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A flexible telecom satellite repeater based on microwave photonic technologies

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A FLEXIBLE TELECOM SATELLITE REPEATER BASED ON MICROWAVE PHOTONIC TECHNOLOGIES

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ABSTRACT

Future telecom satellite based on geo-stationary Earth orbit (GEO) will require advanced payloads in Ka-band so as to receive, route and re-transmit hundreds of microwave channels over multiple antenna beams.

We report on the proof-of-concept demonstration of an analogue repeater making use of microwave photonic technologies for supporting broadband, transparent, and flexible cross-connectivity. It has microwave input and output sections, and features a photonic core for LO distribution, frequency down-conversion, and cross-connection of RF channels.

With benefits such as transparency to RF frequency, infinite RF isolation, mass and volume savings, such a microwave photonic cross-connect would compare favourably with microwave implementations, and based on optical MEMS switches could grow up to large port counts.

1. INTRODUCTION

Global connectivity, broad bandwidth and network re-configurability are paramount requirements driving the current evolution in telecommunications. Satellite communication systems will contribute to fulfil this demand by providing wide-band access to the backbone, establishing shortcuts between backbone edge sites, as well as extending the Earth network in sparsely populated areas, developing countries or during deployment of ground infrastructures.

A prospective broadband backbone telecom mission, supported by a Geo-stationary Earth orbit (GEO) satellite system, shall consist in offering semi-permanent access and mesh connectivity services to a number of Earth stations called gateways. As a matter of example, such a backbone system shall be used by Internet Service Providers to connect isolated nodes to their core network, or by different providers to interconnect their respective networks.

Communications in Ka-band (30/20 GHz) making larger bandwidth available will constitute the baseline

for such broadband satellite applications. The high directivity of Ka-band antennas enables to ensure the link budget from/to GEO systems. Global reach is achieved by implementing complex multiple spot-beam coverage based on frequency reuse.

Such future broadband telecom satellites will receive and re-transmit hundreds of radio-frequency (RF) channels over tens of antenna beams; they will require flexible payloads that outperform the conventional "bent pipe" repeater [1] in order to cross-connect or switch signals on demand.

Due to the long lifetime of a satellite mission (15 years) compared to the fast moving telecommunication market, flexible, versatile and future-proof solutions are mandatory. While digital processors shall offer advanced capabilities like for fine granularity channelizing, packet routing and beam-forming, transparent analogue repeaters will make sense, especially for backbone missions, provided that re-configurability is provided at moderate complexity, mass and volume. So far, this has not been offered by conventional RF technologies. Thus, photonic technologies may bring major benefits in the development of future satellite payloads with broader bandwidth, wider connectivity, and enhanced routing flexibility at low mass and small size [2].

2. FLEXIBLE ANALOGUE REPEATER BASED ON MICROWAVE PHOTONICS

Advanced satellite payload concepts based on photonic technologies were investigated within the ESA SAT 'N LIGHT project [3]. In particular, a new class of analogue repeaters was elaborated, an architecture of which is schematically represented in Fig. 1. It is based on conventional microwave low-noise receive and high-power transmit sections, and incorporates photonic technologies in the centre section to distribute microwave local oscillators (LO), perform frequency down-conversion, and achieve channel routing. All the LO's are generated and transferred on optical carriers

within a centralised unit, and delivered to electro-optical mixers with one microwave and one optical input, and one optical output.

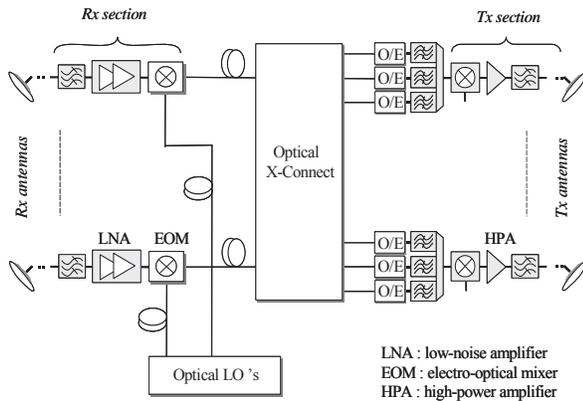


Fig. 1. Schematic of an opto-microwave cross-connect repeater for telecom satellite.

Each microwave telecom signal received from an up-link antenna beam is transferred onto an optical carrier at the electro-optical mixer. This mixer is fed by an optical local oscillator, and converts the input RF frequency down to an intermediate frequency (IF). Once under optical form, the signals are amplified and routed through an optical cross-connect made of passive splitters and switching matrices. Opto-microwave receivers convert the signals back into microwave ones at IF, so that RF channel filtering is achieved by conventional microwave means.

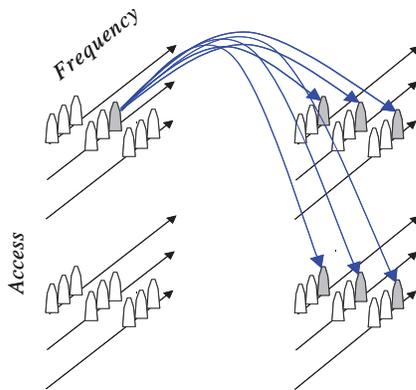


Fig. 2. Channel cross-connection capabilities with access port and frequency sub-band interchange.

Such a flexible repeater enables to cross-connect a large number of channels with antenna access and frequency-band interchange. It compares favourably with microwave implementations in that, it may bring drastic mass savings at identical system functionality

and scale, and could grow up to larger connectivity (10's of beams). Additional benefits should arise from transparency to RF frequency bands, full RF isolation, suppression of EMC/EMI issues, that, at the end, may shorten the design-to-integration cycle.

Architectural variants making additional use of wavelength-division multiplexing (WDM), have also been proposed. These repeater architectures could support more flexible cross-connection capabilities such as frequency-slot interchange, which definitely outperforms the capabilities of microwave implementations.

3. PHOTONIC LOCAL OSCILLATORS AND FREQUENCY-MIXERS

The repeater architectures introduced above are relying on the concept of photonic LO generation and optical frequency-conversion of microwave signals.

More specifically, a microwave LO signal in the 20-30 GHz range is needed under optical form with high power and low phase noise. The transfer of a microwave signal onto an optical carrier through direct modulation of laser current is limited to below 10 GHz. At higher frequency, one makes use of external electro-optical modulators developed for high bit-rate ground transmission. Optical heterodyning based on the interference of two optical carriers onto a photodiode to generate a microwave signal is only constrained by the detector response. For example, two optical carriers at 1550 nm with a wavelength spacing of 0.2 nm that fall on a high-bandwidth photo-detector generate a beat frequency of about 25 GHz. Using two separate laser diodes requires an optical phase-locked loop (OPLL) in order to lock the phase of one laser onto the phase of the other, and also to drastically reduce the phase noise resulting from the beat linewidth.

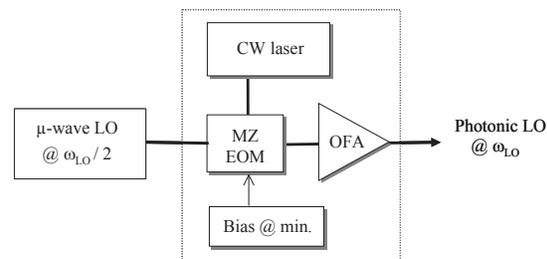


Fig. 3. Photonic LO based on double-sideband modulation with carrier suppression (DSB-CS).

Optical double side-band modulation with carrier suppression (DSB-CS) is an LO generation technique [4] that does not need any OPPL. Its principle is

represented in Fig. 3. It makes use of a high-power CW laser and a Mach-Zehnder electro-optical intensity modulator (MZ-EOM) that is biased ($V_{bias}=V_{\pi}$) for minimum optical transmission. When the MZM 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 since the optical carrier is almost suppressed. Optical heterodyning at the receiver generated a high-purity microwave signal at f_{LO} frequency.

Mach-Zehnder intensity modulators have been reported as attractive electro-optical mixers [5-6] for performing optical frequency-conversion. One of the most efficient arrangements is shown in Fig. 4 and consists in providing the modulator with the LO signal from a microwave photonic oscillator.

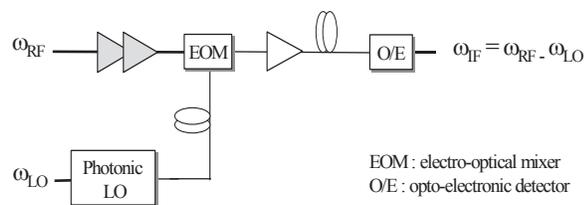


Fig. 4. Principle of photonic RF frequency conversion

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 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 response appropriately and by using conventional RF channel filtering, the LO, RF and the sum frequencies can be cancelled out so that the IF frequency only is made available at the output.

4. PROOF-OF-CONCEPT REPEATER DEMONSTRATION

A system demonstrator was assembled in order to prove the concept, and assess the performance of such opto-microwave repeater architectures. It was designed as a sub-populated repeater breadboard, representative of an end-to-end opto-microwave path. The demonstrator had microwave inputs in Ka band (28-31 GHz) and outputs in so-called C band (3-5 GHz). As shown in Fig. 5, the microwave photonic cross-connect breadboard demonstrator featured all the key building blocks :

- ① Optical Local Oscillator source,
- ② Electro-optical mixer,

- ③ Optical crossconnect,
- ④ Opto-microwave receiver.

The photonic LO source was able to deliver an optical LO signal at any frequency up to 30 GHz with +18 dBm optical power, and a relative intensity noise level below -155 dB/Hz.

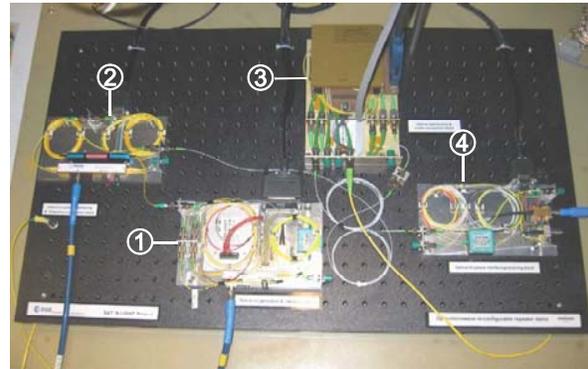


Fig. 5. Opto-microwave cross-connect repeater breadboard demonstrator

This photonic LO was typically tuned around 26 GHz for the system demonstration and tests. A typical optical spectrum is shown in Fig. 5 in logarithmic scale and with 0.1 nm resolution. In particular, it is shown that optical carrier suppression close to 20dB below the sideband level was achieved.

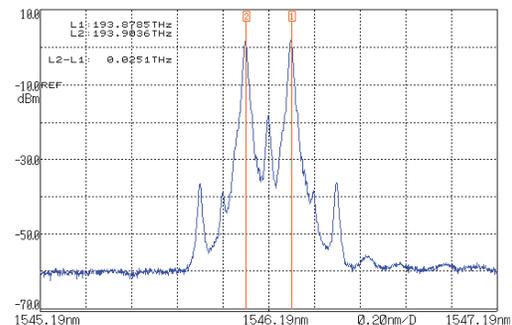


Fig. 6 : Optical spectrum of the 25 GHz photonic LO

The electro-optical mixer consisted in a broadband Mach Zehnder modulator with bandwidth in excess of 30 GHz and 4 dB optical loss. Effective half-wave voltage (V_{π}) and third-order intercept respectively of 12.5 V and +30.5 dBm were measured at 30 GHz. The third-order non-linearities were shown to be almost independent from the modulator biasing, so that the modulator could be operated at bias above the quadrature (i.e. above $\sqrt{2}V_{\pi}/2$) for improving gain and noise figure while maintaining the same linearity performance as achieved at the quadrature

The opto-microwave receiver was a band-pass receiver with flat response from 3 to 5 GHz, thus perfectly fitting the C band. It completed frequency down-conversion, and with effective rejection at frequencies higher than 10 GHz, it lowered unwanted frequency compounds.

Frequency down-conversion was demonstrated from 30 GHz to 4 GHz with a LO at 26 GHz. Fig. 7 gives the typical spectrum of the output RF signal after down-conversion, with residual LO and RF compounds respectively 25 and 30 dB below the IF signal; these unwanted frequency compounds would be further suppressed through the RF channel filters in a real repeater system.

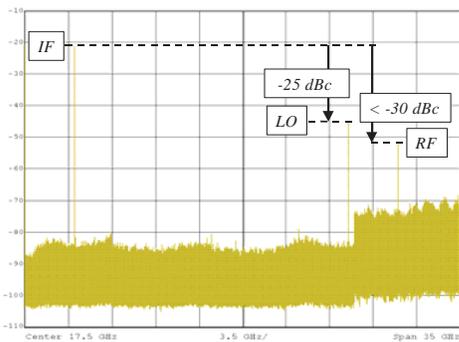


Fig. 7. Photonic RF frequency-conversion : spectrum of signal down-converted from 30 to 4 GHz.

The frequency-converter was proven to operate over the whole Ka-band with excellent response flatness. With an optical LO at 26 GHz, the frequency-conversion bandwidth at -1 dB exceeded the targeted 28-31 GHz range as demonstrated in Fig. 8.

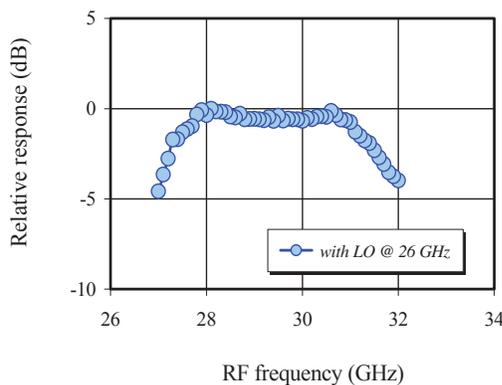


Fig. 8. Photonic RF frequency-conversion : frequency response with LO @ 26 GHz

These performance fairly 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 could be accommodated by an appropriate system design.

The optical cross-connect (OXC), that was to distribute and route the microwave signals, incorporated a low-consumption optical amplifier, an optical power splitter, and an optical switch configured through a PC controller.

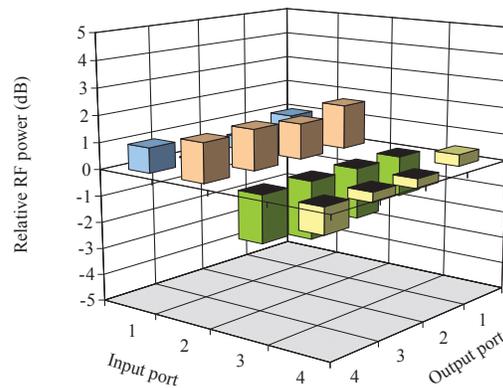


Fig. 9. Optical cross-connection of RF channels : relative RF output power

The optical switch was a commercial, strictly non-blocking 4x4 matrix from Sercalo Microtechnology Ltd, realized by cascading discrete 1x2 and 2x2 MEMS (Micro-Electro-Mechanical System) devices. The main features of the switch are insertion loss lower than 2 dB, crosstalk below -60 dB, return loss higher than 50dB and polarization dependent loss of less than 0.1dB. With these excellent optical performance, flexible repeater system operation was demonstrated with pretty good overall performance. Fig. 9 shows that microwave signals were routed on demand through the 4x4 optical cross-connect under PC control, with limited variations of the RF output power.

5. PERFORMANCE TEST RESULTS

The RF performance of the microwave photonic repeater sub-system were investigated in more detail. In particular, a variable optical attenuator was included in the optical path between the amplifier and the C-band receiver, in order to create the optical losses

corresponding to larger scale repeaters, and to assess the RF performance as a function of their size.

5.1 RF gain and noise figure

The RF conversion gain (a) and noise figure (b) of the optical section are given in Fig. 7 as functions of the amount of optical loss in the optical cross-connection stage.

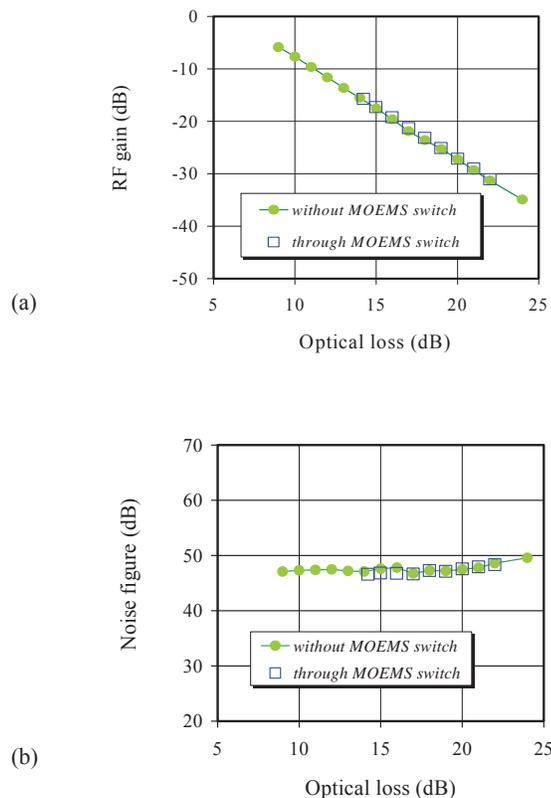


Fig. 10. RF gain (a) and Noise Figure (b) of the microwave photonic cross-connect

An RF gain higher than -25 dB and a noise figure lower than 47 dB were obtained for optical losses as high as 18 dB. Such an optical loss budget is compatible with the implementation of large scale cross-connects with more than tens of ports.

The relatively high noise figure of the optical section is to be tempered by the fact that, in a real repeater, the optical section will be preceded by a microwave low-noise amplifier chain with high gain (e.g. 55 to 60 dB). Thus, its contribution to the overall noise figure will be below a few tenths of dB, so that the overall gain and noise figure can be made compliant with the higher level system requirements.

5.2 Linearity and RF crosstalk

The linearity and crosstalk performance of the microwave photonic cross-connect were also measured. They are illustrated in Fig. 11 and 12 giving the RF spectrum of a 2-tone signal down-converted to C band as observed at the output of the microwave photonic section.

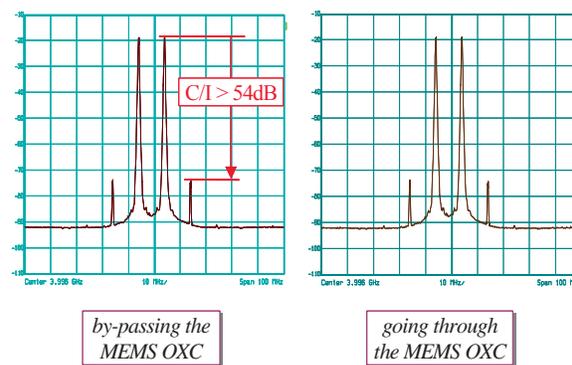


Fig. 11. 2-tone linearity in the microwave photonic cross-connect

Fig. 11 shows that the ratio (C/I) of the carrier to the inter-modulation product was unchanged and higher than 54 dB. It remained at a constant level whatever the OXC route and configuration. Thus, no linearity degradation caused by the optical MEMS switch was observed.

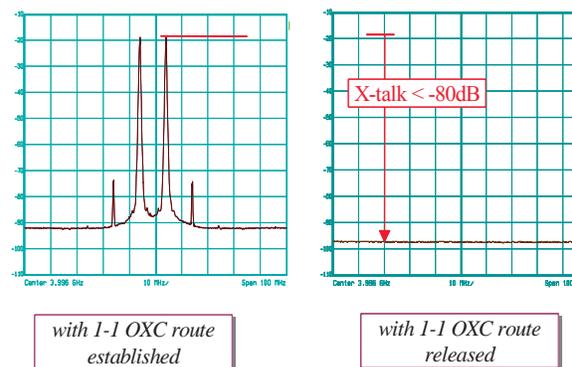


Fig. 12. RF crosstalk in the microwave photonic cross-connect

Fig. 12 shows the RF spectrum when route 1-1 through the OXC was then released, while the other optical routes kept lighted. By comparison, it shows that there was no measurable RF crosstalk. In other words, RF crosstalk was proved to be below -80 dB. Again, the same behaviour was observed for each of the 16 routes through the MEMS OXC.

5.3 Phase noise performance

Finally, the phase noise performance of the repeater sub-system was also investigated under various configurations. In particular, it was measured without and with the MEMS OXC for the same amount of optical losses. As a matter of example, Fig. 13 shows the relative phase noise of the IF signal at 4 GHz, for 17 dB optical losses. The other optical routes were also connected and lighted, and this was found not to affect the phase noise level, whatever the optical route and the OXC configuration.

These curves showed that stringent phase noise requirements could be met, and that no phase noise degradation occurred which could be attributed to the MEMS optical cross-connect.

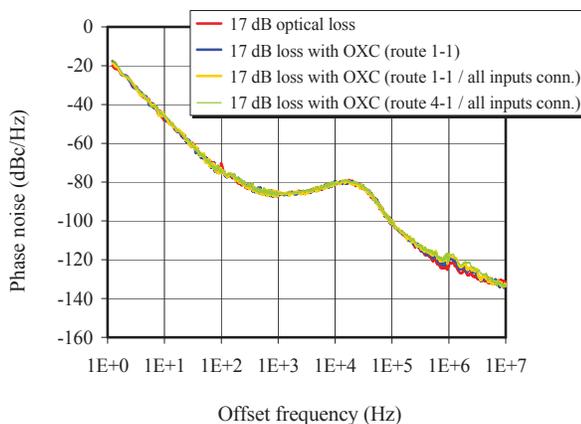


Fig. 13. Phase noise at IF frequency without and through the MEMS OXC

This latter set of results demonstrates that MEMS-based optical switches are pretty well suited for the optical cross-connection of microwave signals with no detrimental effect on their RF performance, neither in crosstalk nor in phase noise.

6. CONCLUSIONS

The concept of a flexible analogue repeater based on photonic technologies for broadband, transparent, backbone telecom missions has been assessed and successfully proven.

The sub-system demonstration included optical distribution of a high-purity local oscillator at 26 GHz, photonic frequency down-conversion from 30 to 4

GHz, and MEMS-based optical cross-connection of microwave signals.

Test results have shown that the achieved RF performance can be compatible with the implementation of such repeaters at large scale with an attractive number of beams. Such microwave photonic repeater architectures offer scalability and versatility features that outperform conventional all-microwave implementations.

Photonics and microwave photonics are emerging as enabling technologies in space, not only for improvement of mass and size figures but also for the practical implementation of advanced satellite payload concepts with enhanced functionality.

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