Reconfigurable microwave photonic repeater for broadband telecom missions: concepts and technologies

M. Aveline

M. Sotom

R. Barbaste

B. Benazet

et al.

International Conference on Space Optics — ICSO 2014, edited by Zoran Sodnik, Nikos Karafolas,
Bruno Cugny, Proc. of SPIE Vol. 10563, 105633M · © 2014 ESA and CNES
CCC code: 0277-786X/17/$18 · doi: 10.1117/12.2304115

RECONFIGURABLE MICROWAVE PHOTONIC REPEATER FOR BROADBAND TELECOM MISSIONS: CONCEPTS AND TECHNOLOGIES

M. Aveline[1], M. Sotom[1], R. Barbaste[1], B. Benazet[1], A. Le Kernec[1], J. Magnaval[1], P. Ginestet[1],
O. Navasquillo[2], M.A. Piqueras[2]
[1]Thales Alenia Space – France, [2]DAS Photonics (Spain)
26, Avenue Jean François Champollion,
BP 1187
31037 TOULOUSE Cedex
France
muriel.aveline@thalesaleniaspace.com

I. INTRODUCTION

Thales Alenia Space has elaborated innovative telecom payload concepts taking benefit from the capabilities of photonics and so-called microwave photonics. The latter consists in transferring RF/microwave signals on optical carriers and performing processing in the optical domain so as to benefit from specific attributes such as wavelength-division multiplexing or switching capabilities.

Microwave photonic repeater concepts have been investigated as a means to provide telecom payloads with enhanced capabilities 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. Their potential application missions was assessed in particular for a prospective multi-beam broadband access mission in Ka-band, where a small number of gateways serve numerous user beams. Today, the gateway-to-user beam interconnection has to be defined from the design phase; a microwave photonic repeater can make this allocation reconfigurable all along the mission. Photonic technologies can make such payload features achievable with a reduced complexity and amount of hardware compared to current Radio-Frequency solutions.

Sub-populated repeater demonstrators have been developed at various levels of technology readiness and representativeness, not only to prove the concept but also to assess RF performance and to demonstrate scalability to larger system sizes.

This paper gives an overview of the concepts and potential application scenario, and presents the main findings and achievements in terms of key technology, functional performance and budgets.

II. MICROWAVE PHOTONIC REPEATER CONCEPT

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]. A new class of transparent analogue repeater was elaborated based on optical technologies, and optical switching of RF/microwave signals was explored for enhancing the reconfiguration capabilities of future telecom satellites in Ka-band with multiple antenna beams. Broadband operation, transparency to RF frequency bands and flexible reconfiguration/cross-connectivity are essential features in future analogue repeaters that will have to adapt to unpredictable changing traffic demands during the complete lifetime of the satellite.

A schematic of such a payload is shown in Fig.1 below. It is based on conventional on microwave low-noise receive front ends and high-power amplification chains in the transmit section, and features a microwave photonic repeater, which acts as a space/frequency switch, and thus enables to route any microwave sub-band from any input access port to any output access port and to shift its frequency position accordingly.

More specifically, the microwave photonic repeater supports the following functions :

- optical distribution of centralized, high-frequency microwave Local Oscillator (LO) signals. They are delivered over optical fibers with excellent performance to 10’s of electro-optical mixers.
- optical frequency-conversion of RF signals by means of electro-optical mixers, that perform simultaneously multiple frequency conversions by using wavelength-division multiplexing (WDM),
- optical cross-connection (circuit-switching) of RF signals by means of micro-optical switches, that handle micro-optical beams in free-space and feature unique capabilities such as scalability to large port counts and RF frequency independence.

All the LO’s are generated and transferred on optical carriers within a photonic frequency generation unit and delivered to modulator-based electro-optical mixers. Microwave telecom 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 up by an optical LO, the input RF frequency is down-converted to an intermediate frequency (IF).

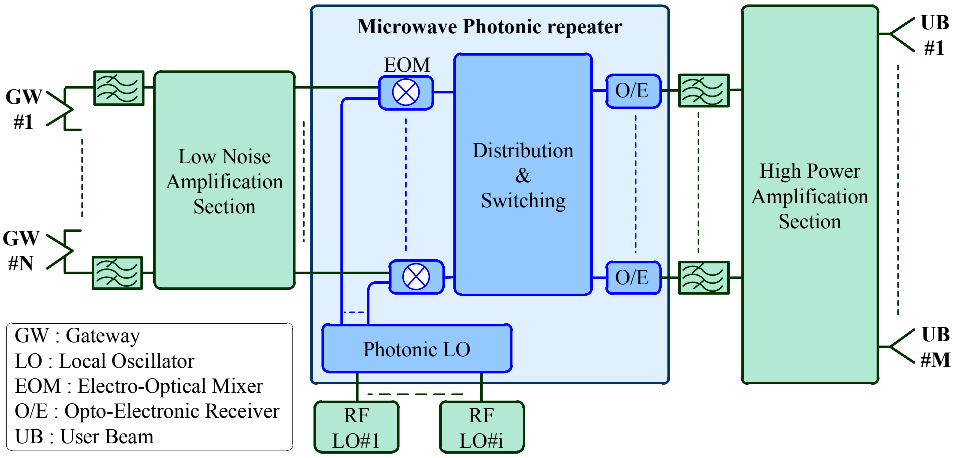

Fig. 1. Simplified block diagram of a microwave photonic repeater

Amplification, distribution and switching are performed in the optical domain by means of optical amplifiers and micro-optical switches. Opto-microwave receivers convert the optical signals back into microwave ones at IF, and RF channel filtering is achieved by conventional microwave technology.

Such microwave photonic analogue repeater architectures are expected to exceed the capabilities of microwave/RF implementations. At identical system functionality and scale, they can bring drastic mass, power and volume savings. They can not only grow up to larger scales than allowed by pure microwave implementations but also cross-connect a larger number of channels. Basically, they enable some in-orbit reconfiguration where RF solutions would be fixed. Also these architectures can be easily extended to other frequency bands thanks to the broadband capability and transparency to RF frequencies of the technology.

Satellite operators have already expressed some interest for higher capacity and payload flexibility [3] [4] . In the specific context of a multi-beam broadband access mission, this optical reconfiguration concept based on optical multi-frequency conversion and optical switching can support flexible allocation of gateway to user beams. This is considered of particular interest as this could offer the possibility for an operator to deploy capacity or services progressively thus lowering risk and initial investments. Whereas RF implementations would result in unaffordable complexity and amount of hardware, microwave photonic architectures can effectively provide in-orbit reconfiguration capabilities, resulting in enhanced capacity, flexibility and accordingly potential for increased revenues.

III. MULTI-BEAM BROADBAND ACCESS MISSION SCENARIO

The following example shows the potentials of the microwave photonic concept in the particular case of a multi-beam broadband access mission, as investigated in the frame of the OWR project.

A. Multi-beam broadband access mission Ka-band

The considered mission was to provide a two-way access service which aims to complement terrestrial ADSL offer. This service is often called “Triple Play by Satellite“, as it includes basically data (Internet), voice (VoIP) and TV (IPTV), all provided over IP through satellite. The targeted subscribers enter into the following two categories :

- Home Users who will be provided a typical 99.5% year availability
- SME Users who will be provided a typical 99.7% year availability

The Satellite Triple Play offer is a DVB-S2 / RCS based system using Adaptive Coding Modulation (ACM). The DVB S2 choice allows to propose an improved range of applications and the most efficient modulation schemes available on the market place.

A broadband access mission in Ka-band was considered as reference. Such a multi-beam broadband satellite coverage over Europe is shown in Fig. 2. The underlying network has a classical star topology, in which the user terminals are connected to the network (e.g. the Internet) Earth stations called gateways, each gateway serving several thousands of users. The need for small and cheap user terminals together with the goal to offer a broadband access competitive with terrestrial solutions (e.g. ADSL), call for small user spot beams. These spot beams (typically from 0.4 to 0.7° in Ka-Band) are arranged in a regular pattern as shown in Fig. 2, allowing to re-use the frequency band available several times. This frequency re-use is performed for instance according to a well-known scheme, like the four-color re-use scheme.

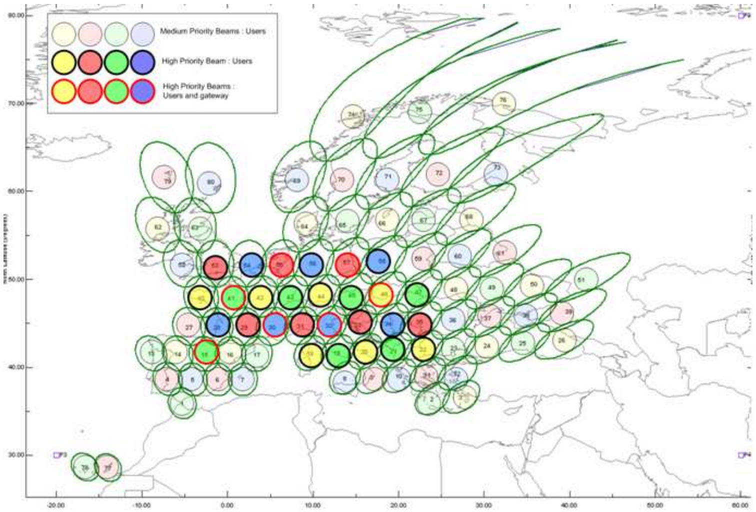

Fig. 2. Multi-beam broadband access mission coverage

The user beams are connected to the gateway through the satellite in the 2 directions (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).

More specifically, the mission coverage taken as reference is illustrated in Fig. 2. It is made of 80 beams of 0.45° aperture, over Europe:

- 73 beams for users only (black contour)
- 7 beams for users + gateway (red contour)

In addition (7*4) =28 beams are pre-defined as High-Priority Beams (HPB), and (7*8 – 4) = 52 beams are predefined as Medium Priority Beams (MPB). High-priority beams are highlighted by intense colour, whereas MPB are in soften colour.

The associated frequency plan is depicted in Fig. 3 below and features the following two types of beam channelization:

- HPB with 250 MHz single channel
- MPB with two sub-channels of 187.5 and 62.5 MHz.

Gateway stations are supposed to manage the whole 1.5 GHz Ka-band in two polarizations. This allows to lower the number of gateways and consequently the number of RF amplifying chains for the Return Path.

Fig. 2 gives an example an European coverage implemented through 80 user spot beams. In this example, up to 12 user beams can be hooked to a gateway, meaning that a total of 7 geographically separated gateways are needed for the system in its final stage of deployment.

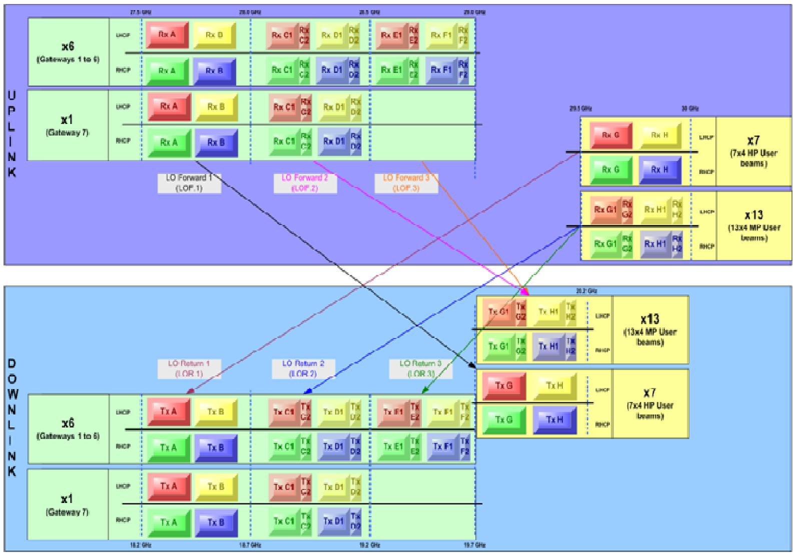

Fig. 3. Frequency allocation plan and flexibility

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 likely not fit with the frequency plan of the gateway feeder link. On-board down- and up-conversion frequencies and associated antenna polarizations will therefore have to be accommodated in a flexible manner at the start of service, and evolve as the network grows and the number of gateways increases.

A communication payload architecture enabling to connect any of the 7 gateways in the above example to any of the 80 user beams would be of a great benefit to the operator. It would permit a smooth initial deployment of the user terminals in the most promising areas and connect them to the first deployed gateway. Then, to add spot beams and connect them adequately while new gateways and user terminals are rolled out.

B. Flexibility for broadband access missions

The mission was derived from conventional broadband access mission extended with an additional flexibility/granularity, to be defined in order to enable service providers to perform a progressive system deployment, and to optimize maintenance / redundancy requirements during operational phase.

Consequently for this mission, the following constraints are taken into account:

- Capability to address all beams in case of any single gateway failure, with a flexible choice on the beams that will share the bandwidth.
- Capability to address all beams with half of the gateways, whatever they are.
- Capability for each beam to have a portion of its bandwidth uplinked by any other gateway.

This flexibility feature on Gateways beams would lead to improve customer business plan then make the solution more attractive at a cheaper cost than if “hard plugged” in terms of:

- Operational expenses associated with the gateway locations
- Initial Deployment
- Backup gateway capability
- Ground system scalability requirement.

The mission main requirements are summarized in Table 1 hereafter.

Table 1. Main mission requirements

Gateway links		
Nb of gateways	7	
Nb of polarizations	2 per gateway	LHCP and RHCP
Gateway bandwidth	Forward: 27.5 to 29 GHz Return: 18.2 to 19.7 GHz	1.5 GHz per polarization (6*250MHz channels per polarization)
User links		
Spot beam angle	0.45°	
Nb of user beams	80	28 High Priority Beams (HPB) 52 Medium Priority beams (MPB)
Nb of polarizations	2	LHCP and RHCP (1 polarization per beam)
User bandwidth	Return: 29.5 to 30 GHz Forward: 19.7 to 20.2 GHz	0.5GHz (2*250MHz) per polarization (One 250 MHz channel per beam)
Re-use pattern	1:4	Frequency and polarization re-use
System capacity		
Forward links	20 GHz	Gateway beams shared with user beams
Return links	20 GHz	
Channelization	HPB: 250 MHz MPB: 187.5+62.5 MHz	
Flexibility		
• Addressing all beams in case of any single gateway failure, with a flexible choice on the MPB beams that will share their bandwidth. • Adressing all beams with half of the gateways. • Capability for each beam to have a portion of its bandwidth uplinked by any other gateway. In any case, each HPB useful bandwidth of 250MHz is ensured, and each MPB useful bandwidth will be chosen between 62.5/187.5/250MHz depending on the available total system capacity.		

C. Payload architecture

The Forward photonic payload consisted in a photonic frequency-generation unit (FGU), a photonic frequency-down-converter assembly, and a so-called flexibility section based on wavelength-selective optical switching architecture. The Return payload was very similar in the principle, but simpler in its implementation. The Forward photonic FGU architecture was designed to provide 6 LO's to all output ports. The Return FGU architecture was optimized to provide 2 LO's for HPB and 5 LO's for MPB as functionally needed.

III. ENABLING TECHNOLOGY AND DEMONSTRATORS

A. Photonic local oscillators and frequency converters

Microwave photonic system concepts above rely in particular upon photonic LO distribution and frequency-conversion of microwave signals. Microwave LO signals in the 10-30 GHz range are needed under optical form with high power and low phase noise. Optical heterodyning of two incoherent optical carriers at 1550 nm wavelength with a spacing of 0.2 nm on a high-bandwidth photo-detector generates a beat frequency of about 25 GHz, but it requires an optical phase-locked loop (OPLL) in order to reduce the phase noise of the beat linewidth. Optical double side-band modulation with carrier suppression (DSB-CS) is another technique [5] shown in Fig. 4, making use of a high-power CW laser and a Mach-Zehnder electro-optical intensity modulator (MZ-EOM) biased for minimum transmission. When the EOM is driven by a high-purity sinus-wave signal at $f_{LO}/2$ frequency, the optical spectrum of the output signal mainly contains the first two side-bands, so that optical heterodyning at the receiver generates a high-purity microwave signal at f_{LO} frequency (see Fig. 4).

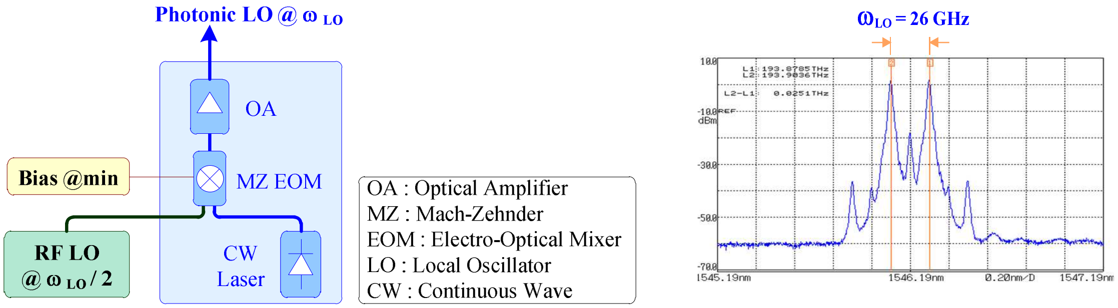

Fig. 4. Microwave Photonic Local Oscillators : principle (left) and typical optical spectrum (right)

Mach-Zehnder intensity modulators were demonstrated as electro-optical mixers for performing optical RF frequency-conversion [6]. One practical arrangement consists 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, thereby superimposing a RF modulation of the optical intensity. Direct detection generates the LO and RF frequencies as well as the beat products, i.e. the frequency sum and the frequency difference. By shaping the optoelectronic receiver frequency response appropriately and/or by using additional RF filtering, the unwanted compounds can be cancelled out so that the IF frequency only is output.

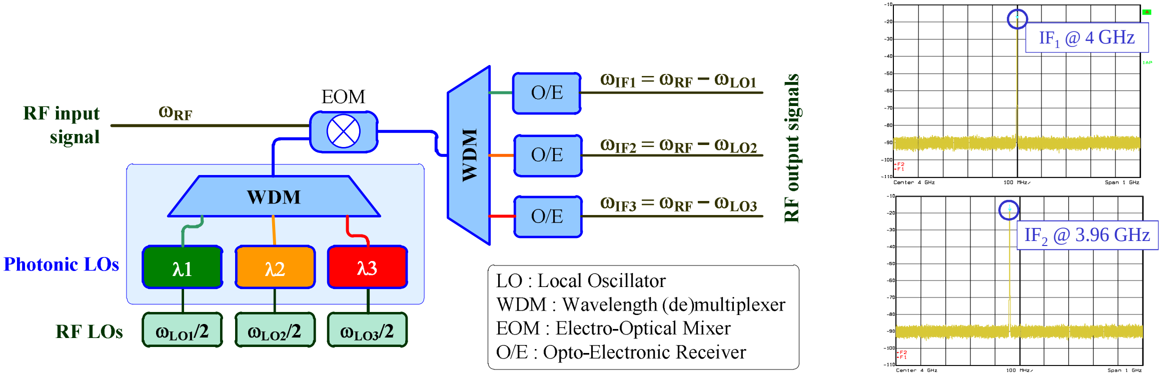

Fig. 5. Multiple-LO photonic RF frequency conversion: principle (left), IF output spectra (right)

Such electro-optical mixers offer very wide bandwidth (i.e. > 30 GHz) and provide infinite LO to RF input port isolation, but the most remarkable feature is that they can support multiple frequency-conversions. As shown in Fig. 5, the electro-optical mixer can be fed by several optical LO's through wavelength-division-multiplexing (WDM). An incoming RF signal can thus be mixed with various LO's and down-converted to several signals at various ω_{IF} frequencies.

Multiple-LO frequency-conversion was already proven in various frequency plans. Fig. 5 shows results of down-conversion of an input signal from Ka-band to C-band with two LO's. It shows the spectra of the two IF signals at 4 and 3.96 GHz as recovered after down-conversion. The IF signals are perfectly well separated and without any extra-mixing product. This double-LO frequency down-conversion was representative of a frequency–slot interchange functionality providing a repeater with appropriate architecture with flexible cross-connection capabilities.

B. *Microwave photonic sub-system demonstrators*

Down-scaled sub-system demonstrators have been developed at various levels of technology readiness and representativeness. Fig. 6 shows an early sub-populated repeater breadboard designed to prove the architecture concept and to assess the RF performance, that was representative of a particular end-to-end microwave path with inputs in Ka-band (28-31GHz) and outputs in C-band (3-5 GHz). As shown in the figure, the breadboard featured all the key building blocks, namely a microwave photonic LO source (1), an electro-optical mixer (2), an optical cross-connect (3) and opto-microwave receivers (4).

Other models with higher representativeness have been designed and developed more recently within the frame of the OMCU project, including an elegant breadboard of photonic frequency-converter assembly shown in the right hand of Fig. 6, and an elegant breadboard of a microwave photonic FGU achieved by DAS Photonics, and a photograph of which is given in Fig. 7. The latter 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 microwave photonic repeater architectures. Fig. 7 also shows as a matter of example, the optical spectrum of the 5-LO signal, and a typical RF phase noise curve of one of these LO's operating around 8 GHz.

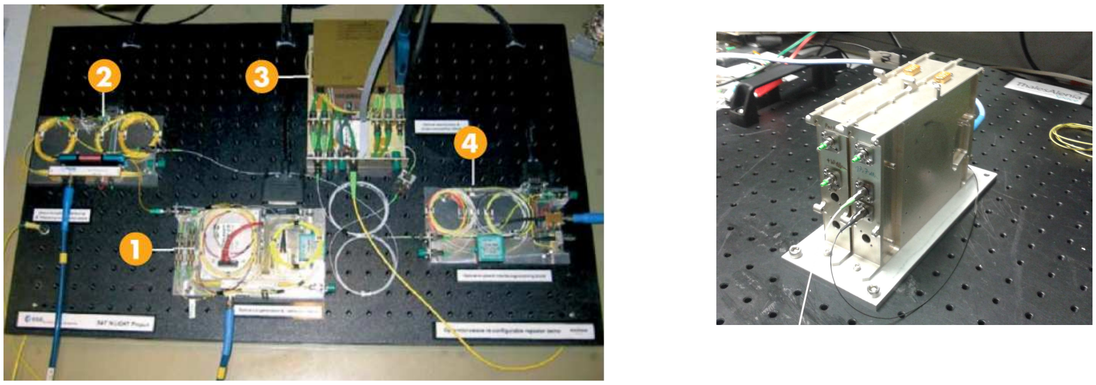

Fig. 6. Microwave photonic repeater demos: down-scaled repeater breadboard (left), elegant breadboard of a photonic frequency-converter assembly (right)

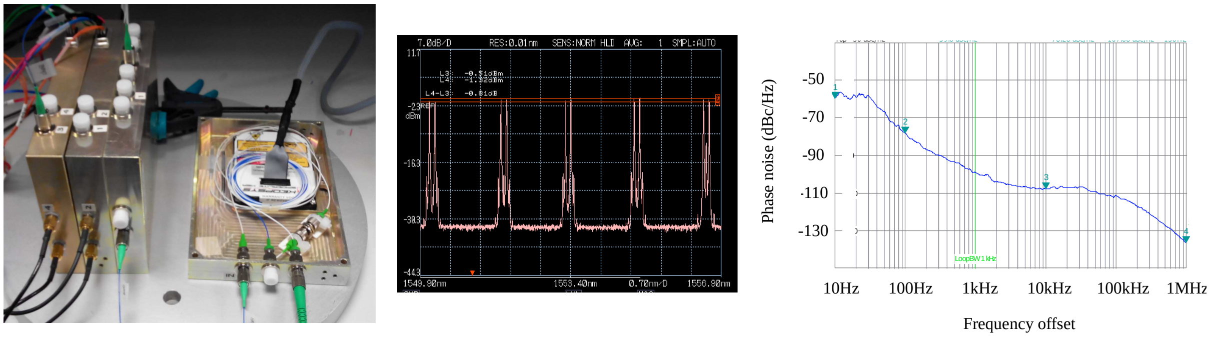

Fig. 7. Microwave photonic FGU : 5-LO elegant breadboard (left), optical spectrum (center) and phase noise performance (right)

IV. PAYLOAD RF PERFORMANCE AND MASS AND POWER BUDGETS

The RF performance of microwave photonic repeater sub-system were investigated in details, experimentally and through theoretical calculations and simulations. Special attention was paid to the essential RF performance namely RF gain, noise figure and linearity considering the ratio (C/I) of the carrier to the inter-modulation product. Table 2 hereafter shows typical RF performance considered for the microwave photonic repeaters. Spectral purity, RF crosstalk and phase noise performance have also been investigated. It was shown experimentally that stringent phase noise requirements can be met. No significant impairment was also found to take place in micro-optical switches, making them well suited for routing microwave signals with no detrimental effect on their RF performance, neither in crosstalk nor in phase noise.

Microwave photonic repeater architectures were also assessed in terms of mass and power budgets. Fig. 8 summarizes this comparison between full RF and optical architecture section for the same mission of reference. It was found that significant mass and power budget savings could be obtained by using photonic technologies. In the particular case of the reference mission, that is shown in Fig. 8, savings were found to be as high as 138 kg in mass (which corresponds to -34% of the trade-off section) and 606W in power consumption (which also represents -34% of the trade-off section). These figures includes both the forward and return payloads. Following this analysis, the photonic solution would be preferred to full RF implementations.

Table 2. Typical RF performance for microwave photonic repeater

	Input level (dBm)	Gain (dB)	NF (dB)	OTOI (dBm)	C/I (dBc)
Forward repeater	< -20	11	< 23	> 11	> 40
Return repeater	< -30	22	< 13	> 12	> 40

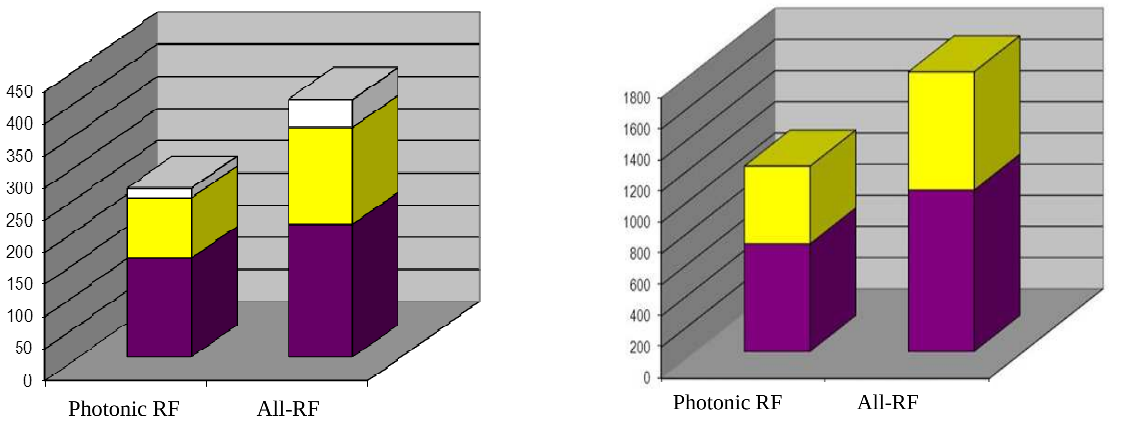

Fig. 8. Comparative mass in kg (left) and power in W (right) for photonic and RF P/L architectures

IV. CONCLUSIONS AND PERSPECTIVES

Thales Alenia Space has elaborated innovative telecom payload concepts making full use of photonic technologies, including microwave photonics, wavelength-division multiplexing and optical switching. These payloads are based on conventional low-noise receive and high-power transmit RF sections and feature a microwave photonic repeater in the center stage that supports optical distribution of centralized microwave LO's, performs multiple-LO photonic frequency-conversion of RF signals, and routes RF signals by means of micro-optical switches and fiber interconnects. It enables to route any RF channel/sub-band from any input port to any output port and to shift its frequency position accordingly. Whereas RF implementations would result in high complexity and large amount of hardware, microwave photonic architectures and technologies can make such flexible payloads achievable with standard RF performance, and mass and power budgets compatible with existing platforms. Although investigated first for Ka-band, these architectures could be easily extended to other frequency bands in particular Q/V, given the broadband nature of the technology and/or its transparency to the RF frequency.

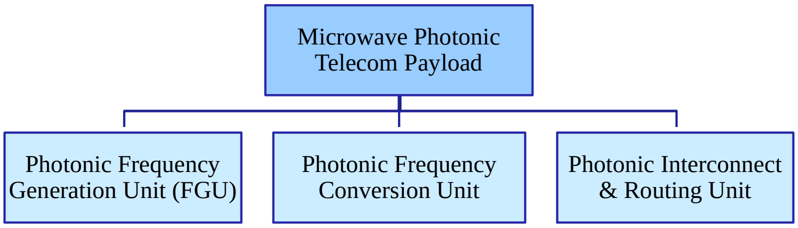

Fig. 9. Microwave photonic payload equipment

These results open the perspective of new payload solutions with in-orbit re-configurability. Their application for a prospective multi-beam broadband access mission in Ka-band was thoroughly assessed. In this such a scenario, a small number of gateways are interconnected to numerous user beams through forward and return payloads. The proposed optical reconfiguration concept enables to support flexible gateway-to-user beam allocation and to change this allocation all along the mission, whereas today this interconnection has to be defined from the design phase and remains fixed.

This may offer for instance the opportunity to deploy capacity progressively, at lower risk and initial investments, or to implement more efficient management and redundancy strategies, which can be turned into larger effective capacity and better exploitation of payload resource at any time of the satellite life.

These concepts and technology reported above and providing future payloads with in-orbit re-configurability and scalability to larger size, are believed to in line with operators demand. Thales Alenia Space is leading the development of this payload technology to bring it to higher maturity levels, and developing early models of microwave photonic payload equipment (see Fig. 9) including photonic FGU and photonic frequency-converters and photonic interconnect and routing solutions.

ACKNOWLEDGEMENTS

This work has been supported by the European Space Agency (ESA) under the TRP contract N. 15695/01/NL/ND - Optical Handling of Microwave and Digital Signals, and within the Artes5 OMCU and OWR ESA projects (contracts N. 21406/08/NL/EM- Optical Multi-frequency Conversion Unit for Broadband Transparent Analogue Repeaters, and N. 000102535/11/NL/NA Optical Wideband Reconfigurable – Receiver front end).

The authors thank J. Perdigues and N. Karafolas as ESA Technical officers at ESTEC, for having initiated and stimulated these activities. The authors also thank their national space agencies CNES and CDTI, and their technical officers in particular L. Gatet (CNES).

They are also grateful to their colleagues at Photline Technologies (F), Vectrawave (F) and Sercalo Microtechnology Ltd (CH) for fruitful cooperation.

REFERENCES

[1] J.M. Perdigues Armengol, M. Sotom, B. Benazet, M. Maignan, T. Merlet, S. Blanc, N. Vodjdani, C. Voland, C. Marxer, H. Porte, “An overview of the SAT ‘N LIGHT ESA project”, OPTRO 2005, Paris, France, May 9-12, 2005.
[2] M. Sotom, B. Benazet, M. Maignan, J.M. Perdigues Armengol, “Flexible Analogue Repeaters Based on microwave Photonic Technologies”, 1st ESA Workshop on Advanced Flexible Payloads November 18-20 2008, ESA/ESTEC Noordwijk, The Netherlands.
[3] Mehmet Yuceer, “Emerging technologies for communication satellite payloads”, Progress in Aerospace Sciences 50 (2012) 27-34, 20.
[4] A. Pisano, A. Santoni, R. Vinci, “Payload Flexibility: units Ka/Ku Payload development on a real application”, 14th Ka and Broadband Communication Conference, September 24-26 2008, Matera (Italy).
[5] J. J. O’Reilly, P. M. Lane, R. Heidemann and R. Hofstetter, “Optical generation of very narrow linewidth millimetre wave signals”, *Electronics Letters*, 3rd December 1992, Vol. 28, n°25, p 2309-2311.
[6] G. K. Gopalakakrishnan et al., “A LiNbO3 microwave-optoelectronic mixer with linear performance”, IEEE MTT-S Dig, 1993, pp.1055-1058.