blue curve). As can be seen, there is an almost perfect overlap between calculation and measurement.

The filter curve is can also be measured by sweeping the laser line over a small frequency range. This way, the filter curve can also be measured by all photodiodes, using an RF Vector Network Analyzer set to time-sweep mode. The measured filter responses measured in this way (for each photodiode individually) are shown in Figure 3.9 to Figure 3.16.
Figure 3.9: measured SSBF filter curve on PD 1

Figure 3.10: measured SSBF filter curve on PD 2

Figure 3.11: measured SSBF filter curve on PD 3

Figure 3.12: measured SSBF filter curve on PD 4
Figure 3.13: measured SSBF filter curve on PD 5

Figure 3.14: measured SSBF filter curve on PD 6

Figure 3.15: measured SSBF filter curve on PD 7
It can be noted from these measurements that the out-of-band suppression of the SSBF in RF seems to be higher than in the optical domain. The reason for this, is that the beating of the RF frequency on the photodiode originates from 2 light fields, so in the RF domain, the filter suppression is the square of that in the optical domain.

As indication, in the 4th branch (i.e., PD 4), we have also switched on the five rings at different coupling coefficients, i.e., at different delays. By tuning the rings closer together and by tuning the intensity of the dips, the true-time delay can be changed. The reason for this is, that time delay is the derivative of the time-sweep as shown in Figure 3.17. A zoom-in on the passband is shown in.

Figure 3.16: measured SSBF filter curve on PD 8

Figure 3.17: measured filter response on PD4, with (blue) and without (orange) rings switched on.
Figure 3.18: zoom-in of the pass-band, showing 5 dips in the blue curve. Each dip represents the resonance of one of the five rings in the path of the OBFN, that goes towards PD4. The derivative of the blue curve gives the true-time delay. By tuning the dips closer together, the delay can be more broad-band. By tuning the intensity of the dips, less or more delay can be applied.

**3.4 RX OBFN backup option**

The RX OBFN is still under measurement at the moment of writing. After basic characterization, it will also be shipped to AUTH to be implemented in the optical link. The OBFNs are shown in Figure 3.19. The modulators are directly connected to the RF connectors.

Figure 3.19: two backup option RX OBFNs
4 Steps towards automated assembly

For mass production, it is not economically viable to manually assemble complete devices. The reason is simply a time-dependent one: a manual assembly easily takes several days, while a proper automated assembly only takes minutes to complete. Therefore, several crucial steps have been investigated for the 5G-PHOS project.

4.1 Waveguide cladding thickness

Passive alignment has always been very difficult, because of alignment tolerances, which are very stringent. In this project, the idea to passively align the chips is as simple as it is elegant. For InP, the cladding layer will be increased compared to its normal thickness, while for TriPleX the cladding layer will be decreased compared to its normal thickness. The goal is to have the center of the mode-field in InP and in TriPleX aligned to each other, as measured from the top. We have chosen a value which is manufacturable in both InP and TriPleX, namely 5.5 μm. Schematically, this is shown in Figure 4.1.

![Figure 4.1: Location of the mode field center, compared to the top of the waveguide chip](image)

The height of the chip can be fairly well monitored; on top of the waveguide layer using LPCVD and PECVD a layer of silicon oxide cladding will be grown to a thickness of about 5 micron, and finally a layer of 500 nm gold/platina will be deposited.

4.2 Etching of facets

By carefully growing the thickness of the wafer and gold, the alignment of the waveguides is significantly simplified. However, since two waveguide chips have to be positioned to each other, the facet of the chip has to be very accurately defined. Because TriPleX is a non-crystalline material, cleaving of chips is not accurate. Therefore, TriPleX chips are diced out with a dicing blade that is many times the allowed accuracy. The facet is required to be straight within 1 μm over the full waveguide chip, whereas by dicing it is easily several tens of microns. By polishing the accuracy can be close, but the yield is very low, roughly 10%.

For this polishing method, alignment marks were placed on the edges of the waveguide chip, as shown in Figure 4.2.
Figure 4.2: alignment marks on the side of the waveguide chip, before and after polishing.

Because this method took a lot of time, and the yield was extremely low, another method of accurately defining the waveguide facet was used. This experimental method uses waveguide facet etching, which is a lot more accurate and straighter, and also faster. The difference between a diced and etched facet is shown in Figure 4.3. This method is mostly accurate, however it has the downside that the whole waveguide chip has to be etched through. This means that the wafer becomes unstable after etching many facets. Also, it is very difficult to etch straight down (both in chemical and dry etching methods). This is shown in Figure 4.4. Here, it is clear that the facet is etched under a slight angle. Luckily, the angle of the etching is small enough to still reach the waveguide facet for efficient coupling of light.
Figure 4.3: Difference between an etched and diced facet.

Figure 4.4: etched facet, side-view.
5 Fiber Wireless transmission through 5G-PHOS photonic components

Following the development of the 5G-PHOS components, there have been a series of Fiber Wireless transmissions that have been performed already, that are now being developed towards the final project demonstrators.

These can be summarized as

- **Lab Trials #1**: Fiber Wireless Transmissions through the mini-ROADM for up to 360° mmWave coverage, *presented and described in detail at D4.3*.

- **Lab Trials #2**: A Two stage optical fronthaul bus using two mini-ROADMs and mmWave MIMO antenna, using two ROADM nodes, that has been performed during the last months towards Demo #3, *described in the section below*.

- **Lab Trials towards Demo #3 (FiWi Demo-link)** Fiber Wireless transmissions using the obtained back up optical components, including commercial InP Tx Rx, the ROADM and the back-up OBFN, that is currently on-going (beginning of 2021), with *progress being included in D7.2*.

### 5.1 Lab Trial #1: 4x FiWi links through the mini-ROADM

This sections presents only a short summary of D4.3, including the work done towards presenting multiple parallel Fiber Wireless transmissions over the 5G-PHOS mini-ROADM that may enable the transmission of multiple beams that can serve areas of higher density and higher capacity.

This scenario is conceptually illustrated in Figure 5.1 along with the experimental setup and the EVM spectrum towards a 360° coverage. Ultra dense networks require multiple millimetre wave beams to several end-point terminals scattered in a small area or neighbourhood. In this case, the capacity of a single Fiber Wireless fronthaul link can be enhanced by multiplying it spatially to implemented multiple Fiber connected antennas with directional beams. The network scenario with four Fiber Wireless links transmitting to four 90° sectors with 360° area coverage, forming the first demonstration of a mmWave Small cell network architecture with complete one-cycle coverage. We present the results obtained, using the 4λ ROADM followed by 4x steerable 60GHz beams of the 32-element Phased Array Antenna to experimentally demonstrate the first multi-wavelength FiWi Point to Multi-Point architecture for 5G small cell environments. The OADM is fabricated on low-loss Si3N4/SiO2 TriPleX platform of LionIX, capable to demultiplex four 100GHz C-band wavelengths. The FiWi links extend across a 10km Single Mode Fiber distance and 1m V-band link, transmitting four 250MBaud QAM16 signals through mmWave beams of 10° width steered across a 90° sector.
5.2 Lab Trial #2: Two ROADM-stage FiWi fronthaul bus

Two cascaded ROADM stages where combined to form a reconfigurable Fiber-Wireless fronthaul bus topology, where the four wavelengths of the WDM downlink traffic transmission could be selectively dropped either at the first or the second stage for wireless transmission. The results and the experimental setup used for this scenario are depicted in Figure 5.2(a)-(d), which the layout being identical with the one that was described in section 1 (figure 1.3).

The 4λ-WDM IFoF modulated data stream was injected into a SSMF spool of 1 km length instead of 10 km of the previous transmission, before reaching the two cascaded ROADM stages interconnected at the through ports in an optical fronthaul bus configuration and featuring four Drop ports at each stage. Subsequently, the four Drop output ports of each ROADM stage, with an average optical output power between all four ROADM channels of -0.4 dBm after the first stage and -5.4 dBm after the second stage, were reconfigurably connected to the PAA transmitter for wireless transmission, after being opto-electrically converted by the APD. Finally, after 1 m V-band link with beamsteering, the signal was received by a portable horn receiver antenna assembly that was connected to SA for evaluating purposes.

The current setup allows hosting four reconfigurable FiWi IFoF/mmWave links, that can be either dropped and transmitted over the air at the output ports of the first stage or at the second stage of the ROADM. The results of the two cascaded ROADM FiWi demonstration are shown in Figure 5.2 (a) and (b), after properly reconfiguring the two ROADM by tuning accordingly the respective heaters, while the signals emerging at each of the Drop ports were wirelessly transmitted by the PAA across 1 m at +45° degrees and received by a portable antenna for evaluation purposes. More specifically, Figure 5-2 (a) illustrates the constellation diagrams of the first scenario denoted as “3-1”, where three ($\lambda_1, \lambda_2, \lambda_3$) of the four streams dropped at the first stage, while $\lambda_4$ propagated to the
through port of the first ROADM and in turn dropped at the respective drop port of the second ROADM. The final received signals featured EVM values of 11.2%, 11.2% and 11.1% for the three signals that are dropped and wirelessly transmitted at the Drop port 1, 2 and 3 of the first ROADM stage respectively, revealing again equal operation with negligible variation, and an EVM of 11.9% for the fourth wavelength emerging at the Drop port 4 of the second ROADM stage. A small degradation of the data streams dropped at the first stage was observed compared to the 4λ-WDM transmission scenario ‘4-0’, when all λ₁-λ₄ were dropped at the first stage, resulting in less than 1% EVM penalty, possibly attributed to a residual thermal cross-talk impact of the drop filter transfer functions during ROADM reconfiguration.

Figure 5-2 Constellation diagrams of scenarios (a) “3-1”, the 1st case where 3 λs dropped at the 1st ROADM and the last one dropped at the 2nd ROADM, (b) “2-2”, the 2nd case where 2 λs dropped at the 1st ROADM, and the remaining two dropped at the 2nd ROADM stage. (c) EVM comparison of the 5 transmission scenarios: Fiber only, FiWi without going through ROADMs, “4-0” 4 lambdas dropped at the 1st ROADM, “3-1” 3 lambdas dropped at the 1st ROADM and 1 dropped at the 2nd ROADM, “2-2” 2 lambdas dropped at the 1st ROADM and 2 are dropped at the 2nd ROADM. d) Experimental setup of two-stage FiWi IFoF beamsteering downlink

Finally, Figure 5-2 (b) showcases the constellation diagrams of the scenario denoted as “2-2”, where two (λ₁,λ₂) of the four streams dropped at the first ROADM stage, while λ₃,λ₄ propagated to the through port of the first ROADM and dropped at the respective drop ports of the second ROADM. The constellation diagrams revealed EVM values of 11.7%, 11.8%, 12.3% and 12.4% respectively, with an average EVM value of 12.05% and 0.7% variation. An almost negligible variation of 0.1% between the EVM values of the signals that are transmitted after the second ROADM stage was also observed, as happens also for the equal performance among the channels transmitted at the output of the first ROADM stage, confirming that the signal quality mostly relies on the power loss and the number of cascaded ROADM stages, rather than exhibiting any wavelength
channel dependence. It is worth mentioning that all EVM values of all cases satisfy the 3GPP limit of <12.5% for QAM-16, while also meeting the 5G KPI requirement for an 1 Gb/s downlink. In order to investigate the scalability of the devices, we evaluated the degradation at each stage of the link by comparing five transmission scenarios as shown in Figure 5-2 (c). Specifically, the first transmission was IFoF wired transmission only, with an average EVM of 4.7%. The second transmission case comprises a simple FiWi without interleaved ROADM, revealing an average EVM of 10.2%. The remaining three scenarios were described in sections IV and V, the “4-0”, the “3-1” and the “2-2” with an average EVM of 11.05%, 11.35% and 12.05%, respectively. These results, reveal that the main source of degradation is the V-band radio, adding +5.8% average EVM penalty compared to the fiber setup only, while the pass through one ROADM stage only adds a small degradation with average EVM penalty of 1% for all channels.

5.3 Lab Trials towards FiWi Demonstrator-links with ROADM, InP EMLs, PDs and OBFN

This section presents a short summary of the FiWi demo link, using the back-up optical components, i.e. commercial EML-based Tx and PIN-PD Rx, the ROADM and the back-up OBFN towards the demonstrators. As these have been made available in January 2021, the current work is in progress and is being reported mainly in D7.2 At the moment, a typical Intermediate Frequency over Fiber link was implemented using the above commercial components, aiming to experimentally benchmark its performance against the targeted specifications of the 5G-PHOS InP components of Section 2. Towards this RoF benchmark-test, the following experimental setup-layout shown in Figure 5-3 was implemented. The commercial EML was driven by an ILX laser source and supplied with a negative DC biasing voltage of -1.7V. After biasing the EML, an analog radio waveform was modulated on the EAM signal using QAM64 and QAM128 (or even higher formats). The radio data stream was digitally synthesized by an Arbitrary Waveform Generator, before being fed to the EML, where it is loaded on an optical carrier for fiber propagation towards a photoreceiver. The received spectrum and constellation IQ diagram for various modulation formats are shown in Figure 5-3, using a 3 GHz IF frequency carrying and 625 MBaud symbol rate. It can be seen that all constellation diagrams were clearly demodulated, featuring Error Vector Magnitude (EVM) values between 0.95 – 1.2 % (for fiber lengths of a few hundreds of meters), being constantly below the EVM threshold values of 3GPP. The next steps are developing complete FiWi links (in extend to simple A-IFoF), and then characterizing and integrating the back-up OBFN.

![Figure 5-3](image-url)

*Figure 5-3  i) experimental setup for testing the IFoF RoF link using commercial components with fiber spools of 1 or 25 km length and ii) Recorded IQ constellation diagrams and respective RF spectrum of the received analog signal for 625 Mbaud data streams of QAM64 and QAM128 and a 3 GHz IF.*
6 Conclusions

This deliverable described the work performed towards the development of optics for Fiber Wireless networks envisioned within the 5G-PHOS project. The document mainly reports the outcomes of: i) the InP PICs, including the EMLs, EAMs and SOA and PD by III-V lab, that were targeted for the Tx and Rx optical interfaces of the FlexBox and RRH, ii) the low-loss TriPleX PICs, including OBFNs and ROADMs by LioniX International, that were targeted for the RRH Tx and Rx version, iii) Back-up options that were implemented for the Demonstrators and iv) a summary of a series of Fiber Wireless mmWave transmissions.