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Novel multi-channel photonic RF frequency converters for wideband telecom satellite payload applications

B. Benazet*, M. Faugeron, M. Aveline, T. Colombo, B. Charrat, M. Sotom
Thales Alenia Space, 26, av. J-F Champollion, BP 1187, 31037 Toulouse, France

*benoit.benazet@thalesaleniaspace.com; phone 33 5 34353778

ABSTRACT

RF frequency conversion is a key function of telecom satellite payloads. Hereafter are presented new photonic RF sub-system concepts supporting multi-channel, wideband frequency-conversion, thus drastically reducing the amount of equipment, for frequency down- and up-conversions respectively at the inputs and outputs of a digital processor. Proof-of-concept demos are presented and the measured RF performance reviewed vs. predictions and system requirements.

The so-called dual-band, multi-LO frequency-converter (DB-MLFC) concept is an extension of the multi-LO frequency-conversion scheme already proven by Thales Alenia Space. It makes use of a dual-drive modulator with wavelength-multiplexed LO input and RF signal inputs in separate frequency bands. It can be applied to digital processor-based payloads and perform down-conversion of Ka or V-band sub-bands to the C-band of the processor input. The DB-MLFC concept was proven to support down-conversion of 2 and 3 sub-bands from the Ka (~30 GHz) and V (~50 GHz) bands to the C (~6 GHz) band of the processor input.

The second concept called multi-RF frequency-converter (MRFC) consists in mixing multiple RF signals on separate optical carriers with an electrical LO signal into one electro-optical mixer. RF signals to undergo the same frequency conversion are combined via a WDM and fed into the optical input port of an electro-optical modulator, the RF port being driven by the LO. The RF performance of the MRFC concept, were measured with up-conversion of up to 8 C-band RF signals from the processor output to Ka-band payload output frequencies (~20 GHz).

Keywords: satellite payload, RF photonics, frequency conversion, WDM, local oscillator

1. INTRODUCTION

RF frequency conversion is an essential function of telecom satellite payloads. In Very High Throughput Satellites (VHTS) handling a large number of wideband RF channels from/to many antenna access ports, the mass and power consumption of frequency converters can significantly contribute to total payload budgets. The best compromise between RF performance, size, weight and power (SWaP) and cost is therefore to be sought and this all the more so in digital processor-based payloads where frequency conversion is required in both their receive and transmit sections.

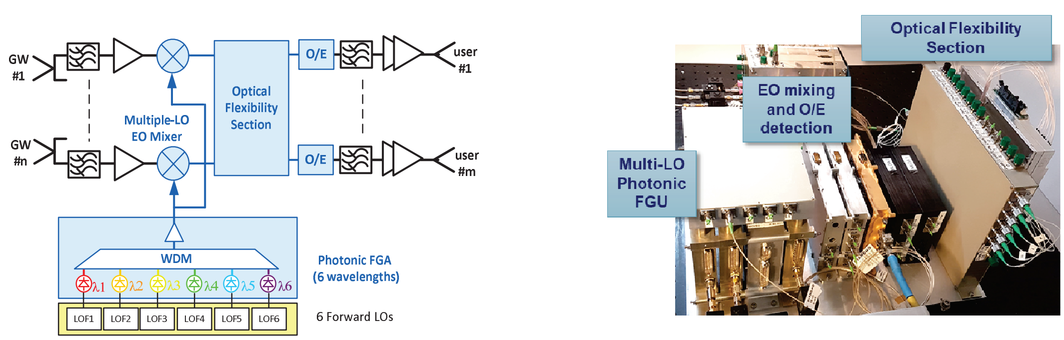


Figure 1. Simplified architecture (left) and demonstration model (right) of flexible photonic RF repeater based on the multi-LO frequency-converter (MLFC) concept

Thales Alenia Space was first to demonstrate payload concepts [1] using photonic RF frequency conversion, with electro-optical mixers fed by multiple LO's. In particular, Fig.1 shows the architecture of a flexible analogue photonic RF repeater for the Forward mission (from gateways to users) making use of multi-LO frequency-converters (MLFC) as well as the demonstration model developed and extensively proven within ESA activities, and already reported in [2-4].

Hereafter are presented two new concepts assessed within R&T activities supported by CNES, the French national space agency, that achieve multiple wideband frequency conversions and thus can reduce drastically the number of equipment required to digital payloads for frequency down- and up-conversions taking place respectively at the inputs and at the outputs of the digital processor.

2. DUAL BAND, PHOTONIC RF FREQUENCY CONVERSION

2.1 Concept and applications

The first concept called dual-band, multi-LO frequency-converter (DB-MLFC), is an extension of the multi-LO frequency-conversion scheme demonstrated by Thales Alenia Space. Instead of using a simple, single-drive Mach-Zehnder intensity modulator (MZM) with wavelength-multiplexed LO inputs, it makes use of a dual-drive modulator, again with wavelength-multiplexed LO input but also with two different RF signal inputs in separate frequency bands. The proposed scheme can be applied to VHTS payloads with high-capacity feeder links and a transparent digital processor where it allows multiple Ka and V-band sub-bands to be simultaneously down-converted to the C-band of the processor input as shown schematically in Fig. 2.

Several missions were identified and their associated payloads with and without digital processor were analyzed. In each case, different photonic architectures have been proposed; the corresponding frequency plan and photonic sub-systems have been defined. For each architecture, the mass and consumption of the photonic section concerned were estimated and compared with those of the corresponding RF architecture.

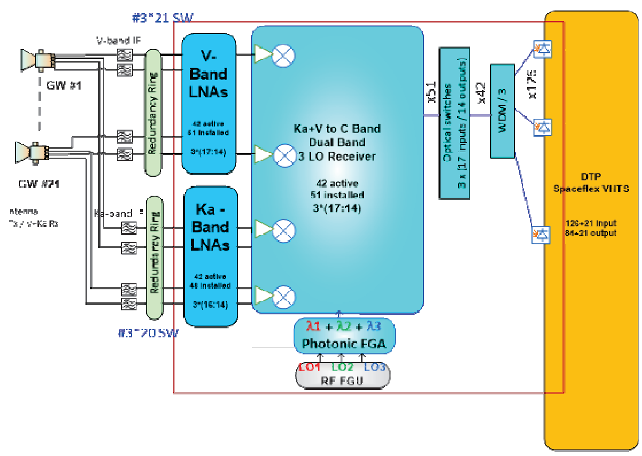


Figure 2. Digital processor-based payload with photonic dual-band frequency conversion (V/Ka to C)

The analysis of the target missions and payloads with and without digital processor led to the following conclusions:

• Dual-band photonic frequency-conversion can be used in all missions considered, either in architectures with digital processor or in traditional payloads. In this case, a study of the frequency plan is necessary to confirm the possibility of introducing this type of frequency conversion,

• The introduction of photonic interfaces is more than compensated by the simplification of hardware. Besides, the use of optical fibers instead of coaxial cables gives flexibility in the repeater layout and its accommodation on the platform,

• In all cases, photonic RF frequency conversion leads to savings in mass and consumption compared to all-RF implementations, all the more important that the payload capacity is large. Thus, a very favorable case is the forward link in Ka and V bands of payloads with digital processor having their access ports in C band, where mass and power savings have been estimated to be in the range of 30-40%.

2.2 Proof-of-concept model

A laboratory model of a dual-band frequency converter with several LOs was implemented according to the architecture defined during the design phase. Fig.3 below gives a view of the demonstrator as assembled in the TAS laboratory. This laboratory model includes a block for the generation and distribution of 2 or even 3 wavelength-multiplexed optical LOs and a second block for electro-optical mixing, optical demultiplexing and recovery of the various signals at intermediate frequency (IF).

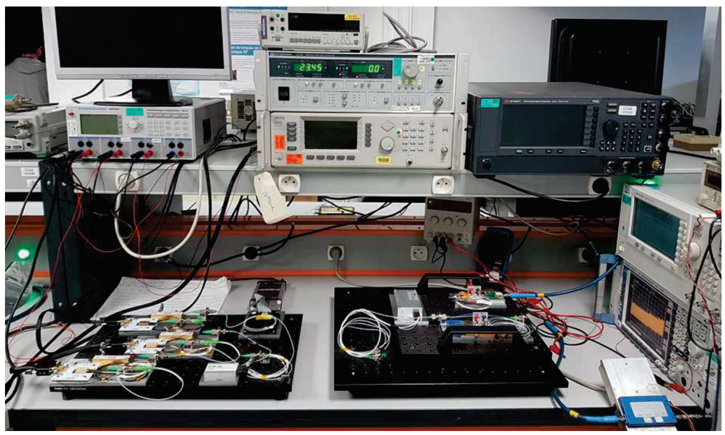


Figure 3. Proof-of-concept model of photonic RF frequency converter dual band with 2 (or 3) optical LOs

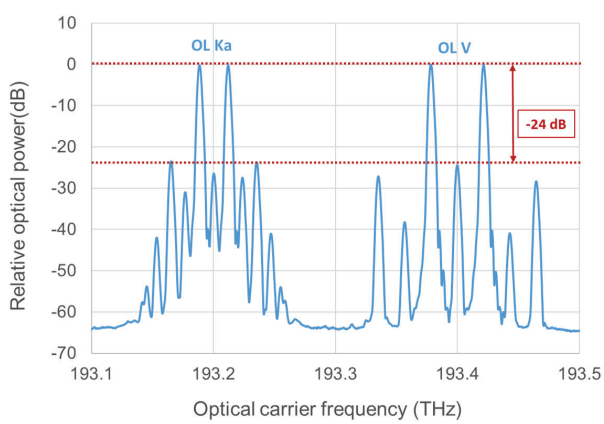


Figure 4. Optical spectrum at the LO block output w/ 2 optical LOs at 23.4 and 43.1 GHz for Ka/C and V/C conversion respectively

Fig. 4 above shows the optical spectrum of the 2 optical LOs generated by dual-sideband modulation with carrier suppression (i.e. DSB-CS) at 23.4 GHz and 43.1 GHz respectively for Ka/C and V/C conversions, for example:

- in Ka/C conversion, from 28.5 GHz to 5.1 GHz central frequencies,
- in V/C conversion, from 48.7 GHz to 5.1 GHz central frequencies.

The minimum rejection obtained for the 2 LOs is close to 24 dB, corresponding to a good compromise between the carrier rejection and the level of the 3rd-order modulation sidebands.

2.3 Experimental results

The test campaign carried out consisted in thoroughly measuring the RF performance of gain, noise figure, linearity and spectral purity for different frequency-conversion schemes with 2 and 3 LOs and in so-called passive or active configuration, respectively without and with optical amplifier. These performances were also measured at different EO modulator biasing points (expressed as a fraction of the wave voltage $V\pi$) as it is a potential setting for performance optimization.

As a matter of example, Fig.5 below shows the results of RF gain and noise figure performance of the V/C frequency conversion in case of a dual-band frequency-conversion (Ka and V) at 2 LOs, in a so-called active configuration, i.e. with an optical amplifier. RF conversion gain of about -23 dB, -18 dB and -10 dB were obtained at a relative EO modulator bias of 0.5 $V_{\pi,DC}$ (quadrature), 0.7 $V_{\pi,DC}$ and 0.9 $V_{\pi,DC}$ respectively.

These RF gains were approximately higher by 12 dB at 0.5 $V_{\pi,DC}$, 17 dB at 0.7 $V_{\pi,DC}$ and more than 30 dB at 0.9 $V_{\pi,DC}$ relative EO modulator bias, compared to those performance obtained with a passive frequency-conversion configuration.

As shown in Fig.5, a very good agreement was found, typically within 0.5 dB between the experimental and the theoretical results.

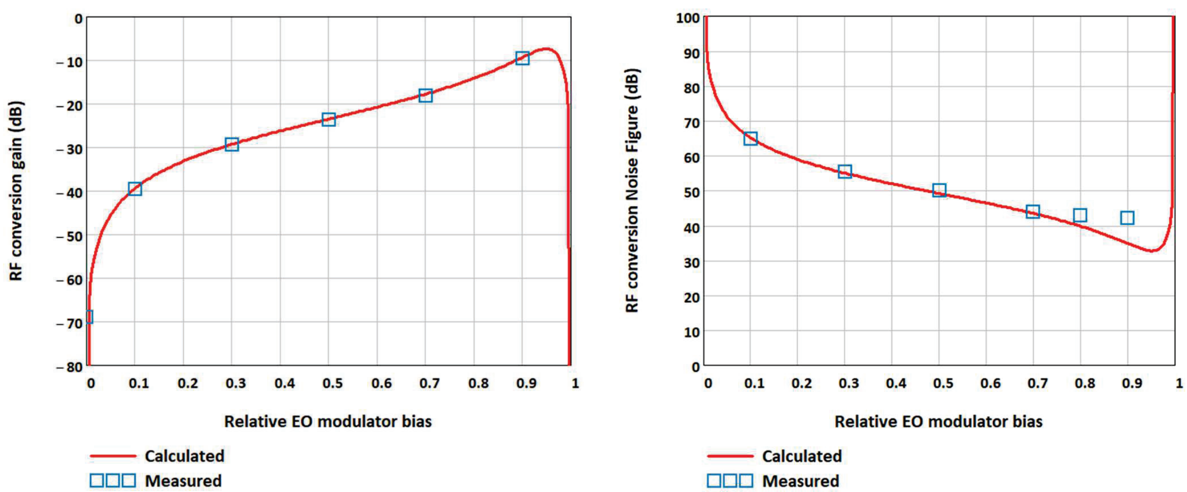


Figure 5. Calculated and measured RF gain and NF for an active V/C frequency conversion vs. the relative EO mixer bias

Noise figure about 49 and 43.5 dB was obtained for a relative EO mixer bias of 0.5 and 0.7 $V_{\pi,DC}$ respectively. A good agreement between the calculated and measured data was observed at least up to a relative EO mixer bias of 0.7 $V_{\pi,DC}$ probably due to the appearance of interferometric noise (due to optical reflections in the demonstrator) combined with the noise floor of the electrical spectrum analyser.

Similar performance were obtained for the Ka/C frequency conversion that was simultaneously supported, with even slightly higher gain and lower noise figure thanks to the higher sensitivity of the EO modulator in Ka-band.

Other results are given respectively in Fig. 6 and Fig.7 in terms of spectral purity, in the case of dual-band frequency-conversion (Ka and V) with 2 LO in the so-called passive configuration. There was also a good agreement between the theoretical and experimental spectra. Only the spurious frequency at $LO_1/4$ (5.85 GHz) falls in the conversion band but at a low level, that could even be lowered by using an LO signal with a higher spectral purity. The spurious frequency compound at $RF_1+LO_1-RF_2$ depends directly on the dual-drive EO modulator bias and completely disappears when precisely biased at quadrature.

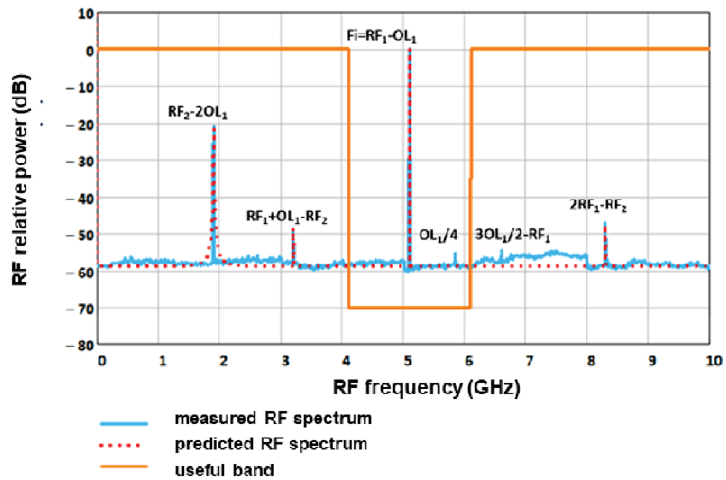


Figure 6. Theoretical and experimental spectral purity in passive Ka/C frequency conversion w/ relative EOM bias of 0.5 Vπ

As for the V/C frequency-conversion, there are 2 additional spurious frequency compounds compared to the theoretical model, among which the $LO_1/2+2.RF_1-3.LO_2/2$ line falls close to the edge of the useful band with a relative amplitude of -41.5 dBc.

As it involves a sub-harmonic of the LO_1 that is used for the Ka/C conversion, this potential issue could be easily overcome by improving the selectivity of the WDM filter or just by increasing the wavelength spacing between the LO channels e.g. from 200 to 400 GHz.

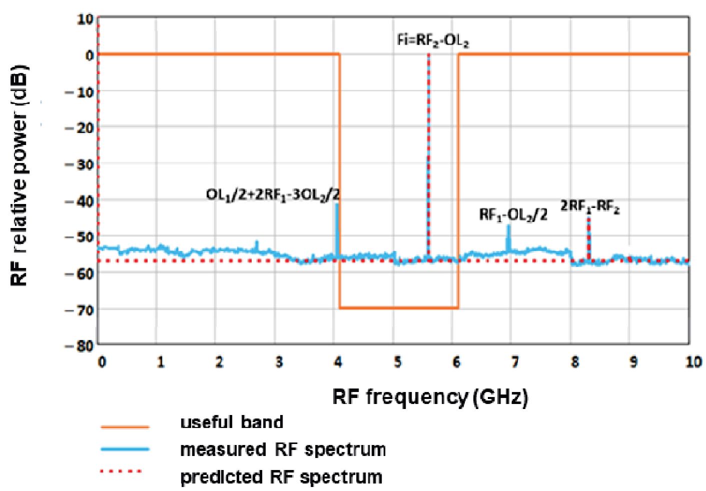


Figure 7. Theoretical and experimental spectral purity in passive V/C frequency conversion w/ relative EOM bias of 0.5 Vπ

3. PHOTONIC MULTI-CHANNEL RF FREQUENCY CONVERSION

3.1 Concept and applications

The second concept, whose purpose is also to reduce the number of mixers, is called multi-RF frequency-converter (MRFC). It consists in mixing multiple RF signals, all with the same RF frequency but on separate optical carriers, with an electric LO signal in a single electro-optical mixer. Each RF signal is transferred to an optical carrier with a specific wavelength. Signals to undergo the same frequency conversion are combined via a WDM and fed into the optical input port of an electro-optical modulator, the RF port being driven by the LO. A WDM is used at the output before separate O/E conversion for each channel. Optical amplifiers can possibly be added to improve RF performance.

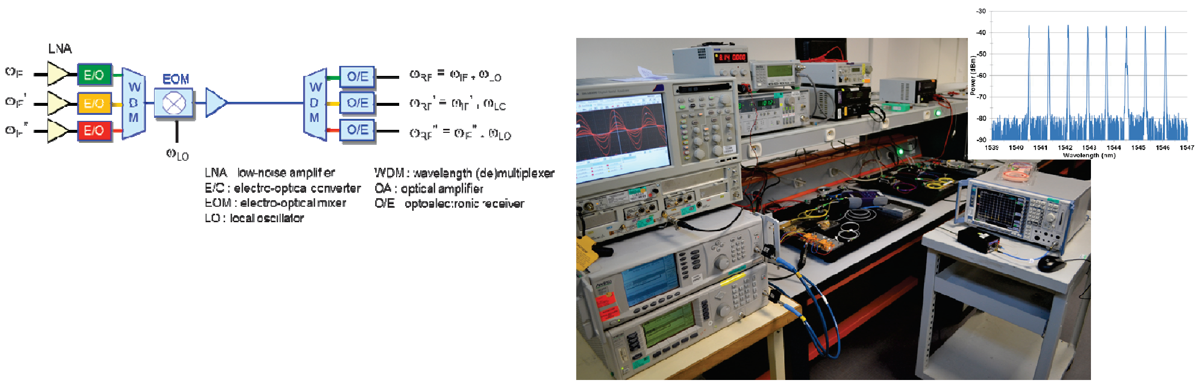


Figure 8. Principle (left) of multi-RF frequency-converter (MRFC) and proof-of-concept model (right) of flexible photonic RF repeater based on the MRFC concept

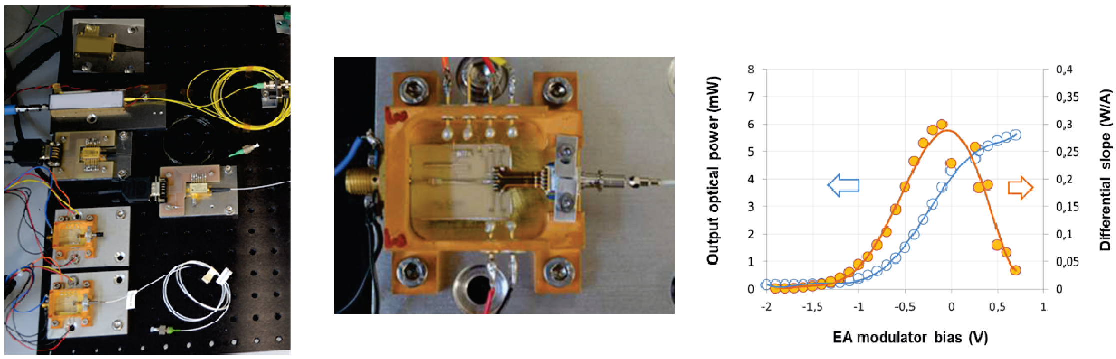
The typical sub-system architecture is as follows: each RF signal is transferred to an optical carrier through an E/O interface and is assigned a specific wavelength. Photonic RF signals to undergo the same RF frequency conversion are grouped together by means of a WDM multiplexer. The WDM composite signal is supplied to the optical input port of an electro-optical mixer, e.g. a Mach-Zehnder modulator, the electrical RF port of which is driven by the RF LO. Then, a wavelength de-multiplexer is used to separate all the channels and O/E detectors convert the optical signals back into an RF signal for each channel. Adding medium-level optical amplifiers to the input and/or output of the electro-optical mixer can help improve the RF gain and noise figure performance.

3.2 Proof-of-concept model

Within an R&T activity supported by CNES, the French Space Agency, a breadboard demonstrator of the MRFC concept was designed and assembled at Thales Alenia Space in order to validate the concept and assess the RF end-to-end performance.

Different types of commercial E/O modules were implemented and various system configurations (number of WDM channels, with and without optical amplification …) were also assessed in order to optimize both the RF performance in terms of RF gain, noise factor, linearity and spectral purity, and the SWaP (size, weight and power) contribution.

The main RF and/or optical parameters of each optical component making up the demonstrator were first measured. Then the functional performance of the MRFC breadboard were measured for each of the photonic sources considered i.e. a direct modulation laser (DML), an electro-absorption-modulated laser (EML), a discrete Lithium Niobate Mach-Zehnder EO modulator (LN MZM) and an integrated Gallium Arsenide Mach-Zehnder EO modulator (GaAs MZM). The use of EML designed for 10 Gbps digital applications and having bandwidth close to the RF frequency to be transmitted, e.g. C-band, was considered as it could provide a fair trade-off encompassing RF performance and SWaP.



(a) (b) (c)

Figure 9. RF photonic transmitters for multi-RF photonic frequency conversion

(a) The different RF photonic transmitter options evaluated (EO MZM, DML and EML)

(b) EML in its test case with polarization maintaining fiber

(c) Emitted optical power and equivalent differential efficiency of an EML

Fig.9 above illustrates the work made in the implementation and optimization of the various sources and in particular of EML components for analog RF applications.

Fig.9-c shows how the operating points (laser current, AE modulator bias voltage) were chosen and tuned to achieve a proper equivalent differential slope.

The RF performance of the MRFC concept were measured for input RF signals in C-band (around 6 GHz) as outgoing from the processor output ports and an output frequency in Ka-band (around 20 GHz) corresponding to Ka-band payload transmit sections.

An all-active configuration with 2 optical fiber amplifiers (OFA) with respective output optical powers of +20 dBm and +17 dBm (to avoid receiver saturation) and a “semi-active” configuration with a single OFA at the mixer input of +23 dBm output optical power were considered. This second configuration would make it possible to reduce the consumption of the system by eliminating an optical amplification stage.

3.3 Experimental results

Measurements were carried out for the different types of commercial E/O modules, under the various system configurations and as a function of the number of channels. Simultaneous up-conversion of up to 8 C-band RF signals was shown to be feasible.

The RF performance obtained in the different configurations were compared with the results of theoretical models developed for predicting RF gain and noise figure for each of the technology and this made it possible to validate the models within 1 dB.

The MRFC configurations based on integrated GaAs MZM and EML modulators, in addition to having a higher potentials for integration than other technologies, offer pretty good functional RF performance as predicted by simulations.

Fig.10 below gives both the calculated and experimental RF performance with an EML as photonic RF source, and shows that RF gain close to - 30 dB, and NF of ~45 dB were achieved for 4-channel all-active frequency up-conversion.

Spectral purity within the full 3 GHz band was also considered acceptable as the output spectrum only features a spurious line of maximum amplitude of -20 dBc relatively to the IF compound, when the EO mixer modulator was tuned at a relative bias of 0.7 $V_{\pi DC}$, which constitutes a compromise between RF gain, noise figure and spectral purity.

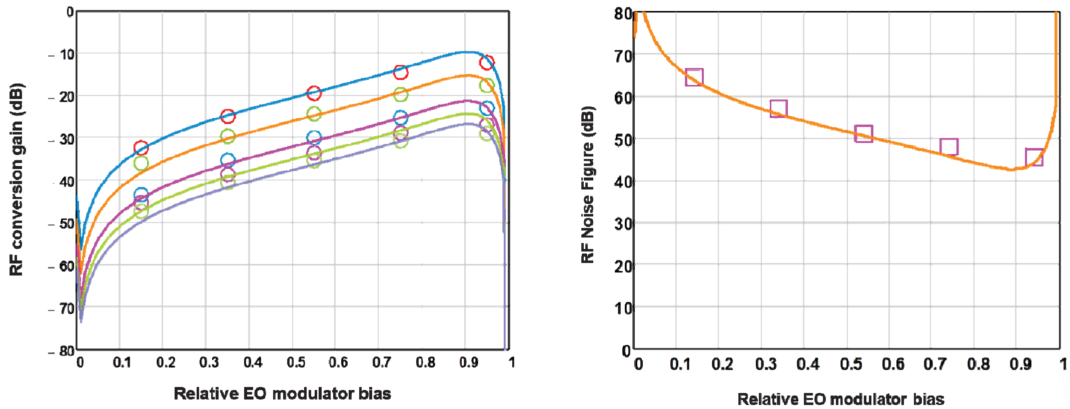


Figure 10. RF performance of multi-RF photonic frequency converter (with EML and +17dBm optical amplifier) vs. the relative EO mixer bias
(left): theoretical (full line) and measured (dots) RF gain for 1, 2, 4, 6 and 8 channels
(right): theoretical (full line) and measured (dots) RF noise figure for 4 channels

Linearity of the various components was also compared and the GaAs integrated Modulator EML was found to have significantly higher third-order intercept (TOI) point compared to the EML. Higher linearity of the modulator then makes it possible to add more gain on the RF chain upstream of the conversion and thus to reduce the impact of the MRFC contribution to the overall payload noise figure.

Overall, the RF functional performance achieved with the MZ type modulators was also good. This should allow for simultaneous frequency-conversion of 4 channels in compliance with the conventional specifications of an equivalent RF equipment. Only DML-based configurations were found to exhibit insufficient RF performances.
On the other hand, the use of EMLs designed for digital applications at 10 Gbps and having bandwidth beyond the C-band to be transmitted, was found to provide a good overall trade-off when encompassing RF performance and SWaP.
The use of a band-pass optical receiver with higher RF gain (or trans-impedance) and lower thermal noise would significantly improve the functional RF performance (especially for semi-active conversion) while maintaining the same acceptable spectral purity.

Mass and power budgets were estimated for the different architectures based on the conversion of 4 and 8 channels. For 8 channels, estimates in mass and power savings were in the order of 20-30 and 40% respectively. It was also found that MRFC configurations based on integrated devices, i.e. GaAs MZM and EML arrays, would offer even more significant SWaP advantages with respect to the other photonic RF configurations and with respect to equivalent RF implementations as well.

4. CONCLUSIONS AND PERSPECTIVES

Two novel photonic RF sub-system concepts, namely a dual-band, multi-LO frequency-converter (DB-MLFC) and a multi-RF frequency-converter (MRFC), have been introduced that support multiple-channel frequency conversion and have been shown to be well-suited for application in digital processor based payloads. The sub-system breadboards developed for proving the concepts have been presented together with the RF measurements. The performance achieved were found to be in line with modeling results and to meet system requirements. In the end, the RF performance required to the frequency-converters taking place at both the input and output stages of a digital processor-based payload can be satisfied at attractive mass and power figures, especially if integrated photonic devices can effectively be used.

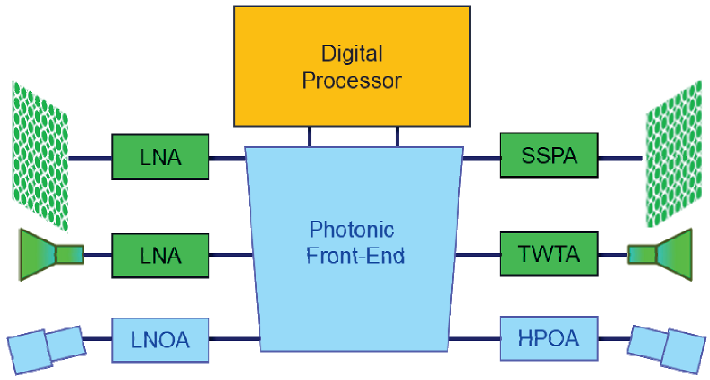


Figure 11. Conceptual view of a future photonics-enabled high-throughput satellite payload

The results reported here confirm that RF photonics can be used to efficiently transfer telecom signals within various payload configurations. Together with other previous sub-system demonstrations, they open the perspective of future payload architectures (an illustration of which is given in Fig. 11) with photonic front-end section capable of handling, interconnecting and routing any type of signals including RF signals from/to various frequency bands and antenna sub-systems, and optical signals from/to optical head units from/to central digital processors either transparent or regenerative, over a single photonic platform based on extensive use of 1.5 µm technologies including WDM.

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The concepts of multi-channel photonic RF frequency converters are protected by patents 070888 EP/US IKH/DSN and 070004 FR/US EPR/PAS, respectively for DB-MLFC and MRFC.

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