

Photonic RF True-Time Delay Beam-Former based on Si Passive Photonic Integrated Circuit

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ABSTRACT

The deployment of ultra/very-high throughput satellites (U/VHTS) including large direct radiating antennas in Ka-band requires the development of new enabling concepts and technologies across multiple domains, such as thermal, mechanical, beamforming, integration, and others. With support from ESA, Thales Alenia Space is investigating these innovative solutions within the framework of the ActA-UHTS (Active Antennas for Ultra High Throughput Satellites) project. This paper reports on a photonic RF beamforming concept developed as part of the program, using a passive beamforming photonic integrated circuit (PIC) designed by VTT in Finland.

Keywords: Beamforming, True-Time Delay, photonic integrated circuit, Si Photonics, space applications

1. INTRODUCTION

Telecom satellite payloads have significantly evolved beyond the traditional “bent-pipe” repeater approach to advanced digital-processor payloads, where onboard digital signal processing (DSP) performs functions such as filtering, switching and/or signal regeneration. Looking ahead, supporting onboard throughput beyond 1 Tbps is a credible target for Ultra High Throughput Satellites (UHTS), provided operator demand materializes in the coming years. However, achieving such high-capacity performance—especially when combining Ka-band operation with large direct radiating antenna arrays—requires the implementation of new enabling concepts and technologies in various fields, including thermal and mechanical design, beamforming architectures, payload integration, and more.

With ESA support, Thales Alenia Space has been investigating these innovative items through the ACTA-UHTS project (Active Antennas for Ultra High Throughput Satellites) [1]. One key challenge is the implementation and management of RF signal delivery across the payload: routing all RF interconnects from the digital processor (DTP) to the array antenna via an RF harness and signal-delivery chain may introduce several drawbacks. These include the need for a very large number of coaxial cables, an increase in mass and stiffness associated with cabling (which can be particularly problematic for deployable antenna configurations), and potential relative RF phase stability concerns—an important issue for phased-array antennas.

Fiber-optic based harness solutions are expected to overcome a number of issues and bring multiple benefits. They can enable mass reduction, reduce the overall number of interconnects through optical multiplexing techniques such as SDM (spatial division multiplexing/parallel fiber ribbons), WDM (wavelength-division multiplexing), and MCF (multi-core fibers), and provide a mechanically more compliant transmission medium. In addition, optical links can improve RF phase stability, particularly when phase-stabilized fibers with low thermal coefficient of delay (TCD) are used.

But the potential of photonic technologies extends beyond distribution harnesses. Thales Alenia Space was the first system prime to deploy optical interconnect solutions within a commercial digital processor, which de facto opens the route for photonics to penetrate other sections of the payload within ESA activities [2–5]. Thales Alenia Space developed photonic RF payload sub-system demonstrators supporting multi-channel, wideband frequency-conversion in Ka-band, with the aim to reduce the amount of equipment and size, weight and power (SWaP). In [5], additional concepts were also proposed and validated to support multiple-channel frequency conversion while further reducing the number of mixers—applicable to digital-processor-based payloads for frequency down- and up-conversion at the inputs and outputs of the processor, respectively.

This paper reports the outcomes of the photonic part within the project, focused on the development of a photonic RF beamformer concept based on a passive beam-forming photonic integrated circuit (PIC) designed by VTT in Finland. The paper details achievements spanning the design of the key component (the passive beam-forming integrated circuit), its integration, demonstration, and the end-to-end evaluation of a Ka-band photonic RF beamformer in both the IM-DD (Intensity Modulated with Direct Detection) and RF frequency-conversion configurations. The photonic RF beamformer concept as well as, the measured RF performance are reviewed vs. system requirements and performance predictions.

2. BEAMFORMER PHOTONIC INTEGRATED CIRCUIT

2.1 Design and manufacturing of BF PIC

VTT designed and manufactured a photonic chip that supports up to 13 antenna beams and distributes the RF signal to 12 output ports with the appropriate differential delays.

The PIC is a passive device, i.e. does not require any electrical control, and the beam direction instead is selected remotely by switching the input wavelength from a tunable laser.

The architecture selected for the photonic chip is depicted in the figure below. The circuit consists of a single input waveguide coupled to a passive power splitter. The output of the splitter is fed into an array of wavelength multiplexers which route the signal to a specific delay line based on the input wavelength. All the delay lines are fed into a second MUX stage which collects the light and routes it to an output waveguide. All the multiplexers are identical, which reduces the design complexity and the architecture requires no waveguide crossings that would induce insertion loss and crosstalk. All the building blocks are designed for TE polarization only and for operation around 1550 nm wavelength.

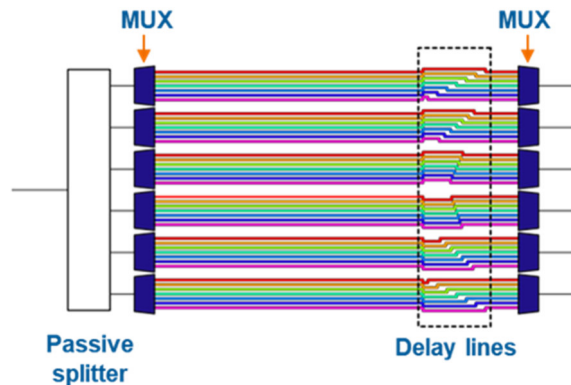


Figure 1. Schematic layout of the chip architecture (the different colours denote the routing of the different wavelengths)

The PIC chip layout includes echelle gratings as the wavelength multiplexers due to their compact size. In the project, the multiplexer layouts were designed to match the target of 12 channels with 0.8 nm wavelength spacing. In addition, designs were made for the input splitter and the optical delay lines with parametrized delay lengths. The multiplexers were designed for 100 GHz channel spacing (0.8 nm) so as to reduce the amount of wavelength tuning needed to select any of the beam angles.

The PICs have been implemented using VTT's 3 μm SOI technology [6]. Compared to mainstream 220 nm SOI technology the platform offers lower propagation losses (down to 0.04 dB/cm) which enables the implementation of low-loss true-time delay lines. The chip footprint is 20×20 mm² and fabricated on 150 mm wafers yielding 32 identical copies per wafer. These chip dimensions correspond to the maximum design area of a lithography reticle.

The fabrication was carried out as a part of VTT's multi-project wafer run using standard passive waveguide process flow. The PIC fabrication process uses hydrogen H₂ annealing to smoothen the etched silicon waveguide sidewalls, which leads to low propagation losses. The figure below gives a photograph of the fabricated PIC chip.

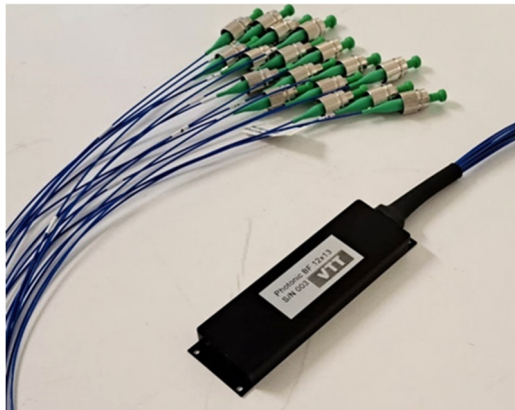


Figure 2. Photograph of the fabricated ACTA-UHTS beamformer photonic chip

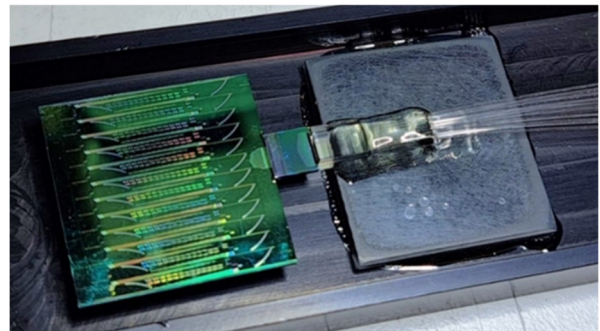
Finally, the PIC chip was successfully packaged in a hermetic metal housing 30x102x10 mm³ for the photonic beamformer demonstrator experiments.

Polarization maintaining fiber arrays with a 127- μ m fiber pitch were used in the packaging. They consisted of a total of 17 channels, with 4 channels allocated for the two alignment loops, 1 for the signal input channel, and 12 for the output channels. For the chip coupling, the fiber array was assembled on a v-groove array part and facet polished.

However, the optical mode field diameter (MFD) of the fibers in the PM fiber array is much larger than the MFD of the 3- μ m waveguides on the SOI PIC. Thanks to the horizontal taperings in the PIC, the MFD of the I/O waveguides already matches with the fiber mode in horizontal direction. To match the modes also in vertical direction for low-loss fiber coupling, a spot-size converter (SSC), so called optical interposer was implemented between the fiber array and the PIC chip. The fiber coupling of the packaged device was evaluated by measuring total insertion losses through alignment loop waveguides on the PIC. The total losses from input fibers to output fibers through the loops were around 2.8 dB, thus indicating 1.4 dB fiber-to-chip coupling loss. The figure hereafter shows an image of the device in the metal housing such as delivered to Thales Alenia Space for experiments. A photograph of the PIC assembled with the SSC chip and fiber array is also shown.



-a-



-b-

Figure 3. Photographs of the photonic ACTA-UHTS beamformer

-a- Fully packaged PIC in metal housing with fiber pigtailed & FC/APC connectors

-b- PIC attached and coupled to SSC chip and fiber array assembly (open package)

2.2 Functional performance of BF PIC

The packaged beamformer device was characterized at Thales Alenia Space in terms of selected output wavelengths, optical insertion loss and True Time Delays.

The set-up for output wavelengths measurement is based on the use of an uncooled optical amplifier used as a broadband noise source (ASE) and an optical spectrum analyzer (OSA). Then, optical spectra from the 12 device outputs are measured in the range 1544 nm - 1557 nm as shown in the figure below.

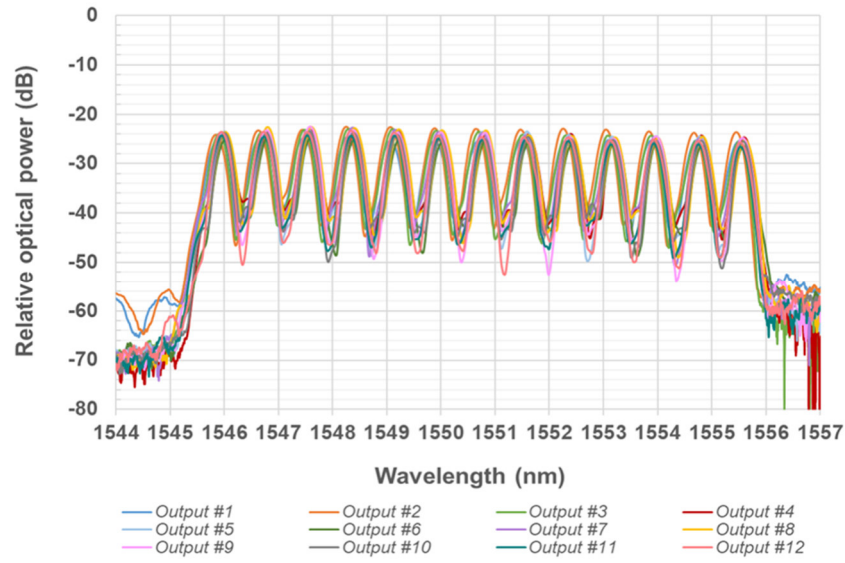


Figure 4. Optical spectra from the 12 outputs ACTA-UHTS beamformer photonic device

Similarly, the output optical power measured for each wavelength of the output spectra is compared with the optical power at the input of the device in order to determine the optical insertion loss. In the relative optical power response, as given in the previous figure, the insertion losses on each output channel correspond to the amplitude of the wavelength peaks. Thus, the measured optical insertion losses are reported in Table 1 hereafter. They range from 22 dB to 27 dB, including 10.8 dB intrinsic losses from the 1x12 power splitter and measured 3.5 dB losses from both wavelength multiplexers and demultiplexers (based on Echelle gratings). Excess optical losses in channels 1, 6, and 11 were caused by point defects in the waveguides.

	IL on O#1 (dB)	IL on O#2 (dB)	IL on O#3 (dB)	IL on O#4 (dB)	IL on O#5 (dB)	IL on O#6 (dB)	IL on O#7 (dB)	IL on O#8 (dB)	IL on O#9 (dB)	IL on O#10 (dB)	IL on O#11 (dB)	IL on O#12 (dB)
λ_1	-25.44	-24.14	-23.96	-23.85	-23.48	-25.22	-23.9	-23.61	-23.82	-23.79	-24.31	-23.57
λ_2	-24.95	-23.28	-23.73	-23.64	-23.5	-24.99	-23.68	-22.59	-23.2	-23.81	-24.54	-23.54
λ_3	-24.83	-23.12	-23.14	-23.17	-23.01	-24.9	-23.22	-22.55	-22.48	-23.47	-24.32	-23.6
λ_4	-24.62	-22.52	-22.96	-23.48	-23.12	-25.04	-22.7	-22.8	-23.19	-23.75	-24.41	-23.32
λ_5	-25.34	-22.6	-22.99	-23.35	-23.18	-25.09	-23.13	-23.06	-23.71	-24.13	-24.34	-23.69
λ_6	-25.49	-22.83	-23.32	-23.75	-23.47	-25.66	-23.58	-23.25	-23.62	-24.9	-24.9	-24.31
λ_7	-25.14	-22.96	-23.51	-24.26	-23.54	-25.15	-23.74	-23.28	-23.7	-24.94	-25.17	-24.63
λ_8	-25.16	-23.09	-24.14	-24.05	-23.48	-25.01	-24.26	-24.25	-25.01	-24.59	-25.03	-24.66
λ_9	-25.45	-22.91	-24.26	-24	-24.15	-25.99	-25	-24.4	-24.59	-24.99	-25.45	-24.71
λ_{10}	-25.19	-23.09	-24.31	-24.96	-24.52	-25.2	-25.21	-24.68	-24.9	-25.18	-26.11	-25.27
λ_{11}	-25.33	-23.48	-24.33	-24.72	-24.41	-25.4	-24.52	-24.88	-24.47	-25.41	-25.93	-25.07
λ_{12}	-25.33	-23.75	-25.3	-24.3	-24.48	-26.38	-24.9	-24.52	-25.16	-25.32	-26.1	-25.41
λ_{13}	-25.52	-23.63	-25.36	-24.68	-26.24	-26.43	-24.92	-25.22	-24.76	-25.5	-26.62	-25.69

Table 1. Optical insertion loss of the ACTA-UHTS beamformer photonic device

In order to perform relative delay measurement, an Intensity-Modulated with Direct Detection (IM-DD) optical link was implemented at 20 GHz (i.e. Ka-band). TTD measurements were carried out by using a Real-Time Oscilloscope (RTO) and the well-known dual-trace method consisting in displaying both reference and under test traces on the screen simultaneously and measuring distance (in time scale divisions) between 2 identical points on the 2 traces.

156 relative delays were measured with wavelength λ_7 as reference. As shown in the figure and table hereafter, there is a very good agreement between the data calculated by VTT and the results of Thales Alenia Space measurements, for delays up to 234 ps with an accuracy about 0.2 ps.

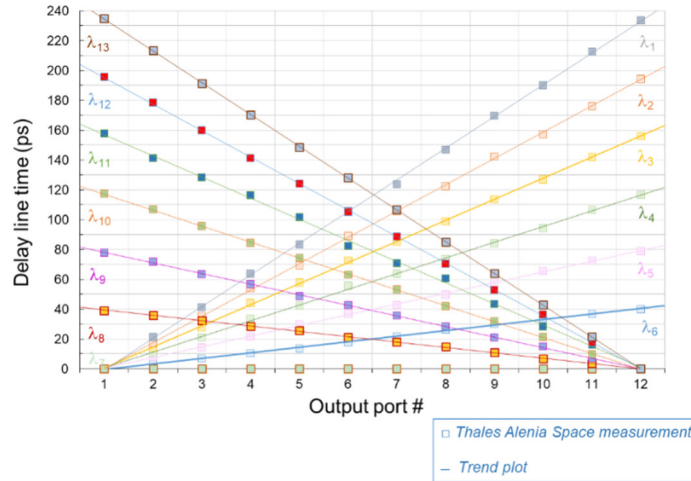


Figure 5. Differential time delays of ACTA-UHTS beamformer photonic device vs. output port & wavelength

3. PHOTONIC RF BEAM-FORMER DEMO

3.1 Test of Photonic RF beam-forming sub-system PoC demo

A Proof-of-Concept (PoC) demo was implemented and tested, based on the beam-former PIC and discrete components at Tx side. It enables to demonstrate photonic RF routing and 1-D beam-forming/switching for both configurations: IM-DD optical link in Ka-band and frequency up-conversion from C-band to Ka-band. In order to keep cost and testing manageable, the demonstrator is a sub-populated breadboard that includes only the most critical components—enough to validate the concept and architecture. As shown in the figure hereafter, the photonic RF BF demo includes 2 main blocks corresponding respectively on microwave-to-optical interfacing and frequency-converting block associated to the RF beam-former PIC and optical-to-microwave interfacing and receiving block with the 2 O/E conversion chains. The demo is optically driven fed and controlled by a Tunable Laser diode (TLD) which enables to select the operating wavelength. A Semiconductor Optical Amplifier (SOA) can be used before optical detection for compensating beam-former optical insertion loss. Overall, the demonstrator can be reconfigured between both configurations and is intended for extensive testing of functional performances in terms of RF gain, noise figure and linearity, with the surrounding RF/optical measurement equipment.

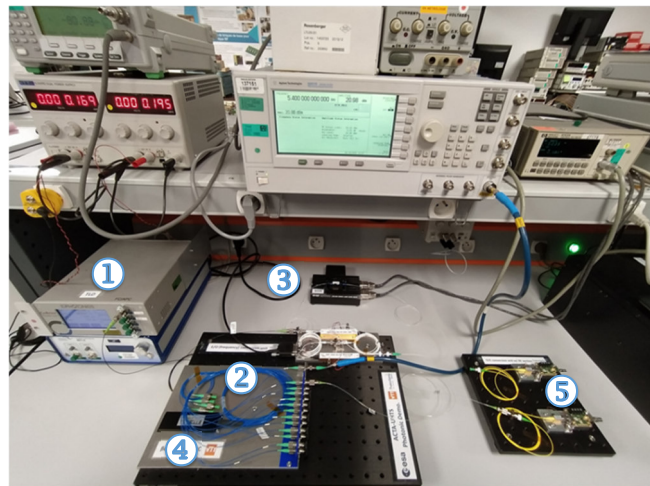


Figure 6. Photonic RF beam-forming sub-system PoC demo

- 1- Tunable Laser diode (TLD)
- 2- E/O interfacing and frequency-converting block
- 3- Semiconductor Optical Amplifier (SOA)
- 4- BF PIC from VTT
- 5- O/E interfacing and receiving block

The best RF gain value, for minimum loss at PIC output, was measured as -17 dB, at low biasing, for RFoF configuration and -41.5 dB, at low biasing, for RF up-frequency conversion configuration for LO at quadrature modulation. Under the same conditions, noise figure was measured respectively as 43.5 dB for RFoF configuration and 66 dB for RF up-frequency. Experimental results exhibit a good accordance with theoretical model with an accuracy of ± 0.5 dB.

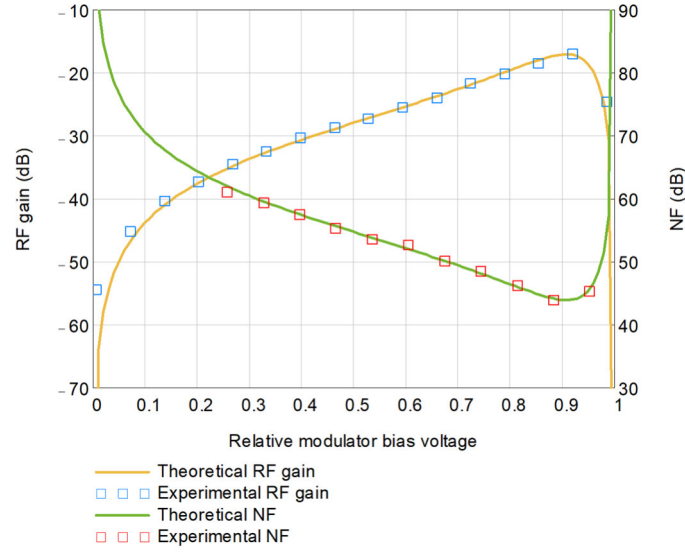


Figure 7. RF gain & noise figure vs. relative modulator bias voltage for RFoF configuration

Non-linearity from the SOA and especially the O/E conversion chain reduces performance in terms of C/I_3 ratio for a relative modulator bias voltage higher than 0.8 for both configurations. If a C/I_3 ratio is ~ 40 dBc is considered as acceptable, the RF drive power must be reduced below -3 dBm/ tone at low biasing.

Concerning the spectral purity in the RFoF configuration, generally no spurious higher than -55 dBc occurred in the transmit Ka-band, with an enhanced rejection close to -63.5 dBc for 0 dBm RF drive power. The RF bandwidth at -3 dB was estimated at 3.2 GHz mainly due to the RF bandwidth of the ORx conversion chain.

For the RF up-frequency conversion only one spurious occurred in the considered transmit Ka-band at $2f_{LO}-2f_{RF}$, for LO modulation quadrature, with an amplitude rejection close to -32 dBc. The amplitude of this spurious could be reduced by decreasing the LO driving power but unfortunately at the expense of RF gain. The RF bandwidth for up-frequency conversion was estimated to 5 GHz.

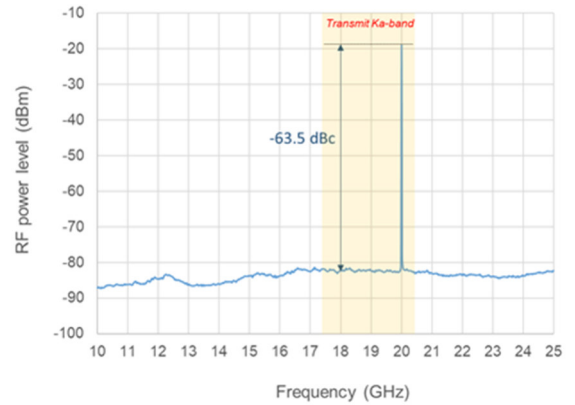


Figure 8. Spectral purity & RF bandwidth for RFoF configuration

3.2 Results analysis & perspectives

A proof of concept of a 1D 13×12 photonic beam former has been achieved using a Si-based PIC with integrated true time delays (156 differential delays up to 234 ps in ~ 2 cm²) and wavelength routing for beam switching. The device shows good time accuracy (~ 0.2 ps) and integrates 25 WDM channels with solid wavelength accuracy and loss uniformity. However, the PIC optical insertion loss are still higher and should be reduced (down to 16 dB) to improve overall photonic RF sub-system performance for both configurations.

No full environmental tests were done at this state, but a wavelength shift with ambient temperature was observed during validation - so the PIC temperature sensitivity must be improved or mitigated (e.g., laser wavelength tuning or TEC control).

From a system perspective, beam switching based on wavelength routing is very depending on switching time of TLD as optical source. A potential candidate for such an application could be a fast tunable low-linewidth InP laser (>30 nm tuning around 1550 nm) with switching around ~5 ns as it is commonly available on the market. But, even if a discrete device has already been identified, the PIC implementation of an equivalent integrated RF Laser transmitter w/ fast wavelength switching capability could also be proven to reduce dimensions of sub-system.

Concerning overall RF performance tests, measured RF gain and noise figure are in good accordance with theoretical predictions, validating the simulation model. Improving PIC insertion loss to 16 dB, for example, could improve gain up to ~13 dB better in the best case. Further loss improvement could also reduce NF substantially to ~37.5 dB for RFoF and ~54.5 dB for up-conversion.

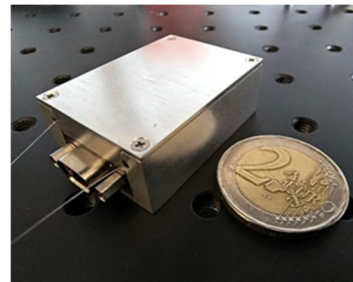
The main non-linearity sources are the ORx conversion chain and SOA. As written in the previous section, an acceptable C/I_3 ~40 dBc is achieved when RF drive power/ tone is lower than -3 dBm, for both configurations.

In order to mitigate SOA non-linearity effects, one option would be to replace it by a compact OFA, known to be perfectly linear with respect to photonic RF signals but this means that the integration of photonic devices into a Photonic Integrated Circuit (PIC) will have to be limited to the TLD source and both RF and LO modulators.

Other optical amplification solutions may also become available in the medium-term, including new generations of Erbium-Doped Waveguide Amplifiers (EDWAs) based on emerging PIC technology platforms (thin-film lithium niobate, silicon nitride ...).

Finally, if the RFoF configuration shows good performances in terms of RF spectral purity (any spurious above -63.5 dBc in the transmit Ka-band), for the RF frequency photonic up-conversion, a photonic LO based on modulator biased at quadrature will be preferred and the LO driving power shall be decreased to reduce the amplitude of the spurious at $2LO-2RF$ below -32 dBc. However, in parallel, a compromise will have to be found because reducing the amplitude of the LO driving signal means a degradation in RF functional performances.

Figure 9. Compact optical fibre amplifier from LEO Space Photonics R&D



4. CONCLUSION

We have reported the last achievements and findings of the ACTA-UHTS project in the field of photonic beamforming, from the design and fabrication of a 1-D beamformer photonic chip to the integration of photonic RF beamforming network demonstration.

ActA-UHTS project has demonstrated significant advances in the development of a 1-D 13x12 beamformer based on integrated TTD on Si-based PIC and wavelength switching by VTT with promising performance and low SWaP.

Indeed, the integration of 156 differential TTD's (up to 234 ps) in 4 cm² chip size with good time accuracy was proven as well as the implementation of 25 WDM multiplexers in small chip size, exhibiting good wavelength accuracy and loss uniformity. Optical insertion losses were measured higher than targeted and expected and should be definitively improved for a better implementation in photonic RF sub-system. Mainly the excess losses were due to manufacturing issues causing point defects in some of delay line spiral waveguides as well as unusually high losses in the (de)multiplexers.

Finally, we presented the development, integration and test by Thales Alenia Space of a photonic RF beamforming PoC demo based on the beam-former PIC and discrete photonic devices at Tx side.

It allows to demonstrate photonic RF routing and 1-D beam-forming/switching for both configurations: IM-DD optical link in Ka-band and photonic RF frequency up-conversion from C-band to Ka-band.

Functional validation of the sub-system PoC and RF performance testing have been successfully completed, with promising results for the RFoF configuration supporting transmission of signals in the transmit Ka-band (20 GHz).

For the second subsystem configuration, which is also to support C/Ka-band frequency up-conversion, the RF performance was found below expectations, in terms of RF gain and NF. This was mainly due to the non-linearity of the SOA, which did not allow the gain it should provide to be fully utilized. In order to mitigate SOA non-linearity and reduce optical insertion losses in the BF PIC, possible improvement measures necessarily include the implementation of linear optical amplifiers such as compact conventional OFAs (optical fiber amplifiers), or in the longer term, new-generation integrated EDWAs (erbium-doped waveguide amplifiers).

As well as the initial target of UHTS application for Telecom market disruption at the expense of LEO constellations, the further development of a 1D Photonic BF/switch at higher TRL could be suitable in other application domains, for example, Observation domain with Synthesis Aperture Radars.

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