OPTICAL TECHNOLOGIES FOR ON-BOARD PROCESSING OF MICROWAVE SIGNALS

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ABSTRACT :

In the last decade, optics has proved a key technology for the transmission and handling of broadband signals in telecommunication networks. Future telecom satellite payloads will have to receive, process, route and re-transmit an increasing number of microwave signals. We have been investigating how the technologies inherited from terrestrial optical communications may bring substantial improvements or provide any breakthrough in satellite sub-systems. Optical technologies may contribute to the advent of new payload designs by enhancing or complementing conventional electronic functions, or by implementing new functions for which there is no satisfactory electronic solution. Critical issues such as EMC/EMI, RF isolation, mass, volume figures could be improved significantly as well.

The investigated functions include optical distribution of high-frequency local oscillators (LO), optical frequency-conversion and optical cross-connection of microwave signals. Optical techniques can be used for distributing LO's directly in the microwave or millimetre-wave range in many sub-systems of future payloads. They comply with low-phase noise requirements, while bringing drastic mass savings and suppressing isolation and EMC/EMI issues. However, it is necessary to produce a microwave LO under optical form, with low phase noise and power high enough to deliver to numerous equipment. This can be achieved for instance through double side-band modulation with carrier suppression of a high-power CW laser, by means of an electro-optical intensity modulator. Optical heterodyning of the first two side-bands at the photo-receiver generates the high-purity microwave signal frequency.

Frequency mixing can be achieved as well by using an electro-optic intensity modulator that both is fed by a photonic local oscillator and is driven by a given microwave signal. The optical signal at the modulator output thus features frequency compounds at intermediate frequencies, so that frequency down-conversion is performed. Unwanted frequency compounds are filtered out after optical detection. A key attribute of such a mixer is its very broadband operation. It could even perform simultaneously multiple frequency down-conversion based on wavelength-division-multiplexing.

An innovative repeater concept is briefly introduced as an example of how these optical building blocks may be combined advantageously and integrated in satellite payloads. It makes use of MEMS optical switches and was elaborated to perform broadband and flexible cross-connection in multiple-beam telecom missions. However, the scope of potential applications is certainly not limited to telecom sub-systems and these optical building blocks may also take place in remote sensing satellites.

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE	2. REPORT TYPE	3. DATES COVERED
13 JUL 2005	**N/A**	**-**

4. TITLE AND SUBTITLE	5a. CONTRACT NUMBER
Optical Technologies For On-Board Processing Of Microwave Signals	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **ALCATEL SPACE, 26, avenue J-F. Champollion - BP 1187, 31037 Toulouse, France**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S)
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release, distribution unlimited

13. SUPPLEMENTARY NOTES
See also ADM001791, Potentially Disruptive Technologies and Their Impact in Space Programs Held in Marseille, France on 4-6 July 2005., The original document contains color images.

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			
unclassified	**unclassified**	**unclassified**	**UU**	**7**	

1 - INTRODUCTION

Future telecom satellites for broadband communications should offer high data rate connections to a large number of terminals. The conventional “bent pipe” repeater cannot meet this demand; C and Ku bands do not offer enough bandwidth for growth, receive performances are not suited for small terminals, and efficient multiple access and switching schemes are needed [1]. Based on geo-stationary Earth orbit (GEO), future broadband payloads in Ka-band, will receive and re-transmit hundreds of radio-frequency (RF) channels over tens of antenna beams, and offer flexible connectivity and protocol transparency so they can meet any mission evolution demand.

Modern RF remote sensing payloads now embrace a wide range of various instruments namely imaging synthetic-aperture radar, altimeters, rain, cloud and other meteorology radar’s. RF sensing applications usually call for various and mission-specific requirements, but they have in common complex antenna designs with up to one thousand radiating elements, specific means for generation and processing of high-frequency microwave signals (including local oscillator and chirped-frequency signals) as well as digital processing capabilities to handle the data output.

A number of optical technologies including so-called microwave photonics are becoming now available so that their use for analogue signal distribution and processing in space-borne sub-systems should be considered. Optical technologies may take a significant place in telecom payloads with broader bandwidth, wider connectivity, and enhanced routing flexibility at ever lower mass and smaller size [2]. Functions that could be implemented with optical technologies include microwave interconnects and switches, local oscillator (LO) generation and distribution in various bands, RF frequency conversion, and connectivity management. In such large and complex payloads, this may turn into drastic mass and volume savings, while suppressing EMC/EMI and RF isolation issues. The migration to millimetre-wave missions likely increases the attractiveness of optical processing. In high-frequency active antennas, small size and low power dissipation at the antenna element side will be critical requirements. Again, photonic solutions may be used not only for distributing LO’s, but also for frequency mixing in electro-optical modulators with optical LO input. Such innovative concepts for the optical processing of microwave signals are subsequently introduced in the overall context of telecom and RF sensing satellite payloads.

2 - OPTICAL DISTRIBUTION OF MICROWAVE LOCAL OSCILLATORS

The optical distribution of LO’s above 10 GHz requires to produce a microwave oscillator signal under optical form, with high enough power and low enough phase noise, so it can be delivered to a large number of receivers with no performance impairment. The transfer of a high-frequency signal onto an optical carrier through direct modulation of the laser diode current is typically limited to 15 GHz or less. At higher frequency, one makes use of external optical modulators (e.g. electro-optical intensity modulators) running at up to 50 GHz and inherited from high bit-rate optical communications. Other techniques referred to as optical heterodyning, are based on the interference of two optical waves onto a photodiode; as a matter of example, two optical carriers around 1550 nm (i.e. 193 THz) with a wavelength spacing of 0.2 nm that fall on a high-bandwidth photo-detector, generate a beat frequency of 25 GHz. So-called dual-frequency lasers are diode-pumped solid-state lasers, emitting simultaneously two cavity modes that are exactly spaced by the LO frequency. An optical phase-locked loop (OPLL) is needed to lock the phase of one laser/mode onto

the phase of the other, and thus to drastically reduce the phase noise resulting from the beat linewidth.

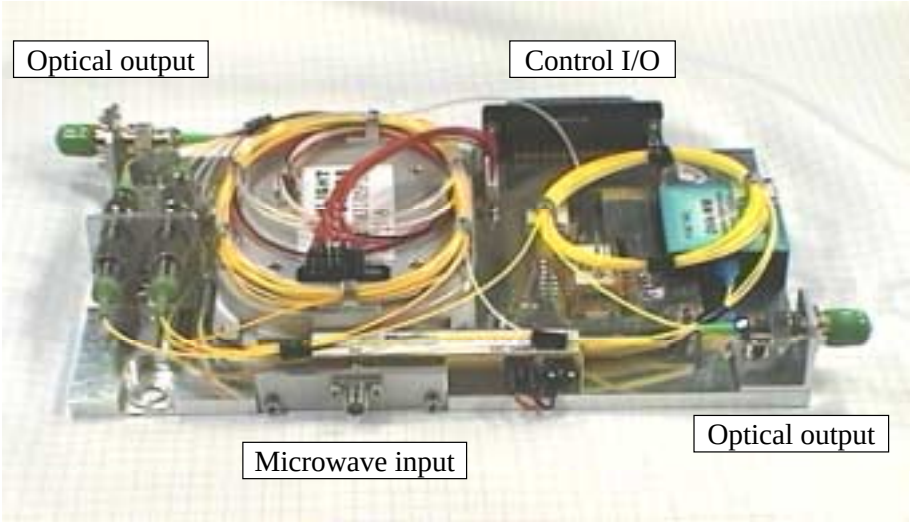

Fig. 1 : Breadboard of the photonic local oscillator block

Optical double side-band modulation with carrier suppression (DSB-CS) is another LO generation technique [3], making use of a high-power CW laser and a Mach-Zehnder electro-optical intensity modulator biased for minimum optical transmission. When the modulator is driven by a high-purity sinus-wave signal at $f_{LO}/2$ frequency, the optical output signal mainly only contains the first two modulation side-bands. Optical heterodyning at the photo-receiver generates a high-purity microwave signal at f_{LO} frequency.

A photonic local oscillator breadboard based on DSB-CS is shown in Fig. 1. The assembled optical source delivers an optical LO at any frequency in the 10-40 GHz range with +18 dBm optical power and a relative intensity noise level below –155 dB/Hz. The optical spectra (in linear scale with 0.1 nm resolution) of the photonic LO successively tuned to 20, 30 and 40 GHz, are given in Fig. 2.

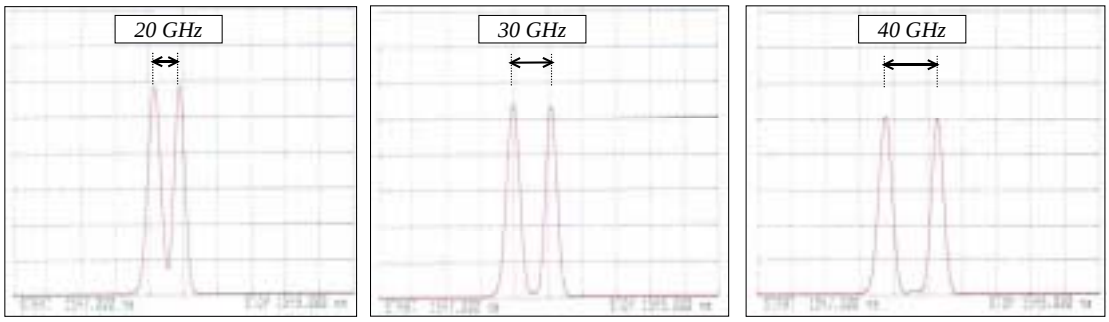

Fig. 2 : Optical spectra (in linear scale) of photonic LO's from 20 to 40 GHz

Measurements of phase noise performance of a photonic LO distribution sub-system at 20 GHz with appropriate photo-receivers are depicted in Fig. 3. The performance is expressed in terms of relative phase noise level as a function of the offset frequency from the carrier for various optical splitting losses. The phase noise curve follows the one of the microwave reference oscillator. The phase noise of the photonic LO at 20 GHz is about 6 dB higher than the one of the reference at 10 GHz. For optical splitting losses of up to 30 dB, the phase noise floor of the optically-distributed LO keeps lower than –130 dBc/Hz. In practice, such an LO can be delivered to several hundreds of

equipment over an optical fibre harness that features about 1 g/m linear mass and distance-independent loss !

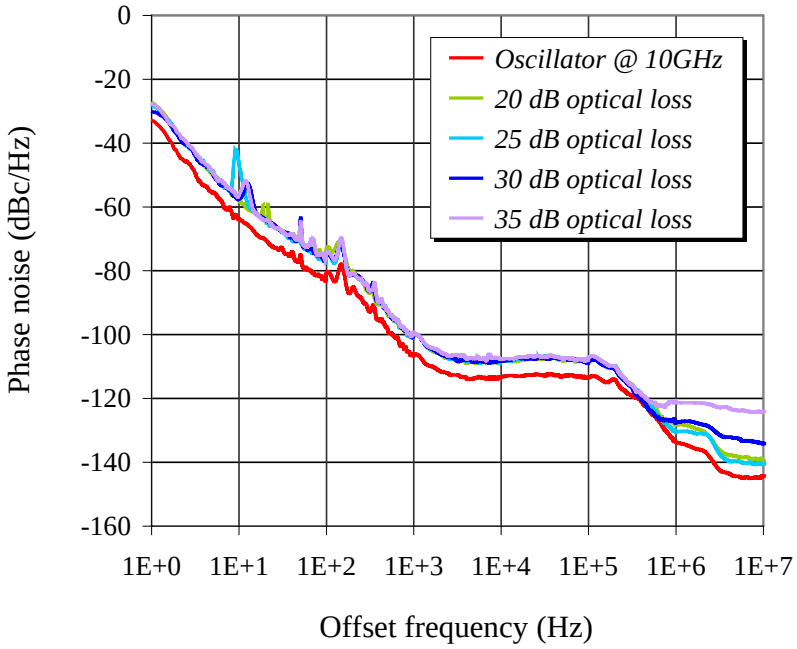

Fig. 3 : Experimental phase noise performance of a 20 GHz photonic LO distribution system versus optical losses

Since generation by double side-band modulation is only limited by modulator bandwidth and photo-detector response, this technique can apply to any frequency band including C, Ku, Ka, Q, V or higher, and find application in many payload sub-systems [4].

3 - OPTICAL FREQUENCY MIXING OF MICROWAVE SIGNALS

Electro-optical intensity modulators can also be used for RF frequency mixing, as initially demonstrated in [5-6]. The sinusoidal transfer function of Mach-Zehnder optical modulators make them attractive as mixers performing both up- and down-conversion of microwave signals. One of the most efficient arrangements for optical frequency mixing consists in providing the modulator with the LO signal directly from a microwave photonic oscillator, as shown in Fig. 4.

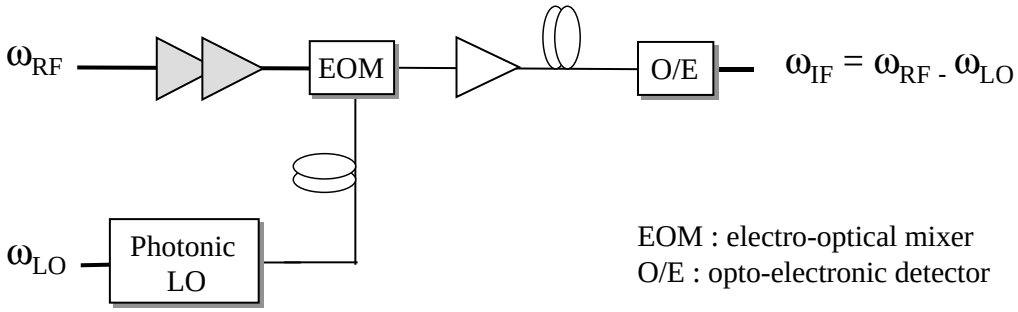

Fig. 4 : Principe of optical RF frequency conversion

The RF signal to be down-converted is applied to the modulator RF electrode, thereby superimposing a RF modulation of the optical intensity. Direct detection generates both the LO and RF frequencies as well as the beat products, i.e. the frequency sum and the frequency difference. By designing the photo-detector bandwidth appropriately, the LO, RF and the sum frequencies can be filtered out so that the IF frequency only is made available at the output.
Fig. 5 gives the experimental RF spectrum of a signal down-converted from 30 GHz to 4 GHz in an electro-optical mixer fed with an optical LO at 26 GHz. Isolation between RF frequency compound and IF signal and between LO frequency compound and IF signal are respectively better than –30 and equal to –25 dB.
As evidenced by the above experimental results, the RF performance of such optical down-converters can compare with those of today's RF equipment. Isolation between the RF input signal and the photonic LO is simply infinite. One concern is the limited efficiency of the frequency-conversion process (i.e. conversion gain/loss). However, this can be accommodated by an appropriate system design.

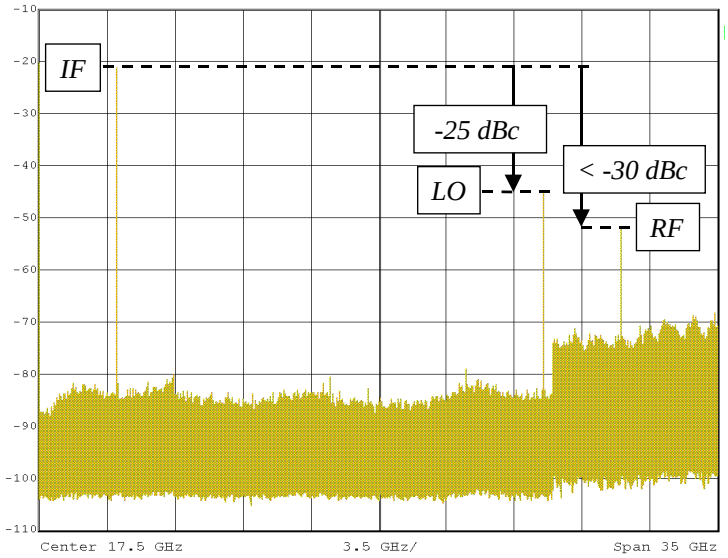

Fig. 5 : RF spectrum of signal after frequency down-conversion from 30 to 4 GHz

Such electro-optical mixers feature specific attributes; they offer very wide bandwidth, and provide infinite LO to RF input port isolation. They can be readily included in the optical LO distribution chain, and enable optical remoting and further processing of RF signals by optical means. Multiple frequency-conversions can also be supported [7]. The optical modulator needs to be fed simultaneously with several optical LO's by implementing wavelength-division-multiplexing (WDM). Thus, it is possible to perform within the same device, multiple frequency down-conversion from a single incoming signal to several signals at different intermediate frequencies carried by separate optical wavelengths.

4 - MICROWAVE PHOTONIC PAYLOAD SUB-SYSTEMS

The above functional blocks can be advantageously combined together in satellite payload sub-systems. As a matter of example, Fig. 6 shows a simplified architecture of a broadband telecom payload, that relies upon conventional microwave low-noise receive and high-power transmit sections, and incorporates photonics in the centre section in order to distribute microwave LO's, perform frequency down-conversion, and route RF channels. Each receiver chain is equipped with

an electro-optic mixer that accepts both a photonic LO and the incoming microwave signal, so that frequency-mixing with the LO is achieved. Then, the optical signals at intermediate frequency are amplified and routed to RF channel filters through an optical cross-connection unit.

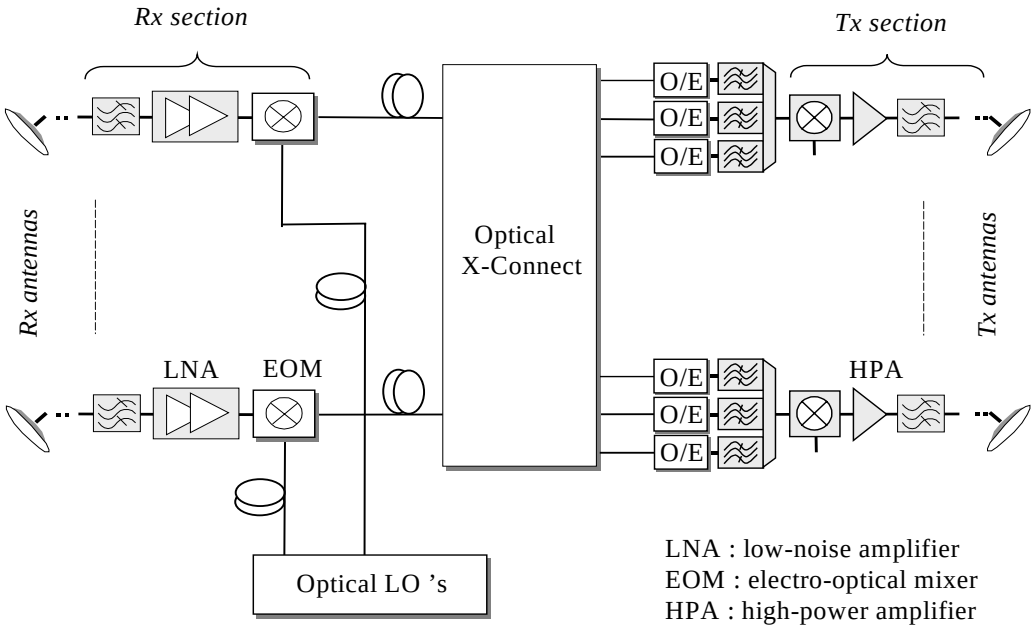

Fig. 6 : Schematic of an opto-microwave cross-connect repeater system

Such an optical cross-connect allows to further increase the flexibility of an analogue transparent repeater. Optical MEMS-based switching matrices will enable to grow up the connectivity over a large number of access ports while maintaining all the advantages of photonic solutions, again mass and volume savings, RF isolation, suppression of EMC/EMI issues. At identical system scale, this concept compares favourably with bulky microwave implementations, but it becomes especially attractive for future larger scale repeaters with numerous antenna beams.

It should be noted that the scope of potential applications is certainly not limited to telecom sub-systems as these optical building blocks may take place in remote sensors as well. Photonic LO distribution and frequency mixing in electro-optical modulators may be beneficial to many advanced active antenna concepts [4], where small size and low power dissipation at the antenna element side, or low mass cabling are critical requirements.

5 - CONCLUSION

Maturity of optical communications technologies and microwave photonics has rapidly evolved in recent years. Their effective use for the distribution and processing of microwave signals in satellite payload sub-systems is presently being assessed, particularly now that that high power handling lasers, optical amplifiers, and photodetectors are available. The overall migration of space missions to millimetre-wave applications also increases the attractiveness of optical processing techniques.

Innovative concepts for optical generation and processing of microwave and millimetre-wave signals have been presented. Local oscillators can be generated under optical form in a wide range of frequencies, and effectively distributed over optical fibre harnesses, with unprecedented advantages. This is expected to turn out into major benefits for on-board applications, namely drastic mass and volume savings, suppression of EMC/EMI issues, simplification of cabling and

shortening of integration and test steps. RF mixing can be achieved as well with RF performance complying with key requirements, which opens the perspective of more complex payload sub-systems. In future telecom payloads, photonic technologies can be considered for distributing LO's, performing frequency-conversion and for RF channel cross-connection, thus becoming a serious option for supporting broadband, transparent and flexible cross-connectivity over multiple antenna beams.

Photonic technologies will not just bring substantial improvements to existing payload sub-systems; they may constitute one of these enabling technologies critically required to the practical implementation of advanced payload concepts.

6 - ACKNOWLEDGEMENTS

This work is being supported by the European Space Agency under the contract 15695/01/NL/ND - *Optical Handling of Microwave and Digital Signals*. The authors are also grateful to their colleagues at Thales (F), Contraves Space AG (CH), Photline (F), University College London (UK), Avalon (CH) and Sercalo (CH) for fruitful cooperation in the Project.

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