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Advanced photonic payloads for broadband telecom satellites : Integration and tests of a representative repeater demonstrator

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ABSTRACT

This paper reports the main achievements in the development of photonic RF payload solutions for telecommunication satellites based on a multiple-frequency conversion scheme. Representative models of photonic payload equipment, including photonic frequency generation assembly and frequency-converters, have been integrated and proven in a system environment. The end-to-end RF performance for various configurations and frequency plans were tested at ambient temperature. The test plan includes forward and return repeater configurations, with photonic frequency down-conversion from 30 to 20 GHz with up to 6-local oscillators in the case of a Ka-band multi-beam broadband mission. In addition, thermal tests were run over the [-5°C, +65°C] temperature range.

The end-to-end RF performances of the photonic repeater demonstrator were assessed in detail experimentally and compared to theoretical predictions. These results are a major step towards new payload solution with enhanced capacity and in-orbit re-configurability.

Keywords: photonic payload, multiple frequency conversion, flexibility, demonstrator, environmental test results

1. INTRODUCTION

Satellite operators have expressed their interest for payloads with higher capacity and flexibility for years. Thales Alenia Space has developed a photonic analogue repeater demonstrator in the frame of the OWR-RFE ESA project (Optical Wideband Reconfigurable – Receiver Front End). Such a repeater implements an Optical Multiple-LO frequency Conversion (OMC) by using Wavelength Division Multiplexing (WDM) as shown in Fig. 1.

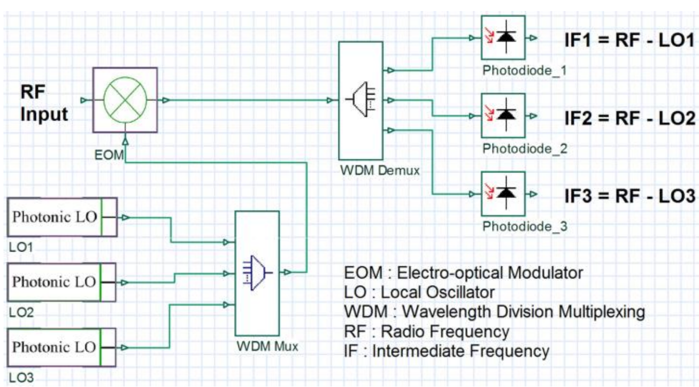

Figure 1. Optical Multiple-LO frequency Conversion (OMC) concept

The OMC concept can help answering this demand using specific attributes of photonics such as small size and low mass of fiber optics as well as WDM capability [1]. Together with optical switching, OMC-based photonic repeater architectures can support in-orbit reconfiguration, for instance for flexible allocation of user beams to gateways in multi-beam access missions, and at the end for better use of resource and increased revenues for operators.

2. MULTIBEAM BRODBAND ACCESS MISSIONS

2.1 Multi-beam broadband access mission scenario

An example of a broadband satellite covering Europe, is given in Fig. 2. The user beams are connected to the gateway through the satellite in the 2 directions, namely Forward, from gateway to users, and Return, from users to gateway. They are arranged in an hexagonal 4-color re-use pattern.

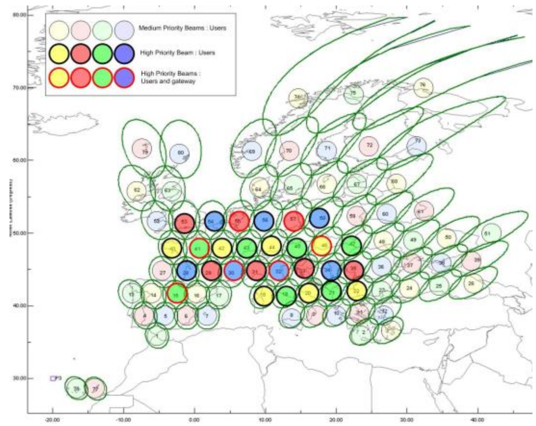

Figure 2. Multi-beam broadband access mission coverage

The mission coverage of Fig.2 was taken as reference. 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 28 beams are pre-defined as High-Priority Beams (HPB), and 52 beams are pre-defined as Medium Priority Beams (MPB). HPB are highlighted by intense colour, whereas MPB are in soften colour. When the system is fully deployed all beams are served with the same 250 MHZ bandwidth. However, by making it possible to reallocate sub-bands among MPB beams, the photonic payload flexibility allows for progressive system deployment, and enables to feed all beams with only 4 gateways instead of 8, MPB beams being served with a smaller bandwidth.

The Forward and Return frequency plans used as reference in OWR project are shown in Fig. 3. For the forward link, uplink frequency is 27.5 GHz to 29 GHz while downlink frequency is 19.7 GHz to 20.2 GHz. For return link, uplink frequency is 29.5 GHz to 30 GHz while downlink frequency is 18.2 GHz to 19.7 GHz. HPB beams are composed by a single 250 MHz channel, and MPB beams are composed by two sub-bands of 187.5 MHz and 62.5 MHz. Moreover, thanks to payload flexibility, 187.5 MHz sub-band can be composed by a single channel, or by 3 sub-channels of 62.5 MHz on gateway side in order to address three different user beams.

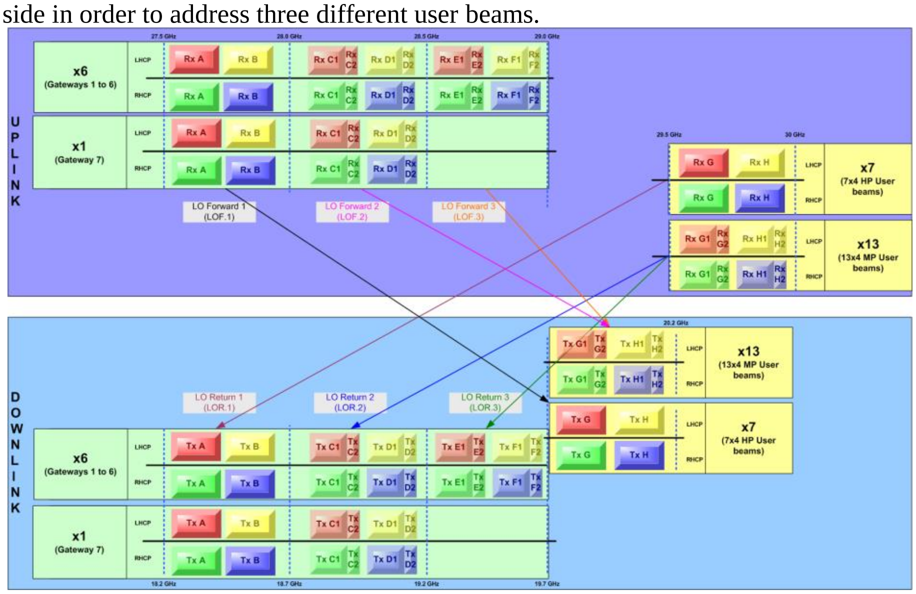

Figure 3. Reference frequency plans of the Forward and Return missions

In nominal configuration 3LO are used for each forward and return repeaters. With flexibility features, the number of LO's needed is increased to 6 for both forward and return links.

2.2 Photonic RF payload architecture

Various implementation options were designed in the frame of OWR project, for Forward and Return repeater respectively, based on similar architectures using the OMC concept and on common optical building blocks. Fig. 4 below gives a typical architecture considered for the Forward repeater, that consists in a photonic frequency-generation assembly (P-FGA), photonic frequency-down-converters, and an optical flexibility section based on a wavelength-selective optical switching stage. All the LO's are generated, transferred on optical carriers, and combined through WDM within the P-FGA, and then delivered to modulator-based electro-optical mixers. The OWR Forward P-FGA was designed to provide 6 LO's, and OWR Return P-FGA was designed to provide up to 5 LO's to EOMs.

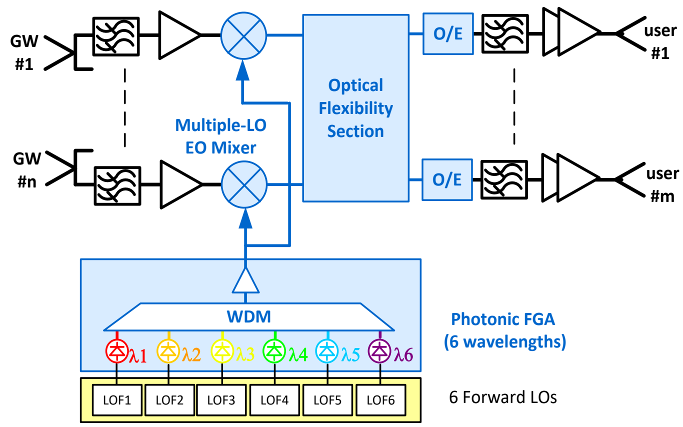

Figure 4. Simplified architecture of Forward photonic RF payload in multi-beam mission

RF signals received from up-link antenna accesses are transferred onto the optical carriers by the electro-optical mixers. When the electro-optical mixer is fed by an optical LO, the input RF frequency is 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 flexibility section. At the output of this latter stage, opto-microwave receivers convert the optical signals back into microwave ones at IF, and RF channel/sub-band filtering is achieved by means of conventional RF filter technology.

In contrast to pure RF implementations that would result in unaffordable complexity, such photonic RF architectures are expected to make advanced payloads achievable with standard RF performance, at mass and power consumption budgets compatible with existing platforms.

3. REPRSENTATIVE PHOTONIC RF REPEATER MODEL

The OWR project demonstrator was designed as a sub-populated photonic RF repeater model featuring high maturity and increased technology readiness level. The constitutive photonic equipment models were designed to exhibit better representativeness in function and performance, fit (physical interfaces) and form, compared to previous demonstrator [2]. Almost all the units were designed so as to withstand with thermal environment constraints.

Fig.5 shows the OWR project demonstration model as it was assembled for thermal testing purpose. From left to right, it features the following units:

- the P-FGA,
- 2 slices of OMC units,
- one slice with the opto-microwave receiver chains,
- 2 slices with medium level optical amplifiers (MLOA),
- 2 passive slices gathering the Wavelength Division de-Multiplexers, filters, and the optical switch.

Figure 5. Integrated OWR demonstrator

The P-FGA is shown on the left of Fig.6. It comprises 3 photonic Local Oscillators (LO) slices assembled by DAS Photonics mainly using CW laser and EOM devices. It also includes passive components as Wavelength Division Multiplexers (WDM) and optical couplers, and an High Power Optical Amplifier slice assembled by Keopsys, to increase the power level of all the optical carriers. This assembly is designed to meet space requirements in terms of temperature range, radiation hardness and redundancy. The P-FGA was combined with 3 other LO slices to deliver up to 6 LOs using a separate optical wavelength for each LO.

The OMC unit model gathers two dual-channel electro-optical mixer slices developed in a previous project [2] and one compact slice with the optical-to-electrical detection stage featuring photoreceivers developed by Vectrawave and outputs RF chains providing adjustable gain compensation with temperature.

Figure 6. Photonic FGA (left), MLOA (center) and OMC unit (right) of the OWR demonstrator

In all configurations except the Return HPB, medium-level optical amplifiers from MPB Communications were also included in the optical path between electro-optical modulators and photoreceivers for optical loss compensation. The two MLOA slices are shown in the center of Fig.6.

4. DEMONSTRATOR PERFORMANCES & CONSISTENCY WITH PREDICTIONS

The end-to-end system demonstration and tests were first achieved in ambient conditions, in various frequency plans and configurations with frequency-down-conversion from Ka- to Ka-band using up to 6 LO's, then RF performances (gain, noise figure, linearity, spectral purity) were measured at three temperatures. This is considered as a major step forward since these performance were measured on a complete sub-system made of several equipment models of each type, representative of future flight units.

Table 1. Elegant BreadBoard End-to-end performances of the repeater model

END-TO-END PERFORMANCES			
With MLOA	Ambient	Cold temperature	Hot temperature
RF gain	-5 dB	-4.5 dB	-5.2 dB
Gain stability	0.25 dB	0.5 dB	0.3 dB
NF	44 dB	44.5 dB	44.5 dB
Output TOI	16 dBm	15.6 dBm	16.8 dBm
Without MLOA	Ambient	Cold temperature	Hot temperature
RF gain	-5.4 dB	-6.6 dB	-5.3 dB
Gain stability	0.3 dB	0.3 dB	0.5 dB
NF	44.8 dB	45 dB	45.4 dB
Output TOI	19.3 dBm	19.1 dBm	18.7 dBm

Table 1 summarizes the worst case RF parameter values as measured in the test campaign including thermal conditions. These performances were found to be compliant with or very close to the targeted specifications. It can be concluded that it is possible for low loss configuration to achieve acceptable performance without intermediate amplification with MLOA.

Fig.7 shows examples of optical spectrum at the photoreceiver input (left), and RF spectrum at the repeater output (right). High RF signal purity was obtained with rejection of unwanted product typically >60 dBc within the band.

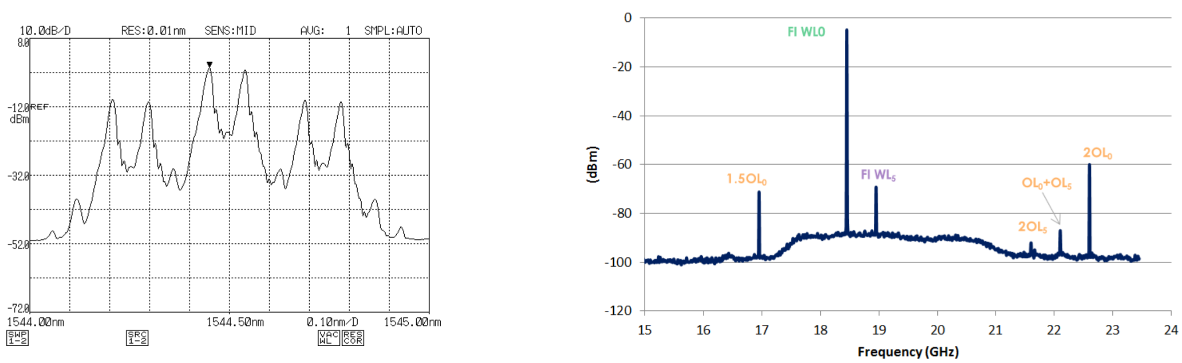

Figure 7. Optical spectrum before photoreceiver (left) and RF spectrum at repeater output (right), at ambient temperature.

Fig.8 shows that very good results were also obtained in terms of RF flatness (left) and RF gain stability (right). An RF gain flatness of less than 0.5 dBpp was achieved over three adjacent 500 MHz sub-bands. The RF gain variation was less than 0.8 dB over a whole thermal cycle including hot, cold and ambient temperatures.

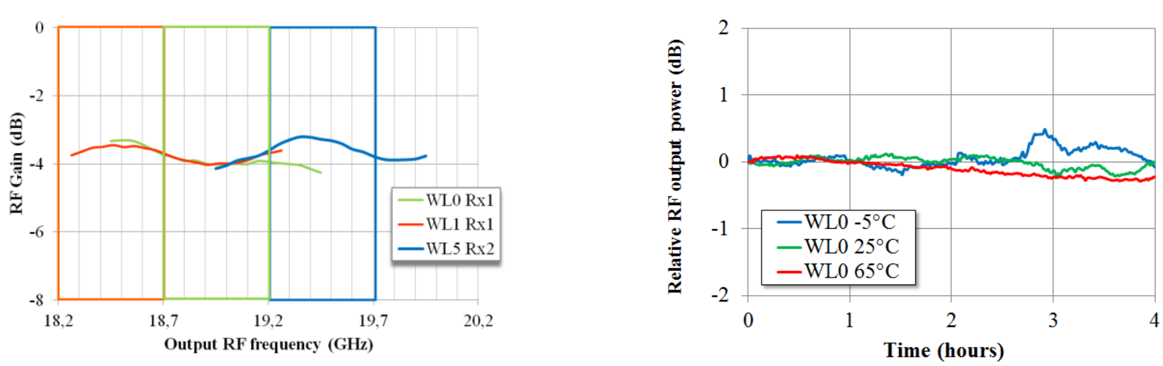

Figure 8. RF performance in Return MPB configuration : (left) RF gain flatness over 3 output sub-bands of 500 MHz each, at ambient temperature, (right) RF gain stability on wavelength 0 at 3 temperature

Theoretical models of the different sub-systems were also developed, which enables to establish end-to-end RF performance predictions of the photonic repeater in both Forward and Return configurations at ambient temperature. These predictions were then compared to end-to-end RF performance measurements as summarized in Table 2. Performance are in-line with theoretical predictions, thus the proposed prediction model is validated. This model is easily scalable to other missions and bands e.g. Q/V, and will speed up the design of future photonic-based repeater solutions.

Table 2. End-to-end RF performance versus predictions at ambient temperature

END-TO-END PERFORMANCE VS PREDICTIONS		
With MLOA	Performances	Predictions
RF gain	-5 dB	-4.5 dB
NF	44 dB	42.1 dB
Output TOI	16 dBm	16.7 dBm
Without MLOA	Performances	Predictions
RF gain	-5.4 dB	-6.6 dB
NF	44.8 dB	42.9 dB
Output TOI	19.3 dBm	17 dBm

5. CONCLUSIONS AND PERSPECTIVES

Thales Alenia Space has assessed innovative payload concepts through the design, integration and test of a sub-populated yet representative model of a flexible photonic RF repeater. These concepts rely upon optical multi-frequency conversion and makes full use of wavelength-division multiplexing and optical switching capabilities. The demonstrator was arranged in different but all representative configuration of multi-beam RF payload architectures. The overall repeater functionality was validated in Ka-band but could be easily extended to a broader range of payloads operating in other frequency bands included Q/V.

Extensive test campaigns were run at photonic RF repeater sub-system level with all conventional RF test items included. Tests were also successfully run over a temperature range representative of the payload environment. The measured RF performance were found compliant with or very close to the target requirements and consistent with theoretical predictions. These results open further perspectives towards advanced payload solutions supporting very high capacity and enhanced in-orbit re-configurability, with application to future broadband telecom missions.

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