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M. Sotom

M. Aveline

R. Barbaste

B. Benazet

et al.



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FLEXIBLE PHOTONIC PAYLOAD FOR BROADBAND TELECOM SATELLITES: FROM CONCEPTS TO SYSTEM DEMONSTRATORS

M. Sotom, M. Aveline, R. Barbaste, B. Benazet, A. Le Kernec, J. Magnaval, M. Picq,
Thales Alenia Space France
26, Avenue Jean-François Champollion
31037 Toulouse Cedex, France

I. INTRODUCTION

In the last decade, Thales Alenia Space has put significant research effort in photonic technologies for satellite applications, with the objective to provide telecom payload systems with enhanced functionality, higher performance and lower costs. Innovative payload concepts have been thoroughly elaborated, taking benefit from the capabilities of photonics. Transferring RF/microwave signals onto optical carriers makes it possible to perform processing in the optical domain and benefit from specific attributes such as small size and low mass of fiber optics, as well as multiplexing or switching capabilities, to name a few.

Such photonic RF payloads rely upon conventional low-noise receive and high-power transmit RF sections, but contain a photonic repeater core, that effectively supports flexible routing of any RF signal from any input port, to any output port at any frequency. Such a payload features optical distribution of centralized Local Oscillators (LO), photonic frequency-conversion and cross-connection of RF signals.

The feasibility and applicability of these concepts have been extensively assessed in the frame of the OMCU (Optical Multi-frequency Conversion Unit for Broadband Transparent Analogue Repeaters) and OWR (Optical Wideband Reconfigurable – Receiver front end) ESA projects. They outperform RF architectures in large-scale, high-capacity payloads, for instance for multi-beam access missions, where a small number of gateways serve numerous user beams. Today, the gateway-to-user beam allocation must be fixed in the design phase whereas a photonic payload enables in-orbit reconfiguration and make this allocation reconfigurable all along the mission.

This paper gives an overview of the payload concepts, and presents the main achievements in the development of system demonstrators. Sub-populated yet representative repeater models were assembled at different technology maturity levels, but all providing end-to-end photonic RF paths, not only to prove the functionality, but also to demonstrate performance and assess the potentials for growth to larger system scales. The end-to-end RF performance as achieved in test campaigns are reported.

II. MICROWAVE PHOTONIC REPEATER CONCEPTS

Innovative microwave photonic repeater concepts have been investigated for years by Thales Alenia Space as a means to provide telecom payloads with enhanced capabilities [1] [2] [3]. A new class of transparent repeater was elaborated based on photonic technologies, and optical switching of RF signals was explored for enhancing the reconfiguration capabilities of future telecom satellites with multiple antenna beams. Broadband operation, transparency to RF frequency bands and connectivity reconfiguration are essential features enabling future repeaters to adapt to evolving traffic demands during the complete lifetime of the satellite.

A typical photonic payload architecture is discussed later, but basically consists in conventional microwave low-noise receive front ends and high-power amplification chains in the transmit section, and features a photonic repeater, which acts as a space/frequency switch, and thus enables to route any RF sub-band from any input access port to any output access port and to shift its frequency position accordingly. More specifically, the photonic repeater core supports the following functions:

- optical distribution of centralized, high-frequency microwave Local Oscillator (LO) signals. The set of LO's is generated and transferred on optical carriers within a photonic frequency generation unit (FGU) and delivered over optical fibers to 10's of electro-optical mixers.
- photonic frequency-conversion of RF signals by means of electro-optical mixers. The electro-optical mixer being fed up by an optical LO, the RF signal received from an up-link antenna is down-converted to an intermediate frequency (IF).
- optical cross-connection (circuit-switching) of RF signals by means of micro-optical switches, that feature unique capabilities such as scalability to large port counts and RF frequency independence.

Electro-optical mixing offers attractive capabilities, out of which multiple frequency-conversion (OMC) performed by feeding the electro-optical mixer with several LO's on separate optical carriers using wavelength-division-multiplexing (WDM). An incoming RF signal at ω_{RF} can be mixed with multiple photonic LO's on

separate optical wavelengths, and it is thus possible to convert this RF signal to several output signals at various ω_{IF} frequencies after optical wavelength de-multiplexing and separate photo-detection.

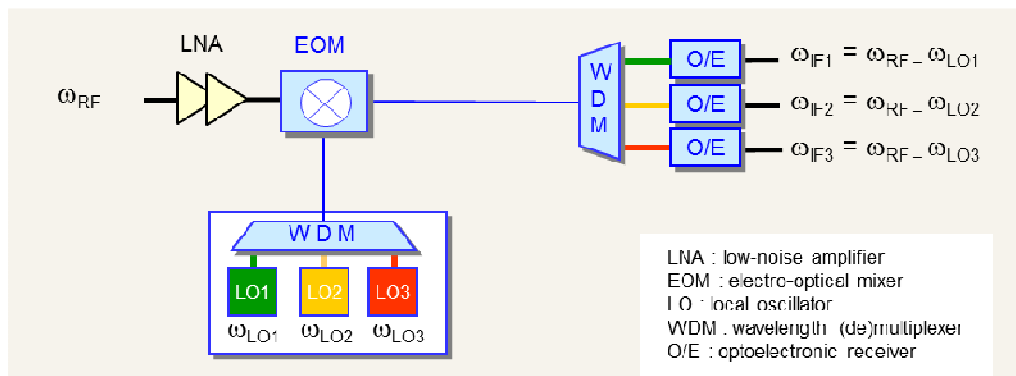


Fig. 1. Principle of optical multi-frequency conversion (OMC)

Functional applications of the OMC technique were elaborated in more detail within the OMCU project. OMC can be used for frequency routing, with frequency-band or frequency-slot interchange and enhance the reconfiguration flexibility of the photonic repeater architectures. It can be used for routing to multiple frequency bands as well. The OMC technique can thus greatly enhance the overall flexibility of photonic repeater architectures by offering the following capabilities:

- full cross-connection functionality (i.e., from any uplink channel to any downlink channel, with physical access, frequency-band and frequency-slot interchange)
- direct single-stage frequency conversion with partial cross-connectivity (i.e. no conversion to IF)
- inter-band reconfiguration capability (e.g., uplink access in Ka-band, and downlink in Ku-band, and later reconfigured depending the actual needs, for example, to Ka-band).

Also, OMC can be used for wideband RF channelization, where a wide input RF band can be down-converted into multiple copies with some frequency shift so as to be sliced by sharp band-pass RF filters.

The present paper focuses on photonic architectures making use of OMC, and designed for multi-beam payload applications, and nicknamed as OMAR (Opto-Microwave Analogue Repeater) architectures in the frame of the OMCU project. Such photonic architectures were expected to exceed the capabilities of microwave/RF implementations, bringing drastic mass, power and volume savings, growing up to larger scales, and/or supporting in-orbit reconfiguration.

III. MULTI-BEAM BROADBAND ACCESS MISSION

Satellite operators have expressed their interest for higher capacity and payload flexibility for years. The proposed optical multi-frequency conversion concept together optical switching can provide optical in-orbit reconfiguration, e.g. for flexible allocation of gateway to user beams in multi-beam access missions. Whereas equivalent RF implementations would result in unaffordable complexity, photonic architectures can provide such capabilities, resulting in enhanced flexibility and/or capacity, and potential for increased revenues.

A. Multi-beam broadband access mission scenario

An example of a broadband satellite covering a region, Europe, is shown in Fig. 2. The underlying network has a classical topology, i.e. star, in which serving several thousands of user terminals are connected to the global network through a gateway. The demand for small user terminals, together with the need to offer competitive broadband access solutions, calls for small user spot beams. These spot beams (from 0.4 to 0.7 deg. in Ka-Band) are arranged in a regular pattern, allowing to re-use several times the available frequency band. This is achieved through a well-known scheme based, for instance, on 4-color re-use, the color of a spot beam being defined by a combination of one out of two frequencies and one out of two states of polarization. The user beams are connected to the gateway through the satellite in both directions, namely Forward, from gateway to user, and Return, from user to gateway. The number of spot beams connected to a given gateway is limited by the feeder link bandwidth available, itself limited by regulatory constraints.

Fig. 2 shows an European coverage with 80 user spot beams arranged in an hexagonal pattern. In this case, up to 8 user beams can be hooked to a gateway, meaning that a total of 10 geographically separated gateways are needed for the system in its final stage of deployment.

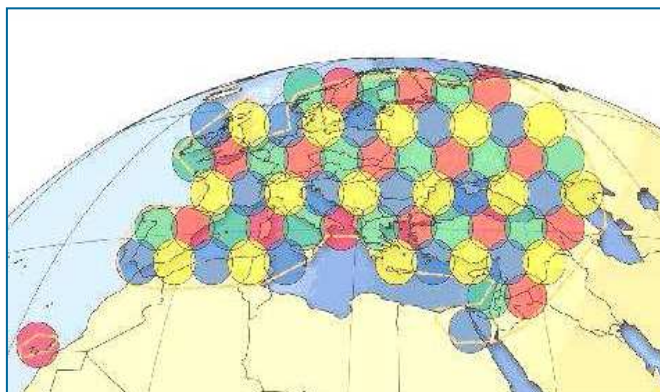


Fig. 2. Example of multi-beam coverage of Europe with 80 beams

A communications payload architecture allowing to connect any of the 10 gateways to any of the 80 user beams would be of a great benefit to the operator. It would permit a smooth deployment of the user terminals in the most promising areas and connect them to the first system gateway. And then, to add spot beams and connect them adequately while new gateways and user terminals are rolled out. To an operator who wants to minimize the risks associated with the ground network deployment, it would be of great help to deploy the system gradually, as this would allow:

- to minimize the ground network CAPEX (Capital Expenditure) at the beginning and test the service with a minimum of initial investment, for instance by starting the service over Europe with only one gateway.
- to have time to roll-out the user terminals: start ad ramp-up their production, put in place the distribution scheme and install them at the customer premises.
- to start service in the areas (beams) having the highest need for the service and the biggest potential.

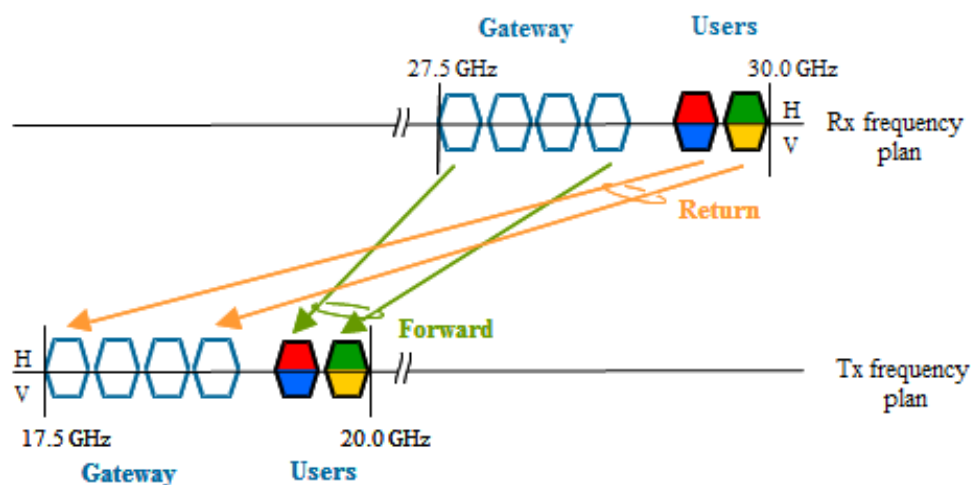


Fig. 3. Reference frequency plan of the Forward and Return missions

These first served spot beams could be spread over the coverage, e.g. with one beam per country located over the most promising part of it. The spot beams to be connected to the first gateway would then be chosen in order to minimize the initial risk and maximize the chance of a fast take-off of service. The color of the chosen beams in the 4-color re-use scheme will then be random and will most probably not fit within the gateway feeder link frequency plan. On-board down and up conversion frequencies will therefore be needed in a flexible manner at the start of service, and will evolve as the network grows and the number of gateways increases. As a matter of example, the forward and return frequency plans used a reference in OMCU project are shown in Fig. 3. There are 4 frequency slots in Receive and 2 frequency slots in Transmit, so that 5 LO frequencies are needed.

B. Photonic RF payload architecture

Various OMAR implementations were designed for forward and return repeater respectively, based on similar architectures all making use of OMC concept, and on common optical building blocks. Fig. 4 above gives one of

the most relevant OMAR architectures considered for the forward repeater, similar architectures having been proposed for the return repeater.

The Forward photonic payload consisted in a photonic frequency-generation unit (FGU), a photonic frequency-down-converter assembly, and an optical reconfiguration section based on a wavelength-selective optical switching architecture. The Return payload was based on the same principle, and on a similar implementation. All the LO's are generated and transferred on optical carriers within the FGU and delivered to modulator-based electro-optical mixers. The Forward photonic FGU architecture was designed to provide 5 LO's to all output ports. The Return FGU architecture was designed to provide 5 LO's as well.

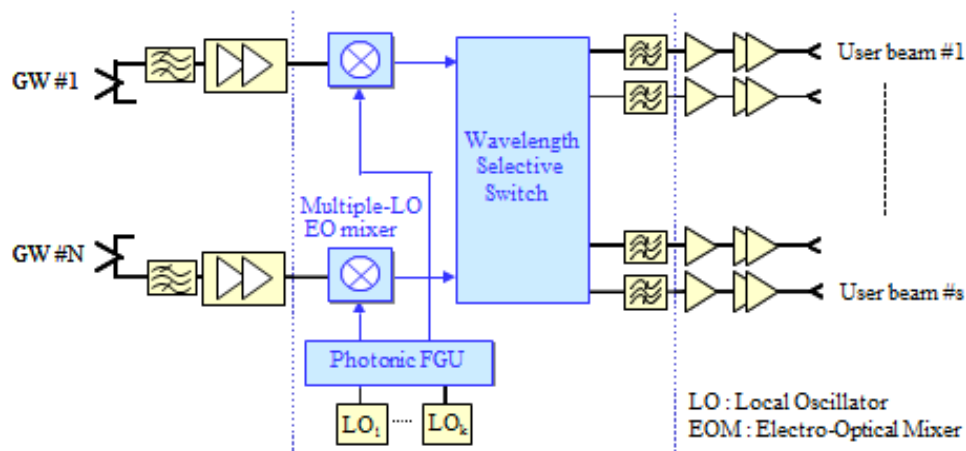


Fig. 4. Photonic RF payload architecture for Forward repeater in multi-beam mission

RF signals received from up-link antenna accesses are transferred onto the optical carriers at the electro-optical mixers. When the electro-optical mixer is fed by an optical LO, the input RF frequency is down-converted to an intermediate frequency (IF). Amplification, distribution and switching are performed in the optical domain by means of optical amplifiers and micro-optical switches in the wavelength-selective switching unit.

At the output of this latter stage, opto-microwave receivers convert the optical signals back into microwave ones at IF, and RF channel filtering is achieved by means of conventional RF filter technology. From preliminary estimations of complexity and budgets, it turned out that equivalent RF payload implementations would result in huge amount of hardware, and were thus considered today as almost unfeasible.

III. ENABLING TECHNOLOGY AND BUILDING BLOCKS

The considered photonic repeater architectures above rely in particular upon photonic LO distribution and frequency-conversion of microwave signals. LO signals in the 8-20 GHz range are needed under optical form with high power and low phase noise. Double side-band modulation with carrier suppression (DSB-CS) of a high-power CW laser carrier through an intensity modulator was used to create such photonic LO's. Optical heterodyning of the first two side-bands at the receiver then generates a high-purity LO signal.

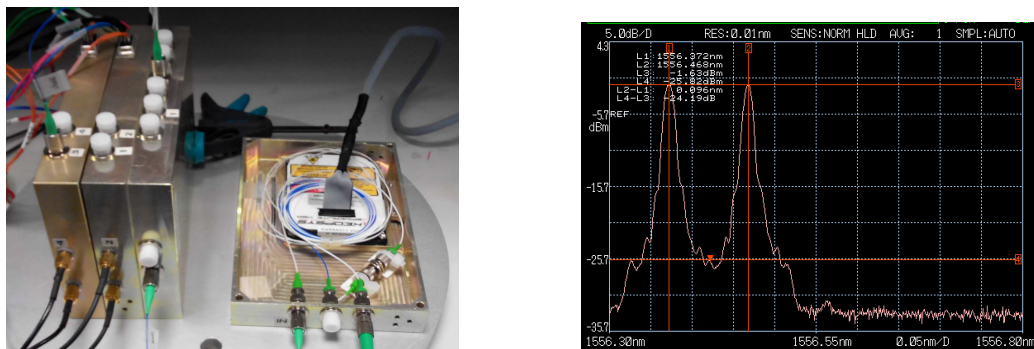


Fig. 5. Integrated photonic frequency-generation unit

- breadboard unit (right)
- single optical LO spectrum (left)

(DAS Photonics courtesy)

The photonic FGU unit gathers all the means for the generating and distributing the photonic LO's to the electro-optical mixers. It comprises photonic Local Oscillators slices mainly using CW laser and EOM devices, passive components including WDMs and optical couplers, and an Optical Amplifier slice to increase the power level for each optical carrier. The photonic FGU breadboard was designed to deliver up to 5 LOs using a separate optical wavelength for each optical LO. Fig. 5 above shows the integrated photonic frequency generation unit, assembled by DAS Photonics, and the optical spectrum of a single LO. The photonic FGU manufactured was shown to comply with all the target requirements.

Mach-Zehnder intensity modulators have been proven to perform well as electro-optical mixers for photonic frequency-conversion for a long time, a particularly efficient arrangement consisting in feeding the modulator with a photonic LO as described above. The RF signal to be down-converted is applied to the modulator RF input, thus superimposing a RF modulation of the optical intensity. Direct detection generates beat products, i.e. the frequency sum and the frequency difference. By tuning the opto-microwave receiver frequency response appropriately and using additional RF filtering, the unwanted frequency compounds can be removed so that the IF frequency only is output.

An OMCU model based on this principle was developed as an assembly of two dual-channel slices, i.e. each slice containing two OMC channels. Each OMC slice mainly contained two electro-optical modulators and electronic circuitry for bias monitoring and control. The modulators were low-drive voltage, electro-optical modulators on Lithium Niobate substrate developed by Photline (F), and assembled in small-form factor package. Fig. 6 shows the integrated two-slice, dual-channel OMC unit model.

The role of the Wavelength-Selective Switch (WSS) unit is to extract individual optical channels from the WDM input optical signal, to route them separately, and to convert these optical single-IF carriers into RF output signals in transmit Ka-band.

A WSS unit as much as possible representative of the OMAR architecture was implemented, but in the form of a breadboard. It featured two optical inputs for WDM-based multiple-IF optical signals, and four optical outputs with single-IF optical signals, than could be connected to four opto-microwave receivers providing RF outputs, out of which two operated in Ka-band. The WSS breadboard consisted of a wavelength demultiplexing slice, an optical switch slice, and an opto-microwave receiver slice. Fig. 6 below shows the WSS unit, with all the three slices assembled together, from left to right: the optical switch slice, the wavelength demultiplexing slice, and the opto-microwave receiver slice.

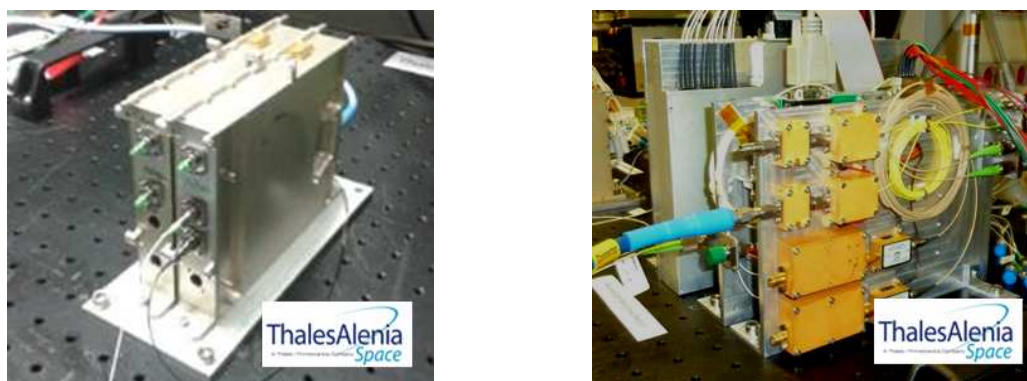


Fig. 6. Two-slice, OMC unit model (left), and Wavelength-Selective Switch unit breadboard (right)

IV. PHOTONIC PAYLOAD SYSTEM DEMONSTRATOR

A down-scaled system demonstrator was developed with building blocks at various levels of technology readiness and representativeness. Fig. 6 shows the OMAR breadboard model designed to prove the architectural concept and to assess the RF performance. It was representative of a couple of end-to-end RF path with two inputs in receive Ka-band (28-30 GHz) and two outputs in transmit Ka-band (19-20 GHz).

The OMCU model and OMAR breadboard as assembled in a laboratory demonstrator are shown in Fig. 7. From left to right the OMAR breadboard demo features the photonic FGU breadboard, the 2-slice assembly of Optical Multi-frequency Conversion Units (OMCU) and the Wavelength-Selective Switch (WSS) breadboard. The photonic FGU can deliver optically to a number of photonic frequency-converters up to 5 photonic LO's at any frequency in the 5-20 GHz range with power and phase noise performance suitable for application in the considered repeater architectures. Fig. 7 also shows the optical spectrum of the 5-LO signal, as made available at the photonic FGU output with LO's operating in the 8-9 GHz range.

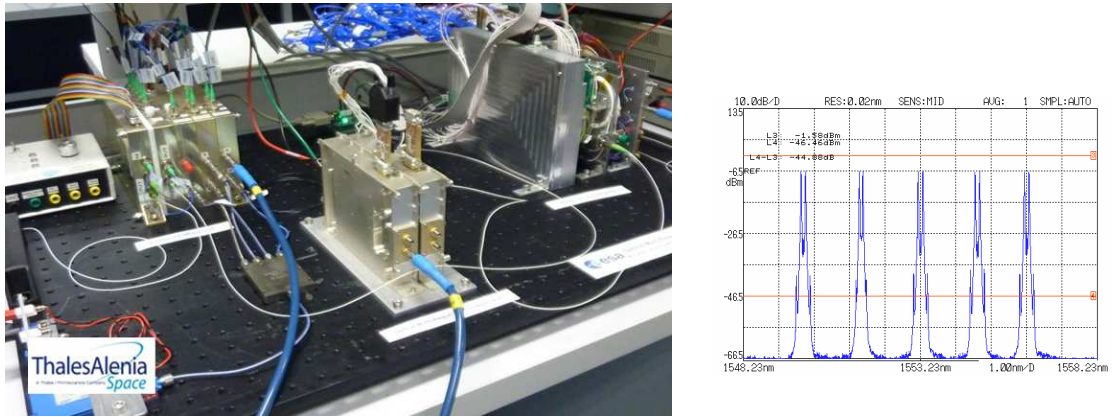


Fig. 7. Integrated photonic RF repeater demo (left) and optical spectrum of the 5-LO signal (right)
IV. DEMONSTRATION AND RF PERFORMANCE

System configurations, frequency plans, and RF input conditions for demonstration and test purposes were thoroughly defined so as to be representative of OMAR architectures in both Forward (FWD) and Return (RTN) payloads. The demonstration was successfully achieved with 5-LO frequency-down-conversion from Ka to Ka band in various frequency plans and configurations.

Fig. 8 below shows the optical spectrum as observed at different stages of the OMAR demonstrator, namely, from left to right, at the output of the photonic FGU, at the output of the OMCU, and at optical output of the WSS breadboard before detection. As a matter of example, one sees the RF modulation superimposed to the LO modulation at the OMCU output, and the selection of the desired channel and rejection of the others at the optical WSS output.

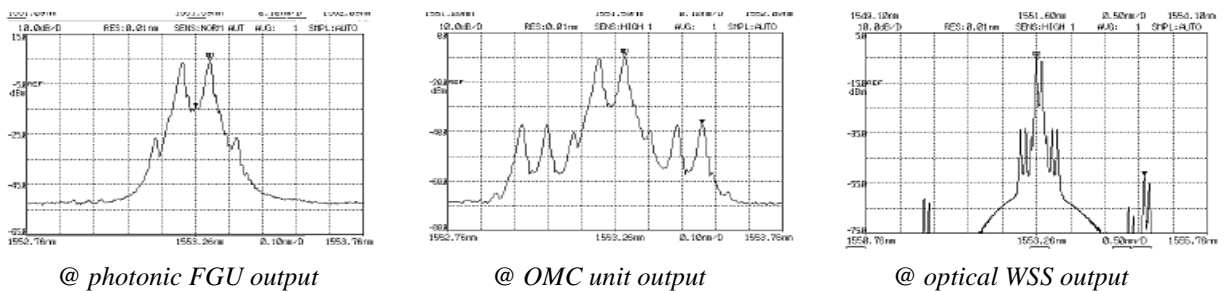


Fig. 8. Optical channel spectrum through the OMAR demonstrator
(w/ down-conversion in Ka/Ka band)

Fig. 9 shows the RF spectrum at the output of the Ka-band opto-microwave receiver, after frequency-conversion to the expected frequency with very good spectral purity in the channel bandwidth, without any unwanted in-band mixing product higher than -75 dBc.

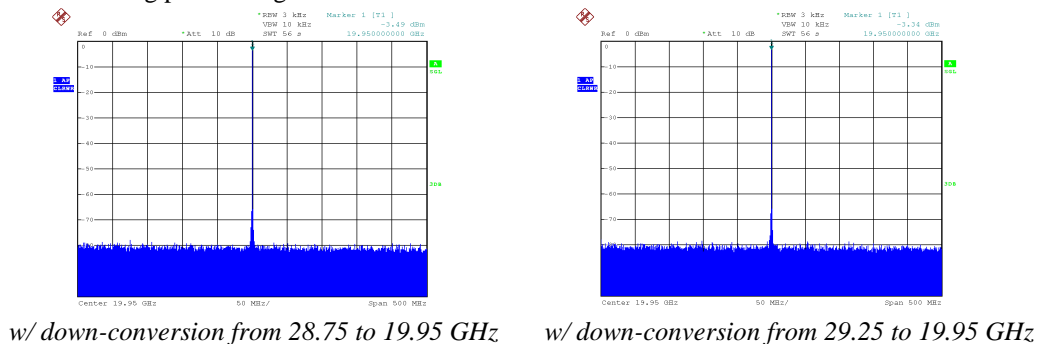


Fig. 9. RF spectrum of the IF output in various frequency plans

The RF performance of the photonic repeater sub-system were investigated in details, experimentally and through theoretical calculations and simulations. Special attention was first paid to the essential RF performance

namely the RF gain, noise figure and third-order linearity considering the ratio (C/I_3) of the carrier to the inter-modulation product, but all the usual RF performance were measured also including spectral quality, gain stability, gain flatness, time group delay variation as well as RF phase noise.

Different system configurations and conditions were assessed and different performance trade-offs were demonstrated, for instance by tuning the output power of the optical amplifier contained in the WSS unit. As a matter of example, the Return payload repeater configuration was proven with RF gain about 0 dB, NF around 43 dB, and C/I_3 ratio that could be as high as 66 dBc at -10dBm RF input power per tone. All together, these performance were compliant with or very close to the specifications targeted for the Return application.

Item	Performance
RF input frequency	27.5 – 30 GHz
RF input power	-20 < - < +3 dBm
RF output frequency	19 – 20.2 GHz
RF spectral purity	> 75 dBc
RF gain	~ 0 dB
Gain stability	± 0.5 dB
Gain flatness	< 1 dB
Noise figure	43 dB
Output TOI	> 23 dBm
Group delay variation	< 1 ns
Phase noise	< -95 dBc @ 1 kHz

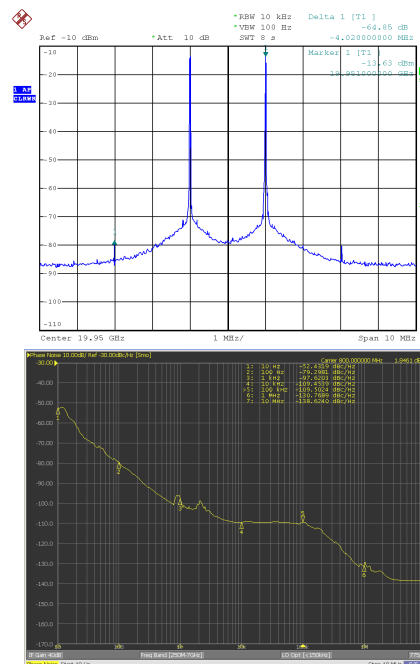


Fig. 10. Typical RF figures and performance (left), 3rd-order linearity and phase noise (right)

Typical RF performance as measured during the OMAR demo test campaign are summarized in Fig.10. Spectral purity, RF crosstalk and phase noise performance were also investigated. Excellent spectral purity (with in-band crosstalk lower than -75 dBc) was demonstrated. It was also shown that stringent RF phase noise requirements can be met. No significant impairment was found to take place, neither in frequency-converters, nor in micro-optical switches, making both of them well suited for handling and routing broadband telecom signals with no detrimental impact on their RF performance, neither in crosstalk nor in added phase noise.

The measured RF performance were also compared with the expected ones. The RF gain and noise figure calculations were updated by taking into account the actual characteristics of the components and units procured or assembled in the project. There was a pretty good agreement between the measured figures and the calculated performance, thus validating our system performance models and prediction tools.

IV. CONCLUSIONS AND PERSPECTIVES

Thales Alenia Space has demonstrated advanced innovative payload concepts making full use of RF photonics, wavelength-division multiplexing and optical switching technologies. This has been achieved through the development of a representative model of an Optical Multi-frequency Conversion Unit (OMCU) and its test in the system environment of an Opto-Microwave Analogue Repeater (OMAR) breadboard.

The demo was arranged in configurations representative of multi-beam analogue payload applications and architectures. The overall functionality of the OMAR demo was successfully validated in Ka band, but these concepts will find applications in a broader range of payloads, with other architectural variants or larger scales, and could be easily extended to other frequency bands in particular Q/V, given the broadband nature of the technology and its transparency to the RF frequency.

An extensive test campaign was run at photonic repeater sub-system level which included all the conventional RF test items, namely RF gain, noise figure, linearity, gain flatness, gain stability, group delay variation, phase noise. The measured performance were found to be compliant with the target requirements, with only minor deviations with respect to theoretical predictions. In addition, preliminary thermal tests were also successfully run over the [-5°C, +50°C] temperature range.

These results open the perspective of new payload solutions with in-orbit re-configurability, with application to multi-beam broadband access mission in Ka-band and above. In such a scenario, a small number of gateways can serve numerous user beams through forward and return payloads. The optical reconfiguration concept supports flexible gateway-to-user beam allocation and enables to change this allocation all along the mission, whereas today this interconnection remains fixed from the design phase. Whereas RF implementations would result in high complexity and large amount of hardware, photonic architectures and technologies can make flexible payloads achievable with standard RF performance, and mass and power budgets compatible with existing platforms. This offers for instance the opportunities to deploy capacity stepwise, at lower risk and initial investments, or to implement more efficient management and redundancy strategies, which both can be turned into larger capacity and better exploitation of payload resource, at any time of the satellite life.

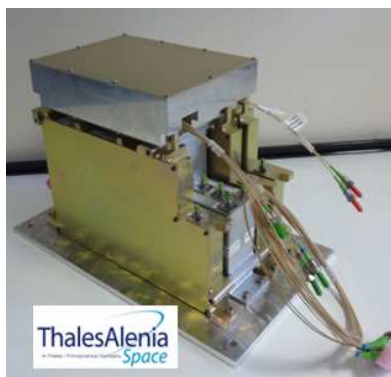


Fig. 11. Photonic Frequency Generation Assembly model, as integrated within the OWR project

Thales Alenia Space is engaged in the development of disruptive photonic payload technology [4], bringing it to higher maturity, and developing representative models of photonic payload equipment, including photonic FGU and frequency-converters and photonic routing solutions. Other models with increased representativeness, as shown in Fig. 11, have been assembled recently, in particular in the frame of the OWR project. The technology is ready for further development, and shall be available for in-orbit demonstration (IOD) in the short term. A “flight proven” label is considered to be decisive for adoption of photonics and introduction in the commercial field. An option in this IOD perspective would consist in a down-scaled, photonic payload system based on the multiple-frequency conversion capability.

ACKNOWLEDGEMENTS

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