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

**Deliverable D4.3**
Report on 2\textsuperscript{nd} generation of optical devices

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Abstract: 5G-PHOS aims to develop and evaluate a converged Fiber Wireless (FiWi) 5G broadband fronthaul/backhaul network for highly dense use cases based, where the mmWave radio signal will be loaded directly on optical Intermediate Frequencies over Fiber (IFoF), to be transported through fiber to long distances, leveraging spectrally efficient, highly-performing and low-cost integrated photonic technologies.

This deliverable reports on the 2nd generation of optical devices, including the InP optical transceivers for the electro-optic and opto-electronic conversion, as well as the TriPleX chips for the Optical Beamforming Networks and the Reconfigurable Add Drop Multiplexers. Finally, using the an early test structure of an Externally Modulated Laser, a multi-band Fiber Wireless V-band/IFoF fronthaul link was demonstrated across 7km of single mode fiber and m V-band distance, showcasing world record capacity for multi-band 5G fronthaul links. The deliverable focuses on the design process and technology associated with the optical chips.

Keywords: Photonic Integrated Chips, InP Externally Modulated Lasers, Photodiodes, TriPleX Si3N4, Optical Beamforming Network, Reconfigurable Optical Add Drop Multiplexer, Fiber Wireless transmission
Disclaimer: The information, documentation and figures available in this deliverable are written by the 5G-PHOS Consortium partners under EC co-financing (project H2020-ICT-761989) and do not necessarily reflect the view of the European Commission. The information in this document is provided “as is”, and no guarantee or warranty is given that the information is fit for any particular purpose. The reader uses the information at his/her sole risk and liability.
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<tbody>
<tr>
<td>AC</td>
<td>Alternating current</td>
</tr>
<tr>
<td>ADC</td>
<td>Analog to Digital Conversion</td>
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<td>ADS</td>
<td>Asymmetric Double Stripe</td>
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<td>AMZI</td>
<td>asymmetric Mach Zehnder Interferometer</td>
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<tr>
<td>APD</td>
<td>avalanche photodiode</td>
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<tr>
<td>AR</td>
<td>anti-reflection</td>
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<td>A-RoF</td>
<td>Analog Radio over Fiber</td>
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<tr>
<td>AWG</td>
<td>Arbitrary Waveform Generator</td>
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<tr>
<td>BBU</td>
<td>Base Band Unit</td>
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<tr>
<td>BtB</td>
<td>Back to Back</td>
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<tr>
<td>DAC</td>
<td>Digital to Analog Conversion</td>
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<tr>
<td>DC</td>
<td>direct current</td>
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<tr>
<td>DEMUX</td>
<td>demultiplexer</td>
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<tr>
<td>DFB</td>
<td>Distributed Feedback</td>
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<tr>
<td>DSP</td>
<td>Digital Signal Processing</td>
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<tr>
<td>EAM</td>
<td>Electro Absorption Modulator</td>
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<tr>
<td>eMBB</td>
<td>Enhanced Mobile Broadband</td>
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<td>EML</td>
<td>externally modulated laser</td>
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<tr>
<td>ER</td>
<td>Extinction Ratio</td>
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<td>EVM</td>
<td>Error Vector Magnitude</td>
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<td>FH</td>
<td>Fronthaul</td>
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<td>FSR</td>
<td>Free Spectral Range</td>
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<td>GSG</td>
<td>Ground-Signal-Ground</td>
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<tr>
<td>IF</td>
<td>Intermediate Frequency</td>
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<td>IFoF</td>
<td>Intermediate Frequencies over Fiber</td>
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<tr>
<td>IIR</td>
<td>Infinite Impulsive Response</td>
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<tr>
<td>IM/DD</td>
<td>Intensity Modulation Direct Detection</td>
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<tr>
<td>InP</td>
<td>Indium Phosphide</td>
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<tr>
<td>KPI</td>
<td>Key Performance Indicators</td>
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<tr>
<td>MFD</td>
<td>Mode Field Diameter</td>
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<td>MIMO</td>
<td>multi input multi output</td>
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<tr>
<td>MRR</td>
<td>Micro Ring Resonator</td>
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<tr>
<td>MUX</td>
<td>multiplexer</td>
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<tr>
<td>MZI</td>
<td>Mach Zehnder Interferometer</td>
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<tr>
<td>NRZ</td>
<td>Non-Return to Zero</td>
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<tr>
<td>OBFN</td>
<td>Optical Beam Forming Network</td>
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<tr>
<td>OOK</td>
<td>On Off Keying</td>
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<tr>
<td>ORR</td>
<td>Optical Ring Resonator</td>
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<tr>
<td>OSBF</td>
<td>Optical Side Band Filter</td>
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<tr>
<td>PCB</td>
<td>printed circuit board</td>
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<tr>
<td>Abbreviation</td>
<td>Description</td>
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<tr>
<td>PD</td>
<td>Photodiode</td>
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<td>PDL</td>
<td>Polarization dependence losses</td>
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<td>PS</td>
<td>Phase Shifter</td>
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<td>QAM</td>
<td>Quadrature Amplitude Modulation</td>
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<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>
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<tr>
<td>RoF</td>
<td>Radio over Fiber</td>
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<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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<tr>
<td>SMF</td>
<td>Single Mode Fiber</td>
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<tr>
<td>SMR</td>
<td>Side Mode Suppression Ratio</td>
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<td>SNR</td>
<td>Signal to Noise Ratio</td>
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<tr>
<td>SOA</td>
<td>Semiconductor Optical Amplifier</td>
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<tr>
<td>TE00</td>
<td>zeroth order transverse electric mode</td>
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<tr>
<td>TEC</td>
<td>Temperature Controller</td>
</tr>
<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 Executive Summary

This document covers the design and initial measurements of the second generation of optical chips for the 5G PHOS project. The optical assemblies contain two general types of optical chips, namely active (InP based) chips and passive (TriPleX based) chips. The assemblies will be used to beam-form the RF signals received and transmitted by the antenna array.

The InP based chips are Lasers, Detectors and Modulators, which are critical components in electro-optic and opto-electric conversion. The TriPleX (Si3N4/SiO2) chips are passive waveguides that provide processing of the RF signal in the optical domain.

The types of InP chips designed and described in Section 4 are:
- Lasers (light source)
- Fast Photodiodes (10 GHz and 60 GHz, for opto-electrical conversion)
- Modulators (for electro-optical conversion)
- SOAs (for optical amplification)

The types of TriPleX chips, as described in section 5, are:
- 1x8 Optical Beam Forming Network (OBFN) for transmit,
- 1x8 OBFN for receiver
- 1x8 splitter
- 1x4 multi-wavelength OBFN for transmit
- Reconfigurable Optical Add Drop Multiplexer (ROADM)
- Fully packaged OBFNs

Finally, in section 6, the development of the assembly process of the optical devices is discussed while section 7 presents the performance of the proposed analog Fiber Wireless link in a series of 5G system level experiments, including the 5G-PHOS optical technologies.
2 Introduction

2.1 Purpose of this document

The objective of this deliverable is to describe the second generation of optical chips and their assembly, both in InP and in the TriPleX platform.

Regarding the InP chips developed by 3-5 lab, due to fabrication delays, the characterization of the 1st generation of InP chips which where not described in D4.2 (because they were in fabrication) will be described in this deliverable. Concerning the 2nd generation of optical chips, we will report its advancement and their measurement will be reported in the last deliverable of this workpackage (D4.4).

The second generation of the SiN TriPleX chips is reported in this deliverable. Concerning the design of the second generation of optical chips, as a large part of the design parameters and choices made in this second generation of optical chips are equal to those described in D4.2, providing feedback to this second generation development. This document emphases the differences between the new designs and the previous designs. For the exact parameter choices, the reader is referred to D4.2. Fully-packaged and fully-functional standalone TriPleX chips are also being developed and reported.

Moreover, the assembly processes and development of PCBs for III-V/TriPleX co-integration is presented.

Finally, Fiber Wireless transmissions and reconfigurable fronthaul links with record capacities and beamsteering functionalities using the developed 5G-PHOS optical technologies are being also reported, validating the high performance of the underlying photonic technologies.

2.2 Document structure

First, we will present a short system overview to remind how the optical components will be used in section 3. Secondly, InP optical chips will be described in section 4, and TriPleX signal processing chips (OBFN and ROADM) in section 5. Finally, assembly process are addressed in section 6, while system experiments will be reported in section 7.

2.3 Audience

This document is public.
3 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. The project is thus 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 3-1. 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

b) low-loss, high-index contrast TriPleX technologies to develop broadband optical beamformers

c) ring-resonator-based mini-Reconfigurable Optical Add/Drop Multiplexers (mini-ROADMs).

![Figure 3-1 5G-PHOS use cases and network scenarios of increasing density.](image)

3.1 High-linear External Modulated Lasers (EMLs)

Considering the large available spectrum of NR systems, a-RoF techniques allow spectrally efficient fronthauling of a mmWave channel, by loading it on a low optical IF with simple Intensity Modulation/Direct Detection schemes without occupying excess spectrum, while multiple IFs can be synthesized on a single aggregate electrical signal of a few GHz bandwidth. However, the linearity of the a-RoF link will play a pivotal role in the overall system performance and thus a-RoF transmitters have mainly relied on costly Mach-Zehnder Modulators (MZMs), owing to their high linearity and chirp-free operation to alleviate the impact of the fiber chromatic dispersion. Towards circumventing the associated costs when considering network densification deploying conventional chirp-free modulators with external laser source, EMLs exploiting a Distributed Feedback Laser and an Electro-absorption Modulator (EAM) as shown in Figure 3-2 form more cost-effective solution, but have been primarily used in digital communications and advanced modulation format transmissions with DSP techniques recovering the non-perfect linearity. However, joint optimizations of the Fiber-Wireless links have been scarce and
constrained to the use of MZMs, few-channels or low bandwidths, and only very recently EMLs were shown to support multiple IF channels with user-rates >1Gb/s and aggregate capacities beyond 10Gb/s, satisfying the respective KPIs for multi-user 5G network environments. In order to achieve this, EMLs need to operate in the linear region of their transfer function, with a steep curve between two voltage values, for low signal distortion recoverable by simple DSP technique allowing to directly transfer the aggregate electrical analog IF signals to an a-RoF optical carrier with low signal distortion.

3.2 Optical beamformers

Beamformers comprise specialized circuitry that provides the delays required by the antenna elements in order to transmit/receive wireless signals to/from the desired direction by means of constructive and destructive waveform interference, a function known as beamsteering, and exist in three main types: Digital, Analog and hybrid beamformers. Digital beamformers utilize digital baseband processing with both amplitude and phase modulating RF chain dedicated per antenna element at a high-power consumption and cost. Analog beamformers employ simple architectures with multiple analog phase shifters (PS) shared between different antenna elements, towards less expensive hardware but with lower system performance and antenna gains. Hybrid beamformers are an intermediate solution with multiple analog sub-arrays of PSs shared among groups of antenna elements offering good compromise between system performance, cost and complexity. On the contrary, optical beamformers so far rely on integrated photonic networks of phase shifting or True Time Delay (TTD) elements only. The most typical configuration of an OBFN relies on tree-based networks of 1x2 splitters with interleaved Optical Ring Resonator (ORR)-based TTD elements. The group delay re-sponse of the ORR is exploited by thermo-optically tuning its resonance frequency, while tuning the coupling coefficient between the bus and the ring waveguide changes the TTD. Implementing analog beamforming exclusively in the optical domain allows seamlessly interfacing with the envisioned optical fronthaul network, as shown in Figure 3-2, to release broad instantaneous bandwidth of tens of GHz, large tunable delays of hundreds of ps, cost-reduction and low energy consumption.

3.3 Optical Add/Drop Multiplexers

Optical Add/Drop Multiplexers (OADMs) have been widely deployed in WDM optical networks for their wavelength multiplexing and selective routing capabilities. OADMs can serve two operations either to “Add”, i.e. insert a new optical wavelength-channel to an existing WDM light-stream or “Drop”, i.e. remove one wavelength channel and route it towards a different spatial output. The two functionalities are schematically shown in Figure 3-2, where an 3-channel WDM-stream of λ1-3 is fed from the Input (In) port at the left side. Two wavelengths-channels of λ2 and 3 are “Dropped” towards the Output ports at the bottom side, allowing for λ1 wavelength to continue its propagation through the Common (Com) port to the rest of the network. Respectively, one new wavelength, the λ4, is “Added” to the WDM stream of the Com port. In order to achieve this, OADMs consist of an optical demultiplexer at the input, an optical multiplexer at the output and an intermediate wavelength-selective device that configures each lightpath connectivity. When the latter relies on static wavelength filtering devices, e.g. Fiber Brag Gratings, freespace grating optics, Planar Lightwave Circuits, OADMs are considered fixed with predefined lightpaths and when it relies on tunable devices traditionally based on Mi-cro-Electro-Mechanical Systems (MEMS), Liquid Crystals on Silicon (LCoS) or Thermo-Optic PLCs, OADMs are considered Reconfigurable. Lately, integrated Silicon Photonics (SiPho)
ROADMs, based on cascaded micro-meter thermo-optic or electro-optic Add/Drop rings, have attracted intense interest, as they support small footprint, low power consumption, fast reconfiguration times with CMOS-compatibility for reduced fabrication costs and recently also polarization insensitive operation. A possible architecture of a SiPho ROADM that implements the previously described Fixed OADM operation. Introducing ROADMs in FH networks allows migrating from the currently fixed PtP links between the RRH and the BBU towards a point-to-multipoint switched infrastructure with reduced hardware and increased gains stemming from statistical multiplexing of user traffic.

![Figure 3-2 End-to-end communication of the analog Fiber Wireless link using an EML, an Optical Beamformer and a Silicon Photonic ROADM.](image)

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<th><strong>Table 1</strong> Key features of 5G-PHOS Optical Technologies for 5G Fronthaul netowrks</th>
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<tr>
<td><strong>OBFN</strong></td>
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<td><strong>ROADM</strong></td>
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4 III-V active components

4.1 InP transmitter (EML & EAM-SOA)

InP transmitters will be implemented both in the OBFN-Rx and in the flexboxes. The different device configurations, which will be used are the following:

- **OBFN-Rx:**
  - DFB lasers.
  - SOA-EAM arrays.

- **Flexbox:**
  - EML-SOAs.
  - EML-SOA multi-lambda arrays.

Due to several complication in the fabrication process (equipment failure, additional process complexity due to the adaptation for flip chip assembly with TripleX), the 1st fabrication run is typical array configurations of the different building block for InP transmitters are shown in Figure 4-1. Further details on component configurations can be found in D4.2. All those components are fabricated on a single wafer, from the integration and the combination of the different building blocks. In this deliverable we shall describe the first fabrication run which is at its last fabrication step (interconnection). We will also report after the progress of the 2nd fabrication run which has been set up.

![Figure 4-1 Typical array configurations for InP transmitter. In (a) a multi-wavelength array of DFB + SSC emitters; in (b) an array of EAM SOA transmittive devices; in (c) a multi-wavelength array of EML-SOA-SSC emitters.](image)
Figure 4-1 shows the layout of the different InP based transmitter which are processed in 5G-PHOS project. We have DFB lasers to feed the OBFN of Lionix, EAM-SOA arrays to convert the radio data from the antennas to an optical signal to be sent to the flexbox and EML SOA to sent the data from the flexbox to the antenna. InP transmitters are based on waveguides fabricated by means of a semi-insulating buried heterostructure (SI-BH), providing key advantages on device performance: high bandwidth for the EAM; good electrical and thermal performance for laser and SOA section; low-loss circular modes.

Moreover, the SI-BH technology provides sufficient flexibility and robustness on waveguide definition to realise spot-size converters (SSC). The latter are of fundamental importance to increase coupling tolerance with passive components (see D4.1). Typical SSCs are based on tapered waveguides, which should allow to reach output mode diameters of 2µm.

**4.1.1 Process Overview**

The SI-BH fabrication process for InP transmitters is based on 5 epitaxial growths, performed using both gas source molecular beam epitaxy (GS-MBE) steps and metal-organic vapour phase epitaxy (MOVPE):

1. Initial epitaxial growth for the EAM stack.
2. Epitaxial regrowth for laser/SOA stack (butt-joint integration).
3. Epitaxial regrowth for DFB grating with optimized doping profile.
4. Epitaxial regrowth of later SI-BH InP blocking layer.
5. Epitaxial regrowth of top InP cladding with optimized doping profile.

The main fabrication steps of the SI-BH technology used for InP transmitters are summarised in Figure 4-2. Each of those steps is crucial to meet component specification. Three fabrication runs have been launched so far: 1A, 1B and 1C. Each of those steps is crucial to meet component specification.
The run 1A has been affected by major issues on main epitaxy equipment during laser regrowth: a poor doping level was measured, with a possible prohibitive degradation of the injection on the laser/SOA section. This run has been interrupted and put in stand-by, in order to start a new run (1B).

For the run 1B, third party epitaxy facilities have been validated for laser and grating regrowth. A major problem during the SI-BH regrowth step, made the processed wafers unusable and the run has been stopped (March 2019).

The run 1A has been resumed in April 2019. An alternative approach for the regrowth of the pInP cladding layer been adopted to compensate for lower doping level within the laser/SOA sections: the different doping elements used on this alternative approach should favour diffusion toward deeper layers with lower doping levels. On the other hand, excessive doping diffusion might have detrimental effects on the EAM performance.

In order to meet requirements for butt-coupling with passive circuits, as well as compatibility with flip-chip integration (cf. D4.2), the standard process has been modified. With this first fabrication run the required adaptation steps of the technology process can be tested and validated. This run should allow to deliver a first generation of devices for January 2020.

The run 1C has been started in April 2019. The process has progressed very slowly due to a major failure of our primary epitaxy equipment. A major maintenance action has been conducted from May 2019 to Oct 2019.

In order to progress with the fabrication run, a new third party solution has been validated and successfully applied for laser/SOA regrowth. This has allowed to obtain high quality laser structures. The grating regrowth has been performed on the III-V LAB primary epitaxy facility at the end of the maintenance period, in November 2019. This fabrication run should be finalised for the end of April 2020.

4.1.2 Technology Adaptation for 1st fabrication run

As mentioned above, two main elements have driven the adaptation of the standard technology process for InP transmitters:

- SSC optimization.
- Flip-chip compatible contact configuration.

For the SSC, the selected configuration is based on a tapered waveguide, with waveguide width reduction from 1.5µm to 0.5µm. Two different configurations have been tested for the SSC (cf. D4.2): straight and 7° tilted. For the 7° tilted configuration a curved waveguide is necessary to transition from the 0° oriented active waveguide to the 7° output.
In order to fabricate taper tips as narrow as 0.5µm, a specific electron-beam lithography step was introduced and validated. The etching + SI-BH regrowth resulted in a smooth morphology without apparent deviations from the standard photolithography process adopted for larger taper tips. The fabricated tapered SSC can be observed in Figure 4-3.

The other critical step is the realisation of metal vias to bring the n-contact metal pad at the same height as the laser and modulator contacts. For this purpose dielectric pads are used to control the height and deposition conformity of both dielectric and metal layers is necessary to guarantee the continuity of the metal contact, as shown in Figure 4-4. Both the vias and the dielectric pad have been realised, as shown in Figure 4-3. Three more metallisation steps have to be performed, in order to finalise the fabrication: heater, top metal pad and back contact.

![Metal contact](image)

**Figure 4-4** A cross-sectional view of the metal routing from the bottom of the via n to the top of the dielectric pads for flip-chip mounting.

**4.2 III-V photodiode**

**4.2.1 Introduction**

The photodiode are based on a planar multimode structure represented in Figure 4-5 and Figure 4-6 show a simulation of the propagation of the light inside the structure. The operation principle of the multimode photodiode and its optimization to obtain
simultaneously a high responsivity and a large bandwidth was fully described in D4.2. In this deliverable, we will describe the results of the 1st fabrication run of the photodiodes and show the advancement of the 2nd fabrication run which is currently under process.

Figure 4-5: Schematic view of the waveguide UTC photodiode.

Figure 4-6: Optical simulation of the photodiode

4.2.2 1st fabrication run

For the first fabrication run, due to a failure of our wafer with a non-optimal epitaxy which is limited by input optical power. This is due to a constant doping profile in the InGaAs absorbing layer which imply a pure diffusive process for the motion of electrons in the absorption layer. Therefore, the bandwidth of this structure is limited by the transit time inside the absorption layer. Figure 4-7 shows the simulation of the responsivity of the photodiode as a function of the position of the fiber relatively to the surface of the photodiode and Figure 4-8 a photograph of the wafer after fabrication. The process was specially optimized to have 5.5 µm between the top of the metallization and the optimum light injection point in order to have a proper alignment between the InP chips and the Triplex chips. This require to remove planarization polymer like BCB or polyimide and to use thick dielectric (SiO2, SiNx) for a proper height alignment.

Figure 4-7: Simulation of the responsivity of the photodiode of the first run

The process required to do the proper pad alignment for flip chip assembly has an impact on the etching of the input facet. To mitigate the risk, we cleaved the 2 inch wafer into 2 pieces. On the 1st half wafer, despite preliminary test, we observe lots of defect on the input facet (Figure 4-9) after etching which result in a large dispersion of the photodiodes.
responsivity (0.56 to 0.77 A/W for 5×25 µm² PD). These photodiodes were sent to IZM for mechanical assembly and preliminary testing. Therefore, after additional process optimization, we etched the second half wafer with very low defect (Figure 4-10).

Figure 4-9: SEM image of the input facet of photodiode of the 1st ½ wafer

Figure 4-10: SEM image of the input facet of a photodiode of the 2nd ½ wafer

On the second ½ wafer we obtain very good responsivity with very low dispersion, as we can see in Table 4-1. We achieve a high responsivity from 0.4 A/W for very short photodiode (10 µm length) to 0.83 A/W for 50 µm long photodiode. We observe a rapid increase of the responsivity between 10 and 20 µm length because the absorption is length limited for 10 and 15 µm PD. For longer diodes, the increase of responsivity with increasing length is moderate because most of the light has already been absorbed. The width has a small effect because the light is efficiently focused by the integrated lens. The PDL is moderate for 10 and 15 µm photodiode (1-2 dB range) and very low (<0.5 dB) for PD length above 25 µm. These photodiodes were sent to IZM for assembly with LioniX OBFN.
<table>
<thead>
<tr>
<th>PD size (L×W)</th>
<th>R_{mean} (A/W)</th>
<th>Standard deviation</th>
<th>PDL_{mean} (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4×10 µm²</td>
<td>0.41 A/W</td>
<td>0.05</td>
<td>2 dB</td>
</tr>
<tr>
<td>4×15 µm²</td>
<td>0.58 A/W</td>
<td>0.03</td>
<td>1.4 dB</td>
</tr>
<tr>
<td>4×20 µm²</td>
<td>0.67 A/W</td>
<td>0.05</td>
<td>0.8 dB</td>
</tr>
<tr>
<td>4×25 µm²</td>
<td>0.71 A/W</td>
<td>0.05</td>
<td>0.1 dB</td>
</tr>
<tr>
<td>5×15 µm²</td>
<td>0.63 A/W</td>
<td>0.05</td>
<td>1.1 dB</td>
</tr>
<tr>
<td>5×25 µm²</td>
<td>0.75 A/W</td>
<td>0.02</td>
<td>0.4 dB</td>
</tr>
<tr>
<td>5×30 µm²</td>
<td>0.76 A/W</td>
<td>0.02</td>
<td>0.3 dB</td>
</tr>
<tr>
<td>5×50 µm²</td>
<td>0.78 A/W</td>
<td>0.07</td>
<td>0.1 dB</td>
</tr>
<tr>
<td>6×50 µm²</td>
<td>0.83 A/W</td>
<td>0.03</td>
<td>0.1 dB</td>
</tr>
<tr>
<td>7×25 µm²</td>
<td>0.81 A/W</td>
<td>0.01</td>
<td>0.5 dB</td>
</tr>
</tbody>
</table>

Table 4-1: responsivity of the 1st run of 5G-PHOS photodiodes

Figure 4-11 shows the influence of the wavelength on photodiode responsivity for 2 photodiodes. As we can see, the variation is very low (a few %), close to the precision of measurement equipment. Therefore, we can confirm that photodiode present a wide optical bandwidth with negligable performance variation over the full C-band.

The photodiodes present a 3-dB bandwidth above 10 GHz for each diode size. We observe a low frequency roll off which is due to a process issue which make the InP substrate conductive as it will be explain in the next section. As expected, the bandwidth decrease with the increase of the photodiode area due to the RC time constant.
The S parameters of the photodiode was measured with a Vector Network Analyser (VNA) to extract the equivalent circuit of the photodiodes. Figure 4-13 shows the measurement of the S parameter of a 5G-PHOS photodiode and the result of its simulation with the equivalent circuit described below the Smith chart. We can see that there are losses at low frequency which can be explained by the conductive behaviour of the substrate. This create additional RC losses. This behaviour is due to an issue during the etching of the etching of the N contact of the photodiode, which transform the semi-insulating substrate in a conductive substrate and will be corrected in the second fabrication run.
To optimize photodiode geometry and check design hypothesis for run 2 design and performance analysis, it is important to extract the intrinsic capacitance and resistance of the photodiode. Therefore, we report in Table 4-2 the junction capacitance, the series resistance and the associated theoretical RC bandwidth of the different size of diodes we have designed in run 1. It is worth noting that the final bandwidth of a photodiode will be lower than the RC limited bandwidth because of the transit time limitation ($f_t$ around 50-60 GHz on run 1 and expected >100 GHz on run 2) and potential parasitic.

We can see from Table 4-2 that all size of diodes are compatible with 10 GHz applications (4×15 µm² PD was not reported due to an issue with their electrodes). Therefore, we can plan to use long photodiode (5×30 µm², 5×50 µm, 6×50 µm²) for this 10G photodiode in run 2 fabrication. For 60 GHz applications, we should target close to 100 GHz RC bandwidth. Therefore, we focus on 4×10 and 4×15 µm² PD for this particular application.

<table>
<thead>
<tr>
<th>Diode size (W×L)</th>
<th>Capacitance (fF)</th>
<th>Series resistance (Ω)</th>
<th>RC limited bandwidth</th>
</tr>
</thead>
<tbody>
<tr>
<td>4×10 µm²</td>
<td>17</td>
<td>30.1</td>
<td>117 GHz</td>
</tr>
<tr>
<td>4×20 µm²</td>
<td>30.7</td>
<td>14.4</td>
<td>80 GHz</td>
</tr>
<tr>
<td>5×15 µm²</td>
<td>25</td>
<td>25.8</td>
<td>84 GHz</td>
</tr>
<tr>
<td>5×25 µm²</td>
<td>39.3</td>
<td>11.6</td>
<td>65 GHz</td>
</tr>
<tr>
<td>5×30 µm²</td>
<td>51.3</td>
<td>9.2</td>
<td>52 GHz</td>
</tr>
<tr>
<td>5×50 µm²</td>
<td>81.3</td>
<td>6.2</td>
<td>34 GHz</td>
</tr>
<tr>
<td>6×50 µm²</td>
<td>95.5</td>
<td>5.4</td>
<td>30 GHz</td>
</tr>
<tr>
<td>7×25 µm²</td>
<td>56</td>
<td>8.3</td>
<td>48 GHz</td>
</tr>
</tbody>
</table>

Table 4-2: Junction capacitance and series resistance of the 1st run of UTC photodiode

4.2.3 2nd fabrication run

The second fabrication run is based on new wafers made by MOVPE epitaxy specifically designed for 5G-PHOS project. We first optimize the absorbing section of the photodiode...
to improve its bandwidth by implementing a gradient in the doping profile of the InGaAs absorbing layer to improve electron transit time in the absorbing section (band structure described in Figure 4-14). For the multimode waveguide, we implement 3 different structures: 2 of them (Structure A&B) used aluminium based material (AlGaInAs) for the multimode waveguide as it is the reference material in our MOVPE reactor. Structure A is based on our standard structure and structure B is a more risky optimized structure. The simulation of this 2 structures are described in D4.2. The last structure (structure C) is based on InGaAsP waveguides and is optically equivalent to structure A.

![Diagram](image)

**Figure 4-14: band structure of a UTC photodiode**

We first realize a fast process on 1 wafer of each structure to validate the optical performances (responsivity) of the photodiodes. Structure C was validated with very good responsivity varying from 0.65 A/W for 15 µm photodiode (minimum length in this test photomask) to 0.81 A/W for 30 µm photodiode (maximum length available in this test photomask).

However, we discover that deep etch of AlGaInAs alloys creates cylindric shape which prevent efficient coupling of light from an optical fiber or a SiN waveguide. Therefore, we launch the process of 2nd wafer of structure C which are scheduled for end Q1 2020.

<table>
<thead>
<tr>
<th>Diode length</th>
<th>15 µm</th>
<th>20 µm</th>
<th>25 µm</th>
<th>30 µm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Responsivity</td>
<td>0.65A/W</td>
<td>0.71 A/W</td>
<td>0.71A/W</td>
<td>0.81A/W</td>
</tr>
</tbody>
</table>

**Table 4-3: responsivity of structure C**
Figure 4-15: SEM image of an input facet of structure B PD
5 SiN optical processing of TriPleX components

5.1 OBFN RX

5.1.1 System overview and operating frequency

Originally, the second run of chips was meant to provide optical beam forming at 60 GHz. During the project, it became clear that the electronic upconversion, provided by Siklu, from a 5 GHz modulated optical frequency to 60 GHz RF signal, was also very stable. Therefore, it is likely that the optical part of the RRH-system, including optical beamforming, filtering and optical transmitter/receiver, will need to work at 5 GHz, feeding the integrated electronic upconversion system of the MIMO antenna, while the full 60 GHz optical beam forming will be evaluated and demonstrated as standalone technology. Nevertheless, the OBFNs in this second run are designed to be capable of processing 60 GHz signals, as well as 5 GHz signals. Three possible routes for 60 GHz identified are:

(a) optical upconversion of a laser that is modulated at 5 GHz with a second laser either 55 GHz or 65 GHz separated from the first laser,
(b) 60 GHz direct modulation.
(c) 5 GHz direct modulation. With a filter, unwanted frequencies can be filtered out.

Schematically, this is shown in Figure 5-1 (a), (b) and (c).

![Figure 5-1: block-schematic drawing of the generation of 60 GHz signals. (a) contains two lasers with frequencies v1 and v2 respectively, 65 GHz separated. Laser 1 is modulated at 5 GHz. The filter removes the unwanted v1 and a single side band. (b) contains a single laser at frequency v1. The light is modulated at](image-url)
60 GHz, and the filter removes a single side band. (c) contains a single laser modulated at 5 GHz. The filter removes a single side band.

For option (a) we have chosen to have a laser at 65 GHz separation from the first laser. This means a single filter will have to be designed capable of filtering unwanted frequencies at 65 GHz and filtering single-side band for the 5 GHz and 60 GHz direct modulation. It is worth noting, that the OBFN requires a stable phase-relation between the carrier and the sideband. This means that the two lasers in option (a) somehow need to be actively phase stabilized.

The RX OBFN system overview remains the same as in D4.2, with the exception of two parts: 1) a second laser at frequency $v_2$ needs to be added and 2) the single side-band filter (SSBF) will have a different free spectral range (FSR). The schematic design is shown in Figure 5-2, where the differences compared to the RX in D4.2 are highlighted in orange.

![Figure 5-2: schematic design of the RX OBFN.](image)

Figure 5-2: schematic design of the RX OBFN. The flow of light in this figure is mostly from left-to-right (except $v_2$ which starts right-to-left and after a bend goes left-to-right). The white-colored blocks are TriPleX based, the purple colored blocks are InP based waveguide chips. The orange parts are updated to fit to the 60 GHz scheme.

### 5.1.2 TriPeX chip

In this section, the TriPeX chips for RX will be discussed. After the laser signal has been split into eight branches, each light path is amplified by an SOA and modulated by an EAM. After this, the light is coupled into the 1x8 RX OBFN. The OBFN consists of 8 branches, each containing a multitude of optical ring resonators, that can provide an arbitrary true-time delay to the signal, up to a maximum value. After combining the delayed signals from the 8 branches, the signal travels through an optical side-band filter and a super-OBFN. For completeness, we first present the full chip design in Figure 5-4.

After this, the individual components and reason why we have chosen these components are discussed.
Figure 5-3: (top) schematic overview, with highlighted in red the part for which the chip design is shown below. (left) Mask design overview of the 1x8 splitter. The size of this chip is 6030 x 6030 µm. The gold pads can be used for flip chipping. There are no electronic leads on this chip. The input and output waveguides are tapered towards an MFD of 3.0 x 2.0 µm (x-y direction, where x-direction is in-plane, and y-direction is out-of-plane). Yellow color represents the structures in the gold layer, black and red colors represent the structures in the waveguide layer, red represents the waveguide path the light follows from 1 input to 8 outputs.
Figure 5-4: (top) schematic overview, with highlighted in red the OBFN part of the assembly. (below) RX OBFN chip design. Red lines represent structures in the waveguide layer, yellow represents gold and gray represents Pt heaters.
After light has passed through the five rings, all eight branches are combined using tunable couplers. These couplers are used for two reasons: first, to efficiently couple the light into a single output waveguide without significant optical loss and secondly, to provide amplitude tapering (which is useful for the RF antenna beam-forming and side-lobe suppression in the RF radiation patterns).

Figure 5-5: (top) schematic overview with in red a single ring highlighted (bottom) chip mask-design with that same single ring resonator highlighted in red.
Figure 5-6: (top) schematic overview with in different colors the eight tunable true-time delay lines, (bottom) chip mask-design with in the same colors the eight tunable true-time delay lines.

The eight true-time delay lines are combined using a 1x8 combiner comprised of tunable couplers that can also provide amplitude tapering to the RF signal. The 1x8 combiner is shown in Figure 5-7.
Different OBFNs can be combined provide a >350 ps true time delay by using the Super OBFN part of the chips, as highlighted in Figure 5-8.
The FSR of the ring resonators in the true time delay line is chosen to be 35 GHz, one frequency (band) can be delayed using these rings.

The OSBF should have the same optical properties as the OSBF of the first run. With the exception, that in this device, the OSBF should be capable of additional filtering, so that the 60 GHz, 65 GHz and 5 GHz modulated signals can pass through. The OSBF is chosen to have an FSR of 34 GHz, so that the rings inside the OSFB have an FSR of 17 GHz. This choice has been made to accommodate the following arguments. For the 65 GHz modulation scheme, when light enters the SSBF, the cross-state for v2 should be the bar-state for the wanted modulated light of v1. For 60 GHz direct modulation, v1 and a
single side-band should pass through the bar-state of the SSBF. For 5 GHz, v1 and a single side-band should pass through the bar-state of the SSBF.

Figure 5-9: SSBF response with 34 GHz FSR and modulations options above the graphs. The vertical arrows represent optical carriers v1 and v2, the squares represent the side-band of the modulated carrier v1. The pink color represents the wanted frequencies, the black color the unwanted frequencies that will be filtered out. (a) shows the 5 GHz modulation of v1, with v2 added at 65 GHz separation. The pink square (sideband) of v1 will go in the bar of the SSBF, while the pink arrow v2 is added in the other input port of the SSBF and will go towards the cross. The black arrow and sideband of v1 will go cross into a fiber-
dump. (b) shows the 60 GHz direct modulation of v1. The pink square and arrow will be filtered into the bar port of the filter while the black square will go cross into a fiber-dump. (c) shows the 5 GHz modulation of v1. The pink square and arrow will be filtered into the bar port of the filter while the black square will go cross into a fiber-dump.

Figure 5-10: (top) schematic overview with the OSBF highlighted in red, (bottom) chip mask-design with the OSBF highlighted in black.
5.2 1x8 OBFN RX Backup

In this project, many components and processes are new. Indicatively, the InP-TriPleX passive butt-coupling envisions merging the high performance modulation and light generation of III/V components with ultra-low loss multiplexing, filtering and beamforming functionalities of SiN waveguide platforms in a cost-effective passive manner and has not been performed before. One of the crucial steps in this packaging is the layer stack thicknesses, which needs to be controlled very carefully during processing. If either the InP or the TriPleX has the wrong top-cladding thickness, or gold-layer thickness, the passive alignment may induce losses in the coupling of light from one waveguide core to the other, risking the proof-of-concept demonstration of the OBFN functionality fabricated for this project. This coupling may also be hindered by any InP-TriPleX mode-mismatching, where light may be lost, resulting in no proper signal being detected after the OBFN. If any of the InP chips (DFB / SOA + EAM / Detector), assembly process or TriPleX chips fails, the envisioned 5G-PHOS OBFN functionality of the RRH system would not be fully demonstrated.

So, to have a risk mitigation backup route, LioniX International chose to have an assembly route in-house, based on proprietary skill and knowledge. LioniX has gained a lot of experience in designing and packaging full OBFNs with both active and passive components over the past few years, after the project proposal was written. The risk mitigation route means that LioniX will provide a transmit and a receive OBFN, with the same passive functionalities as for the project-proposed devices, however with InP detectors and modulators commercially bought (from parties outside of the consortium) and packaging done in-house.

In this chapter, the 1x8 OBFN RX backup assembly is discussed. In Chapter 5.4, the 1x8 OBFN TX backup assembly is discussed.

5.2.1 System overview

In this section, the TriPleX chips for RX backup will be discussed. Because the assembly contains no lasers, the light has to come from a fiber. The light in the fiber will contain v1 and v2, and will have to be separated via a filter. For this, we have chosen to use a design very similar to the ROADM filter fabricated in Run 1 (see D4.2).
5.2.2 TripleX chip

![Diagram of TripleX chip with labels for v1, v2, 8-array modulator, and ROADM filter]

Figure 5-11: schematic overview of the backup RX assembly, with 2 lasers externally, fed to the chip via a single fiber. The 8-modulator array is in InP and contains phase modulators.

After the laser signal has been split into v1 and v2, v1 is split into eight branches, each light path is modulated by a phase modulator. After this, the light of each path is coupled into 8 separate delay lines, each containing a multitude of optical ring resonators, that can provide an arbitrary true-time delay to the signal, up to a maximum value. After combining the delayed signals from the 8 branches, the signal travels through an optical side-band filter, where v2 is added and v1-carrier and a single side band are filtered out. Then, light travels through a super-OBFN. The ROADM filter and OSBF can also be set such that, in case v2 does not exist, v1 will travel through the modulators and the OSBF will filter out only 1 of the side bands of v1, but not the carrier. For completeness, we first present the full chip design in Figure 5-4. After this, the individual components and reason why we have chosen these components are discussed.
Figure 5-12: (top) schematic overview, with highlighted in red the OBFN part of the assembly. (below) RX OBFN chip design. Red lines represent structures in the waveguide layer, yellow represents gold and gray represents Pt heaters.
Light enters the ROADM filter from the fiber, and splits v1 and v2 into two different branches. For this, the filter has the following transfer response.

Figure 5-13: ROADM response with 120 GHz FSR and the two input options above the graphs. The vertical arrows represent optical carriers v1 and v2, squares are not drawn in yet, because the modulation occurs at the chip-level. The pink color represents the frequency that is filtered out by the ROADM filter, to go directly towards the SSBF, while the black color represents the light that will be split into 8 branches and will be modulated. (a) shows the 65 GHz separation between v1 and v2, as discussed before. (b) shows the options for either 60 GHz direct modulation of v1, or direct 5 GHz modulation of v1. For both, v1 needs to travel directly to the modulator array.
Figure 5-14: (top) schematic overview with in red the ROADM filter highlighted (bottom) chip mask-design with that same filter highlighted in red.

After the ROADM filter, light will go into the 1x8 splitter.
After the modulator, the signal will pass through the delay lines.

Figure 5-15: (top) schematic overview with in red the 1x8 splitter, (bottom) chip mask-design with in red that same splitter.
Figure 5-16: (top) schematic overview with in different colors the eight tunable true-time delay lines, (bottom) chip mask-design with in the same colors the eight tunable true-time delay lines.
After the delay lines, the signal is combined into a single path via an 8x1 combiner.

Figure 5-17: (top) schematic overview with 8x1 combiner highlighted in red, (bottom) chip mask-design with the 8x1 combiner highlighted in red.
After the 8x1 combiner, the light is fed into the OSBF.

Figure 5-18: (top) schematic overview with the OSBF highlighted in red, (bottom) chip mask-design with the OSBF highlighted in black.
After the OSBF, the light travels through the Super-OBFN and exits the chip.

Figure 5-19: (top) schematic overview with the Super OBFN highlighted in red, (bottom) chip mask-design with the Super OBFN highlighted in red.
5.3 1x8 OBFN TX

5.3.1 System overview

The TX OBFN system overview remains the same as in D4.2, with the exceptions that a second laser at frequency $v_2$ needs to be added, so the single side-band filter (SSBF) will be equal to the one discussed in Figure 5-9. To split $v_1+\text{mod}$ and $v_2$ from each other the ROADM filter as discussed in Chapter 5.2 is also added. The schematic design is shown in Figure 5-20.

![Figure 5-20: schematic design of the TX OBFN. The flow of light in this figure is from right to left. The white-colored blocks are TriPleX based, the purple colored blocks are InP based waveguide chips. The orange parts are updated to fit to the 60 GHz scheme.](image)

5.3.2 TriPleX chips

The individual components in the TriPleX chip are similar to those in the RX OBFN TriPleX design, with the exception that the output waveguides are not under an angle but are straight, to couple to the photodiode array. Also a ROADM filter is added to split the $(v_1+\text{mod})$ from $v_2$, after which it can be fed into the single-sideband filter. The InP PD is designed to couple efficiently to an MFD of $3.0 \times 3.0 \, \mu m$. Based on simulations, the dimensions of the output waveguide on TriPleX will be $75 \, nm$ waveguide layer thickness and a waveguide width of $2.5 \, \mu m$, resulting in an MFD of $3.62 \times 2.82 \, \mu m$ and a corresponding coupling loss due to modal field overlap of $-0.27 \, dB$, for optimal alignment.

The mask design for the TX TriPleX chip is shown in Figure 5-21.
Light originating from two lasers, with frequencies v1 and/or v2, and a modulated 5 GHz signal on v1, enters the chip at the ROADM filter. The ROADM filter can split up v1 and v2 into two branches, as indicated in Figure 5-22.
Figure 5-22: (top) schematic overview with the ROADM filter highlighted in red, (bottom) chip mask-design with the ROADM highlighted in red.

After the ROADM filter, v1 and it’s modulated frequencies will pass through the super OBFN, as indicated in Figure 5-23.
Figure 5-23: (top) schematic overview with the Super OBFN highlighted in red, (bottom) chip mask-design with the Super OBFN highlighted in red.

After the Super OBFN, the light from v1+mod and v2 are combined and filtered in the single-side-band filter (SSBF), as indicated in Figure 5-24.
Figure 5-24: (top) schematic overview with the SSBF highlighted in red, (bottom) chip mask-design with the SSBF highlighted in red.

After the SSBF, a single side band and a single carrier are split into 8 branches, as shown in Figure 5-25.
Figure 5-25: (top) schematic overview with the 1x8 splitter highlighted in red, (bottom) chip mask-design with the 1x8 splitter highlighted in red.

After the 1x8 splitter, light travels through a set of five true-time delay optical ring resonators, performing the beam forming, as indicated in Figure 5-26. After the ring resonators, light is detected by the photodiodes in InP, and thus transferred into RF.
Figure 5-26: (top) schematic overview with in different colors the eight tunable true-time delay lines, (bottom) chip mask-design with in the same colors the eight tunable true-time delay lines.

5.4 1x8 OBFN TX backup

5.4.1 System overview

In this section, the TriPleX chips for TX backup will be discussed. Because the assembly contains no lasers, the light has to come from a fiber. The light in the fiber will contain v1 and v2, and will have to be separated via a filter. For this, we have chosen to use a design very similar to the ROADM filter fabricated in Run 1 (see D4.2).

The TX OBFN system overview is exactly the same as described for the 1x8 OBFN in Chapter 5.3. The difference is in the photodiode array and in the packaging.
5.4.2 TriPleX chip

The TriPleX chip is 100% in functionality to the chip presented in Chapter 5.3. The chip layout is shown in Figure 5-27. The chip layout is only slightly different to the chip described in Chapter 5.3, distinctly in chip footprint and tapering. The chip footprint is larger to accommodate the electronic lead fan-out to come to a 300 micrometer pitch between the wire bond pads, which are interleaved in a double row. The taper is shown on the left-hand side of the chip, and is indicated with the red colored waveguide in Figure 5-28.

![Figure 5-27: (left) Chip layout without heaters and electronic leads, (right chip layout with heaters and electronic leads.](image1)

![Figure 5-28: Taper towards InP detector array.](image2)
5.5 Packaging of the backup options

The packaging of the backup options have not fully been designed yet, however in order to provide the reader with an idea on the packaging, in this section a similar packaged OBFN with InP detectors is shown. For 5G-PHOS a similar package will be designed and produced as backup option for both the TX and RX OBFNs.

Figure 5-29: An example of a previously packaged OBFN with 8 photodiodes connected to a TriPleX OBFN chip, with fibers in-and-out and electronic PCBs attached.

5.6 Mini-ROADM measurement results

As discussed in D4.2, a mini-ROADM has been designed. For the design parameters and design choices, the reader is referred to Deliverable D4.2. Here, the packaging and the measurement results of the ROADM are shown.

As reminder, the filter should have a frequency spacing of 100 GHz and a modulation frequency of 5 GHz and a bandwidth of 2 GHz, as can be seen in Figure 5-30.

Figure 5-30: schematic representation of the carrier, signal bands and channel spacing.
5.6.1 ROADM packaging

In Figure 5-31, the designed and fabricated package for the ROADM are shown. The individual components are indicated in the schematic drawing bottom-left.

![Schematic design of the packaging](image1)

![Fabricated ROADM package](image2)

**Figure 5-31**: (left top and left bottom) schematic design of the packaging, (right top) fabricated ROADM package.

5.6.2 Measured frequency response of ROADM filter

In the following, the measured results are shown for both DROP and ADD ports for the fabricated ROADM. As can be seen in these measurement results, the ROADM has a total insertion loss (fiber-to-fiber) of roughly 2.5 dB, indicating a fiber-chip loss of ~ 1 dB and an on-chip propagation loss of ~0.5 dB, while the filter imposes no additional loss (other than propagation loss).

The calculated wavelength response results for dropping all 4 wavelengths is shown in Figure 5-32. For this calculation, a fiber-chip coupling loss of 1 dB is assumed and a propagation loss of 0.1 dB.
Figure 5-32: calculated results for dropping all 4 wavelengths.

In the following Figure 5-33, the measurements are shown for all possible iterations: dropping 0 up to 4 wavelengths simultaneously, also showing the through ports of the filter. These graphs show an excellent out-of-band suppression of >30 dB. The results are shown in no particular order.
Figure 5-33: results of the frequency responses of the ROADM for 16 different iterations, showing the four drop-ports and the two through-ports simultaneously. This shows the insertion loss and the out-of-band suppression of the ROADM device.
6 Integrated Tx and Rx

6.1 Integration Concept

Fraunhofer IZM developed a flip chip bonding concept where optical waveguides of two different components are coupled by passive alignment and precision bonding. Fraunhofer filed a patent for this passive alignment approach.

The RX substrate will integrate two TriPlex chips (SiP), one DFB laser (InP) and two bars of EAMs (InP). The TX substrate shows two PD bars (InP) and one TriPlex (SiP). The wire bond pads are located at three sides whereas an optical interface is located on one side.

![Figure 6-1 Substrate floor plan shown above for RX and TX substrate.](image)

6.2 Substrate Fabrication

6.2.1 Design

The substrates were designed based on high resistive silicon to address RF compatible routing. For the substrates a routing layer of 3 µm gold was chosen. Gold bumps of 20 µm and 30 µm diameter were designed for flip chip bonding. Alignment marks are added in the routing layer for all components.
Figure 6-2 The RX substrate will be used for the integration of a DFB laser (left), a 1x8 splitter TriPleX, 2 bars with 4 SOAs + EAMs each and a 1x8 RX OBFN based on TriPlex (right). 50 Ohm terminals will be flip chip bonded.

Figure 6-3 The TX substrate will be used for the integration of two PD bars (left) and one OBFN based on TriPlex. 50 Ohm terminals will be flip chip bonded.
6.2.2 Fabrication

High resistive silicon wafers of 200 mm diameter were used for fabrication of RX and TX substrates as well as for RF test chips provided for IMEC.

Figure 6-4 Lithography of first metal layer (left) and after plating first gold layer with 3 µm height (right)

Figure 6-5 Lithography for bump layer with 20 and 30 µm bump diameter
Tests dummy chips fabricated by IZM were used to have enough components available for assembly trials. Dummy chips were patterned with the layout of partner components.
by sputtering and etching an Au layer on silicon. These components were used for first alignment tests.

**Figure 6-9 Dummy chips in fabricated in silicon for alignment and assembly trials**

### 6.3 Assembly Process

For flip chip assembly a uniform bonding height is intended to reach in order to align the optical waveguides in the vertical direction. Different parameters with respect to bonding temperature (160°C to 250°C) and bonding pressure (100 MPa to 175 MPa) were investigated.

**Figure 6-10 Gold bumps as planarized (left), TC bonded to test chip (center) and to Triplex chip (right)**
Shear test were used to qualify different sets of bonding parameters.

Figure 6-12 Design overlay of different components on both substrates. Not shown are the 50 Ohm components.

Alignment trials were done manually as well as in an automated mode using the vision recognition functions of the flip chip bonder. Precision contours of alignment marks and good contrast are essential to reach the required alignment accuracy. Further assembly tests are ongoing and the assembly with functional parts are planned.
7 System measurement

The 5G-PHOS project foresees a centralized optical A-RoF fronthaul network topology with all complex processing performed at a single powerful baseband engine placed at the premises of the Central Office. This allows shifting the DAC/ADC from the Remote Radio Head to the centralized Baseband unit, reducing the cost and complexity of the antenna in C-RAN topology [1]-[3]. At the same time it facilitates loading native wireless radio signals directly on an IFoF subcarrier, modulated on low-bandwidth Intensity Modulation Direct Detection scheme, bypassing the high bandwidth penalty of the CPRI protocol that requires high performance NRZ-OOK D-RoF transceivers.

Following the time-progress and development of the optical components of the 5G-PHOS project, the developed devices are gradually being inserted in Fiber Wireless A-RoF transmission scenarios, aiming to demonstrate the proof-of-principle and the unparalleled benefits that integrated photonics can introduced to A-RoF Fiber Wireless networks for 5G. The 5G-PHOS devices tested in system level scenarios of gradually increasing complexity and use case scenarios so far include:

- **InP EML chips for application in Dense Urban areas:** The 3-5 InP EMLs were utilized as spectrally efficient, high power transmitters that can transport immense capacities of mmWave MIMO antennas across typical fronthaul distances of up to 10km and 25 km met in Urban areas

- **Multiple parallel Fiber Wireless transmissions for Ultra Dense areas:** Multiple parallel (fixed and predefined) optical transmissions through Spatial Division Multiplexing (SDM) or Wavelength Division Multiplexing (WDM), either using 3-5 EMLs or TriPleX OADM or commercial devices, to fiber-connected mmWave MIMO antennas for multipoint and multibeam transmission for high density environments found e.g. in city centers and enterprise areas.

- **Reconfigurable Add/Drop Optical Wavelength Multiplexed Transmissions for Hotspot areas:** The TriPleX ROADMs developed were used in multiple reconfigurable multi-wavelength Fiber Wireless A-RoF optical transmissions, where the wavelength transmissions can be dropped at different multi-wavelength mmWave antennas, for application in hotspot areas of ultra-high user density, e.g. stadiums during games, concert hall during public events etc.

Using the above combinations of optical chips and scenarios, the end-to-end fiber Wireless fronthaul links for the physical layer evaluation of the transport networks between the optical transceivers of the FlexBox to various locations of the mmWave MIMO antennas with directional antenna beams and flexible beamsteering capabilities transmitting to the final endpoint mmWave terminals (e.g. Small Cell access points, rooftop antenna, street level antennas or mmWave users) are evaluated and presented below.

### 7.1 Single Wavelength EML-based Fiber Wireless A-RoF/mmWave fronthaul links for Dense Networks

Within this activity, some first InP EML chips, fabricated by 3-5 lab and provided to AUTH and IZM within the frames of the project, were utilized in the first application scenario of Dense Urban areas, in order to implement spectrally efficient, high power transmitters for the 5G-PHOS mmWave MIMO antenna fabricated by SIKLU and typical fronthaul distances.
We initially experimentally demonstrate an IFoF/V-band FiWi link modulated on a cost-effective high power linear EML and transmitted over-the-air at 60GHz by a beamforming antenna with 32-radiating elements. The experimental setup, the EML, the antenna boards and the antenna tile are depicted in Figure 7-1 (i)-(iv) respectively. The end-to-end link is initially evaluated in a 100Mbd wireless link under at beam angle of 45° using QPSK, 8-PSK and 16-QAM for user rates of 200Mb/s, 300Mb/s and 400Mb/s respectively, as envisioned for dense urban and hotspot areas. The link is then combined with a high-power linear EML, shown in Figure 7-1(ii), in an end-to-end FiWi transmission of up to 7km with the antenna configured at three different states, i.e. isotropic transmission at 120° degrees from -60° to +60°, an incident angle of transmission of 0° or an angle of 45° and the performance of the FiWi link is thoroughly investigated for all antenna configurations.

The experimental setup includes the EML, a Single Mode Fiber (SMF) length of 7km and a 32-element 60GHz antenna with beamsteering capabilities. A zoom-in photo of the 32-elements Tile is depicted in Figure 7-1(iv). The carrier was modulated under QPSK, 8-PSK or 16-QAM waveform with a symbol rate set at 100Mbd, before being combined with a DC biasing signal through a Bias-T and connected to the GSG pad of the InP EML before optical transmission through 7km of SMF. The EML integrates a 500μm long DFB laser and an 150μm EAM on an InP platform and is packaged on a TEC-PCB [3]. It exhibits flat top S21 frequency response for up to 10GHz and 3dB bandwidth of 17GHz [4], while the voltage swing of the signal was set to 1.1V and the DC bias at -1.6V, to match the linear region of the P-V curve. Injected with a current of 90mA, it provides an optical power of 2.7dBm. Details on FiWi links employing EML can be found in D8.1. It is worth highlighting that, this was the first end-to-end A-RoF FiWi demonstration of a beam-steerable 60GHz antenna up to 45°, including 32 antenna elements and a cost-effective EML[2]. Moreover the EML has been deployed in Fiber Wireless experiments with commercial mmWave horn antennas, demonstrating the record transmission capacity in fronthaul networks, as detailed in D8.1, validating the spectral and cost-efficiency benefits of InP-technology of 5G-PHOS.
7.2 Multiple parallel Fiber Wireless transmissions for Ultra Dense Networks

In this section, we describe the work done towards presenting multiple parallel Fiber Wireless transmissions over the 5G-PHOS technology 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 7-2(i), where 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. Conceptually, the schematic illustrates 16x multiples of a single 25Gb/s Fiber Wireless link, to build an aggregate capacity of 400Gb/s. Such record high capacity links have been demonstrated by the 5G-PHOs consortium within the course of the project[4],[5].

In this case, two multi-beam scenarios have been evaluated using the 5G-PHOS hardware technologies of increasing coverage:

- **One network scenario with three point terminals scattered within a 90° degree sector**, forming the first mmWave multi-user demonstration enabled by Frequency Division Multiplexing or Spatial Division Multiplexing [7]. The links were tested using 100 Mbd QPSK signals. The corresponding mmWave frequencies of the Tx1,2, 3 were 60.33 GHz, 60.64 GHz and 59.43 GHz placed at an angle of 30°, 0° and -30°, while the Rx was set in isotropic mode. The constellation
diagrams of the received signals after the 10 km fiber propagation and the PD are shown in Figure 7-2 (ii), featuring EVM values of 19.50%, 20.68% and 20.25%. It is worth noting that these results have been obtained for IQ data inputs at Tx1,2,3 of 190 mV, 500 mV and 350 mV, resulting in average power levels for each channel with less than 5dB power variation after the FiWi link, as shown in the RF spectrum. More details in this demonstration are presented in D8.1.

- **A 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. In Figure 7-2(iii), we present the results obtained, using the 4λ Optical Add/Drop Multiplexer (OADM) 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 [8], capable to demultiplex four 100GHz C-band wavelengths. The FiWi links extend across a 10km Single Mode Fiber (SMF) distance and 1m V-band link, transmitting four 250MBaud QAM16 signals through mmWave beams of 10° width steered across a 90° sector. More information in this demonstration is being included in D3.2, detailing the mmWave 5G-PHOS components, including their fiber connected A-RoF experiments.

![Figure 7-2](image_url)

**Figure 7-2:** i) Schematic of envisioned Ultra Dense scenario employing Spatial Division Multiplexing of several Fiber Wireless parallel links to serve high capacity and high density. ii) Three parallel beams transmitted from a single MIMO antenna Tile. iii) Four parallel Fiber Wireless links with parallel mmWave beams covering a sector area of 360°.

### 7.3 Reconfigurable Fiber Wireless fronthaul enabled by Si3N4 ROADM for Hotspots

In this section, we present for the first time four reconfigurable 1Gb/s FiWi A-RoF/mmWave beamsteering links through the novel four port low loss TriPleX ROADM device of the 5G-PHOS project and the 32-element V-band 5G-PHOS MIMO antenna with 90° beamsteering. The ROADM relies on the cascaded MZI-based interleaver layout fabricated on a low-loss Si$_3$N$_4$ TriPleX platform with 100GHz channel spacing and 30GHz...
flat top channel spectrum. Four 250Mbd QAM16 waveforms are selectively and reconfigurably dropped and transmitted through the antenna, forming the first demonstration of a SiPho ROADM for A-RoF/mmWave links for 5G C-RAN networks.

The experimental setup used for the evaluation of the ROADM-based FiWi A-RoF transmission is shown in Figure 7-4 (ii). At the transmission stage, a 4λ-WDM A-RoF stream is generated by multiplexing four Continuous Wavelengths (CWs) spaced by 100GHz, namely λ1-λ4 at 1545.6nm, 1546.4nm, 1547.2nm and 1548nm. The four CWs are modulated by an Arbitrary Waveform Generator using a 250 MBd QAM16 waveform loaded on an 5GHz IF to generate four 1Gb/s Double Side Band (DSB) A-RoF streams on λ1-4. The 4λ WDM A-RoF stream is launched through a 1km-long SMF spool before passing through the ROADM.

The TriPleX ROADM layout used is shown in Figure 7-3(i) was designed in a cascaded MZI-interleaver-based Add/Drop filter configuration, as described in D4.1 and D4.2. The Add/Drop filters were designed with 100GHz channel spacing, targeting flat-top response with 32.5GHz pass-band, power-variation of less than <0.02 dB across the 10GHz DSB signal bandwidth, as detailed in [3]. The ROADM was fabricated on the ultra-low loss Si$_3$N$_4$/SiO$_2$ TriPleX platform [6]. In order to ensure a flat-top response and compensate any non-ideal filter transfer function due to fabrication processes, the MZIs relied on tunable optical couplers shown in Figure 7-3 (ii). The Si$_3$N$_4$/SiO$_2$ ROADM was assembled on a TEC-controlled PCB and electro-optically interfaced with wire-bands and fiber array in a bench-top package, as shown in Figure 7-3(iii), to assist easier testing, while it was combined with the MIMO antenna shown in Figure 7-3(iv).

Initially, the ROADM was evaluated in a single stage reconfigurable optical transport network concept, as shown in Figure 7-4(i), using the experimental setup of Figure 7-4(ii).
The ROADM was statically characterized by inserting ASE noise at the input port and evaluating the spectrum at each drop port using an Optical Spectrum Analyzer. The channel spectra superimposed using different coloring are shown in Figure 7-5(i), featuring a flat-top response across at least 0.25nm and 3dB bandwidth of 0.66nm, while the crosstalk between the pass-band at the central peak compared to the stop band of neighboring channels was at least 18dB, allowing clear demultiplexing of A-RoF streams without significant power imbalance.

**Single Channel Wavelength Switching**

Afterwards a single wavelength channel and an optical A-RoF transmission only was implemented at first, carrying QPSK signal, without any wireless transmission. The signal was initially passed either through the ROADM or dropped at wavelength channel λ2, and the received signals were evaluated through constellation diagrams and EVM measurements. When the channel was dropped at wavelength λ2, at Drop Port 2 of the ROADM, the result obtained is shown in Figure 7-5(ii). On the other hand, when the signal passes through the ROADM stage and was not dropped at the wavelength λ2 / Drop port 2, its signal quality was evaluated to feature an EVM of 4.7%, i.e. indicating a negligible distortion between the two channels. This verified the high performance and negligible distortion of a single ROADM channel.
Figure 7-5 i) ROADM transfer function. ii) QPSK constellation diagrams of optical-only switching Performance.

Four channel ROADM FiWi operation:
Following the single channel optical fiber only single A-RoF channel evaluation of the RAODM, we proceeded with investigating the possibility to additionally introduce the V-Band wireless transmission within each of the multiple ROADM-based optical links, leading to four FiWi parallel transmission lines, one for each ROADM channel. Thus, four Fiber Wireless mmWave directional links from the optical transmission to the Photodiode, and then through the MIMO to a portable V-band antenna was implemented. The four parallel FiWi links were set up, where all four λ1-λ4 250Mbd QAM16 streams were demultiplexed and dropped at the four ports and wirelessly transmitted by the PAA at 45°. The received signals, shown in Figure 7-6(i), reveal clearly demodulated constellation diagrams with average and almost equal EVM of 11.1% with only 0.3% variation.

Figure 7-6 Constellation diagrams of transmissions resulting from each ROADM channel
8 REFERENCES:


[6] 3GPP TS 38.104, "5G; NR; Base Station (BS) radio transmission and reception", v. 15.2.0, 2018-7


[10] 3GPP TS 38.104,"5G; NR; Base Station (BS) radio transmission and reception",v.15.2.0, 2018-7