Recent advances of photonics processing in the satellite market

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Abstract—**The ability of photonic processing to manage high data rates and RF bandwidth and its potential for integration and mass reduction is critical in advance on-board satellite applications like beamforming, frequency conversion or data-converters. This paper reviews the latest demonstrations on-board of this technology and the evolution towards flexible architectures.**

Keywords— Optical Payloads, Photonic Processing, Flexible configurations, frequency conversion, photonic-assisted data converters, optical beamforming, in-orbit demonstration.

I. INTRODUCTION

Global demand of broadband communication services is growing year by year with a forecasted double-digit growth in the coming decade so new satellite systems able to provide high capacity and flexibility are needed to satisfy every user on the network at the minimum in-orbit cost per Gbps. The space industry is proposing two alternatives to cope this demand: Very High Throughput Satellites (VHTS) mainly in GEO, and mega constellations of small/medium LEO satellites, named commonly New Space.

The transitions from standard, classical GEO systems to the New Space approaches, in combination with the global situation of crisis and uncertainty, is blurring the traditional clearness of the space business cases. Designing a space system with static coverage and capacity for the typical mission lifetime of 15 years is not compatible with such uncertainty. At the end, the problems to solve are to have solutions with extreme capacity (multi-Tbps in VHTS), low size, weight, and power consumption for small LEOs and for ultra-high-density VHTS payloads, low price-per-Gbps and with flexibility to enable a given satellite on command to support different frequency plans, re-configure coverage in response to changing traffic demands and re-configure interconnectivity between coverages [1,2].

In general flexibility would enable a satellite system to adapt to changing circumstances over its lifetime and thereby maximise its utility and profitability. Microwave photonic technologies could be key enablers to overcome the challenges required to provide the capacity and flexibility to dynamically manage future Terabit/s communication and New Space satellites payloads. The ability of photonics to manage high data rates and RF bandwidth and its potential for large integration and mass reduction in advance applications like antenna beamforming, multi-frequency conversion or photonic-assisted data-converters at very high frequencies is critical in this scenario, especially when the optical fibre is included in the payload design substituting waveguides or coaxial cables [3].

II. PHOTONIC PAYLOAD CONCEPT

The introduction of payload equipment based on photonic technology within the commercial satellite market is becoming a reality with different on-ground and in-orbit demonstrations implementing photonic assemblies with the following features:

- generation and fibre-optic distribution of multiple Photonic Local Oscillator
- the multiple, simultaneous signal mixing (RF conversion to IF with a photonic Local Oscillator) in a single device, which enable to reduce the number of equipment
- the demultiplexing and routing of the different frequency conversions (associated to multiple LOs).
- ultra-broadband electro-photonic interfaces covering up to V band, which enables to have a single photonic solution for any frequency band. This concept simplifies the architecture and reduces the need of "payload personalization" to the RF interfaces.
- use optical fibre within a distributed architecture enables satellite designers to have a new degree of freedom and flexibility in the allocation of the hardware thanks to these characteristics of the optical fibre:
  - The propagation losses are independent of the fibre lengths required in a satellite
  - Optical fibre is completely immune to RF interference, so it can be routed freely
  - The mass of the optical fibre is much smaller than coaxial cables and RF waveguides and is easy to route and bend.
  - Optical fibre can multiplex many channels/signals in a single fibre by using wavelength (de)multiplexing schemes (WDM) so the number of fibres can be reduced compared to RF cables.
  - Incorporation of flexibility with reconfigurable channel routing and filtering enabling the dynamic bandwidth allocation to different users.

A simplified scheme of this concept is shown in the Fig. 1. Different demonstrators of this concept have been developed and implemented with different levels of maturity, from lab-demo to In-orbit demonstrations. The full realization of this architecture opens the door to construct advanced payloads based on analog signal processing with efficient SWaP (size, Weight and Power consumption) and flexibility, suitable for the next generation of HTS and small LEOs.

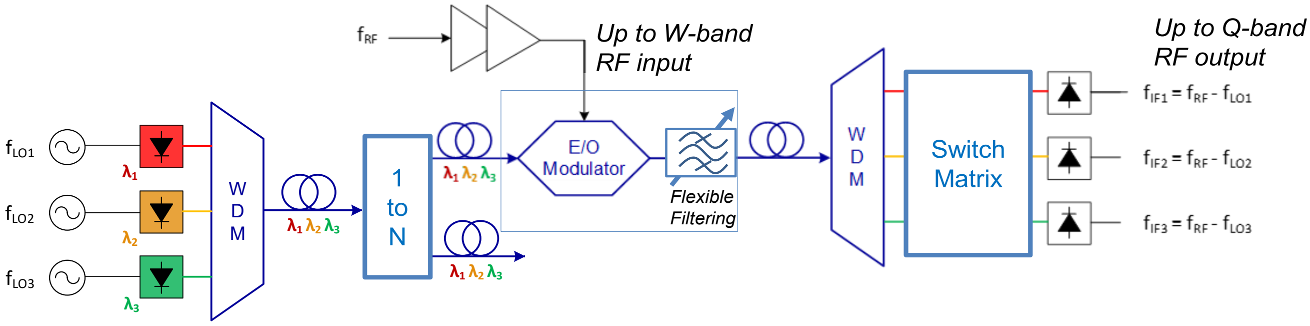

Fig. 1. Concept of photonic frequency conversion with multiple LOs. Simplified scheme with 3 LOs modulated in three optical carriers, multiplexed (wavelength multiplexing), simultaneous mixing with the RF signal in an electro/optical mixer, demultiplexed and photodetected. Flexibility is incorporated by flexible RF channel filtering in the optical domain and by optical switch matrixes.

III. PHOTONIC CLK AND LO DISTRIBUTION IOD

In the September 2017, an In-Orbit Demonstration (IOD) Photonic Technology was launched in the Hispasat Amazonas 5 satellite, integrated by Space Systems Loral and manufactured by DAS Photonics [4]. It included On-board Reference, LO and RF distribution by using optical links with the following characteristics (see Fig. 2):

- In-Orbit test of the optical links, including a fibre of 10 meters and a power splitter.
- Phase drift of 10 MHz reference by measuring the Allan deviation introduced by the optical link
- Power stability of both optical links (low and high frequency) tested at 10 MHz and 10 GHz.

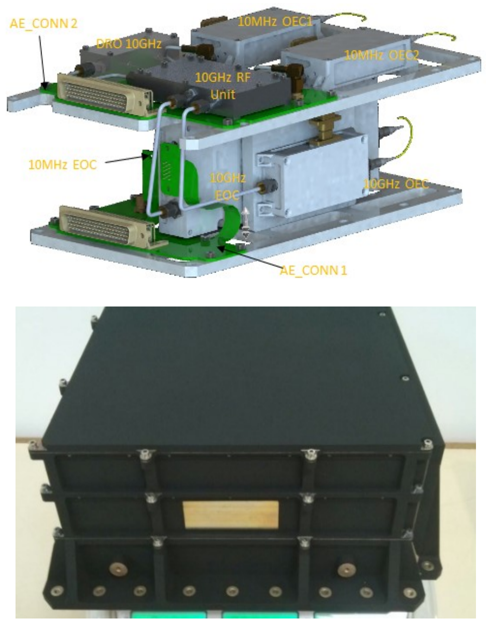

Fig. 2. 3D view of the optical assembly including the optical links and the 10 GHz oscillator and power detector (*top*) and Photograph of the enclosure of the flight unit of the Amazonas 5 Photonic IOD (*bottom*).

IV. PHOTONIC FREQUENCY CONVERTER IN KA-BAND IOD

In March 2018 the first Photonic Ka-band Down-Converter was launched in the Hispasat 30W6 satellite, integrated by Space Systems Loral and designed and manufactured by DAS Photonics [4]. It consisted in an assembly composed by two modules interconnected by optical fibre. Each module had its own DC power and TM/TC interfaces, as well as the specific optical and electrical ports. These modules are:

A. Photonic Local Oscillator Module (PhLO)

This module oversees generating an optical local oscillator using in the photonic frequency conversion process. Basically, it is an optical transmitter that convers an electrical Local Oscillator to the optical domain. A booster optical amplifier and a 1 to 16 optical splitter was included in the module to demonstrate the capability of LO splitting and distribution. An optical multiplexor (WDM) was included to be tested in orbit to prove as much elements of the architecture shown in the Fig 1 as possible.

B. Photonic Downconverter Module (PhDOCON)

This module was basically a photonic mixer that mixes the photonic LO with an RF signal to generate a set of mixing product and a photodetector that generates the IF signals. In this process only 1RF+/-nLO spurs are produced. This assembly integrated optical amplification (pre and post amplification) and optical demultiplexer to demonstrate the impact of the demultiplexing in orbit. Specific pre and post amplifiers were designed and manufactured by SSL and integrated in the PhDOCON module, obtaining a conversion gain higher than 17dB and OIP3 better than 21dBm. This equipment was included in the Ka payload as a redundant converter (see Fig 3).

V. PHOTONIC FREQUENCY CONVERTER IN Q/V-BAND IOD

The first Photonic Local Oscillator and photonic frequency converter able to operate up to V/Q band was designed, manufactured, tested by DAS Photonics and integrated by MAXAR (formerly SSL) in the commercial telecom satellite Eutelsat 7C [5]. It implemented a Single String of the Photonic Payload (SSPP) shown in Fig 1, i.e, one Photonic LO, one photonic DOCON and one receiver, all these parts being interconnected by optical fibre. Thought it was qualified up to V/Q band, due to its broadband characteristics it is operated in orbit at Ka-band. The photonic equipment is able to work with LO frequencies beyond 35GHz and RF input/output frequencies beyond 51.4/42.5 GHz. The interconnection among the photonic modules (LO, DOCON, Receiver) is achieved through optical fibre, which replaces of segments of waveguides and/or coaxial cables in the payload, thus reducing the overall mass and footprint of the RF harness.

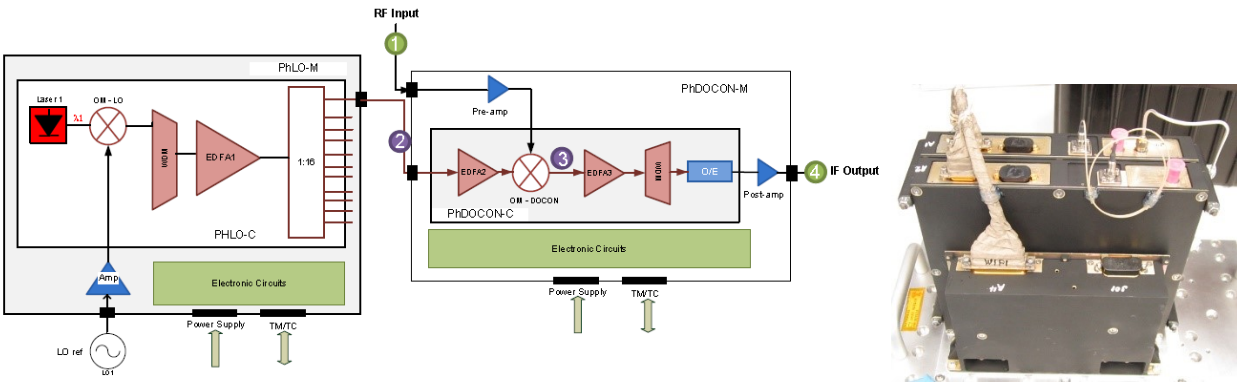

Fig. 3. Ka-band Single String Photonic Payload block diagram. The PhLO module (left) is connected with the PhDOCON module (right) with optical fibre (point 2). External LO reference at 3.25GHz is injected at the input of the PhLO, which generates 16 replicas of the optical LO signal. On replica is mixed (point 3) with the incoming Ka-band signal (point 1) to generate the IF signal at the output (point 4). The RF amplifiers (LO, DOCON pre and post-amps) are shown in blue. photo of the flight unit photonic assembly (right).

This photonic unit was designed and constructed following the standard requirements for a 15-years missions in GEO orbit and qualified at module level with a qualification vehicle (qualification-like model). A specific process for up-screening and qualification of the photonic parts (not available in hi-rel, rad-hard version) was specifically designed and implemented. Functional test results have demonstrated the broadband operation of this photonic solution and its suitability for commercial telecom satellites, especially for HTS in which a large optimization of mass, size and power consumption is foreseen with respect to a traditional RF implementation.

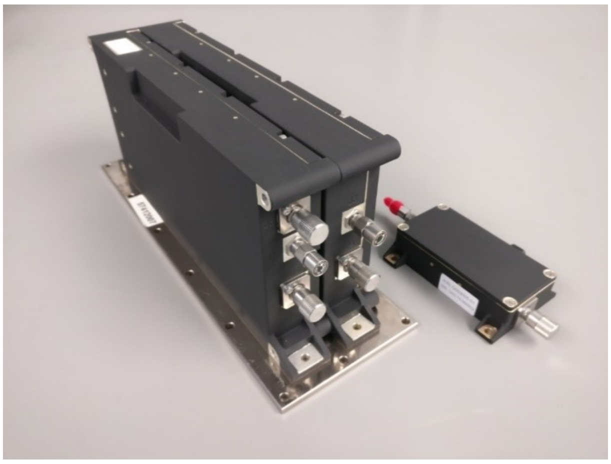

Fig. 4. Picture of the SSPP Flight Model. The PhLO and PhDOCON are stacked together in a single assembly. The connection between the units is done by optical fiber (not shown in this picture).

The RF transfer parameters were tested in Ka band for the final configuration hosted on E7C. The capabilities of the unit to be operated in different frequencies (from Ka to Q/V) were assessed as well. The Ka band tested frequencies were:

- Input frequency: 27.1 to 31 GHz
- Output Frequency: 17.3 to 21.2 GHz
- LO frequency: 9.8 and 10.2 GHz

And the Q/V band frequencies tested were:

- Input frequency: 47.2 to 51.4 GHz
- Output Frequency: 37.4 to 41.6 GHz
- LO frequency: 9.8 GHz

VI. Flexible Multi-String Photonic Payload Demonstration

The architecture shown in the Fig. 1 was implemented and tested in the H2020 program OPTIMA [6] up to TRL 5, except the flexible filter functionality.

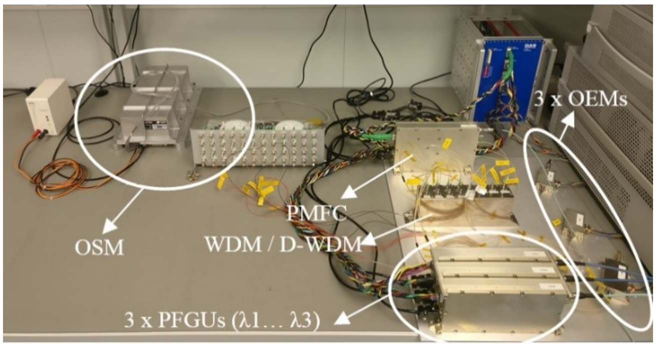

Fig. 5. OPTIMA demonstrator.

A. Qualification test conducted

At component level, the targeted test campaign was focused on evaluating the impact of the radiation (Gamma and proton), shock and temperature environmental constraints on the photonic components. At module level, the targeted test campaign was focused on evaluating the impact of the vibration, shock and temperature vacuum environmental constraints on the different units

B. Performance tests

The demonstration was comprised of three laser wavelengths set in ITU channels centred at 1558.17 nm, 1549.32 nm, and 1555.75, and the electrical LO frequencies selected for the demonstrator were 9, 10.5 and 12 GHz. A fully functional validation was carried out, measuring performance parameters such as system conversion gain, SFDR, noise figure, etc, as well as performing a fully functional dynamic validation demonstrating the flexibility of the photonic payload in terms of channel selection, routing and allocation.

C. Flexible RF channel Filtering

The functionality of the RF channel flexible filtering was demonstrated in the ESA Contract No. 4000109590/13/NL/RA - *Photonic RF Filtering*. The solution designed was based on narrowband optical amplifiers based on Brillouin Back-scattering. This amplifier enables the channel amplification directly in the optical domain resulting in a channel selectivity (or filtering) once the optical signal is photodetected and translated to the RF domain. This filter was demonstrated in the X-band with bandwidths from 56 to 170MHz and 2GHz frequency tunability. The following figure shows the filters response tested in the lab (S-parameters).

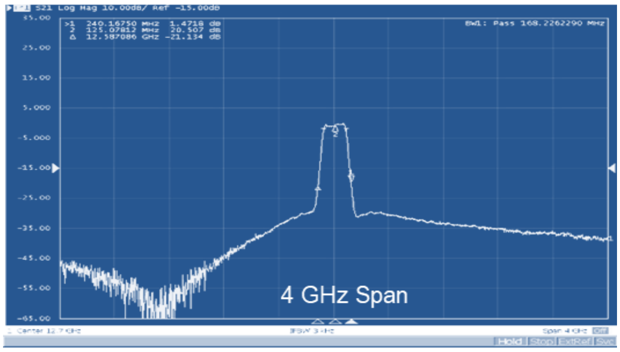

Fig. 6. 170 MHz BW Flexible RF-Photonic Filter

VII. Photonic Processing for Digital Payloads

The most recent trend in the Telecom Space market is the implementation of the paradigm of full flexibility defined by software. This idea consists of having all the signals in the satellite in the digital domain in order to use digital signal processing enabling the full control the satellite by software, including routing, switching, filtering, regeneration and dynamic coverage allocation (if digital beamforming is implemented with phased-array antennas).

The digital repeater requires the conversion of the RF signals (from/to the satellite) to/from the digital domain. This process is normally done, firstly by a frequency conversion with traditional RF means to an Intermediate Frequency (IF), and then the signal is digitized by an Analog-to-Digital Converter. After the digital processing, the signal is converted again to IF by Digital-to-Analog Converters and up-converted to the required RF frequency again by traditional means. Recent advances in the data converters enables the increase of the IF frequency up to Ku-band, or even to Ka-Band with some limitations, but the rest of the process is needed to be done still by RF signal processing. The major limitations of this solution are the large power consumption required for the digital processing and the hardware complexity: analog front-end (Up/Do-con, signal conditioning…) and Digital IF/BB processors.

The above-described photonic processing could alleviate the limitation of the hardware complexity and reduce the power consumption of the analog section, which can be re-allocated to the digital processor. On the other hand, the architecture could be even more optimized by implementing photonic-assisted data-converters. These data-converters uses the photonic sampling to extend the analog input frequency of the traditional electronics ADC/DACs without the frequency limitation imposed by the electronics (mainly the distortion vs frequency). The most recent advance in photonic-assisted data-converters is being done in the H2020 PhLEXAT project [7]. In this activity, photonic data-converters working up to W-band with fibre-optic remote sampling are being developed targeting large level of photonic-electronic integration and sampling rates large enough to be capable to directly digitize the complete communication bandwidth allocated in Ka, Q, V and W bands.

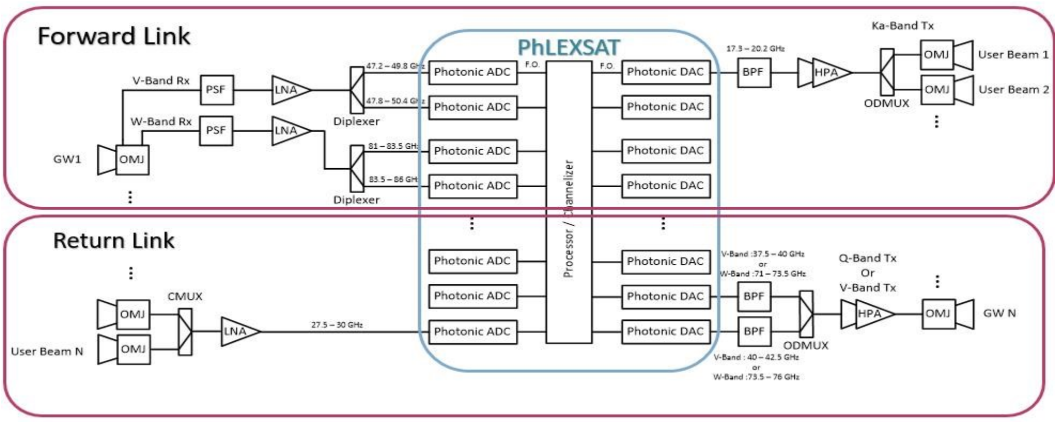

Fig. 7. Photonic-based ADC and DAC for digital payloads, able to digitize directly the RF signals up to V/W-band and to generate digitally the signals up to Q/V-band, applicable to flexible HTSs with on-board processing

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