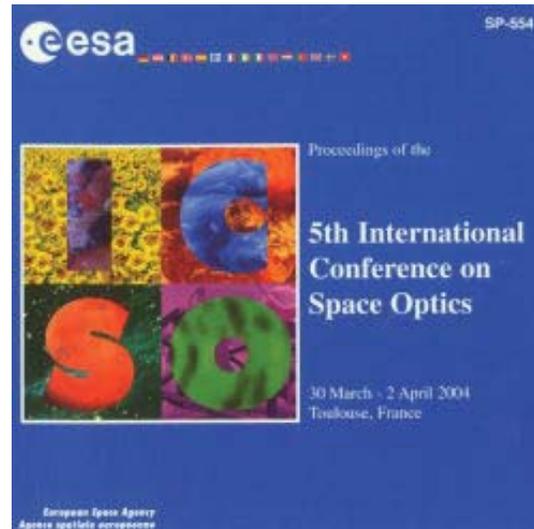


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## *Optical distribution of local oscillators in future telecommunication satellite payloads*

*Benoît Benazet, Michel Sotom, Michel Maignan, Jacques Berthon*



# OPTICAL DISTRIBUTION OF LOCAL OSCILLATORS IN FUTURE TELECOMMUNICATION SATELLITE PAYLOADS

Benoit Bénazet <sup>(1)</sup>, Michel Sotom <sup>(1)</sup>, Michel Maignan <sup>(1)</sup>, Jacques Berthon <sup>(2)</sup>

<sup>(1)</sup> Alcatel Space, 26 avenue J-F. Champollion, BP 1187, 31037 Toulouse Cedex 1, France

<sup>(2)</sup> CNES, 18 avenue E. Belin, 31401 Toulouse Cedex 4, France

contact : benoit.benazet@space.alcatel.fr

## ABSTRACT

The distribution of high spectral purity reference signals over optical fibre in future telecommunication satellite payloads is presented. Several types of applications are considered, including the distribution of a reference frequency at 10 MHz (Ultra-Stable Reference Oscillator) as well as the distribution of a radio-frequency oscillator around 800 MHz (Master Local Oscillator). The results of both experimental and theoretical studies are reported. In order to meet phase noise requirements for the USRO distribution, the use of an optimised receiver circuit based on an optically synchronised oscillator is investigated. Finally, the optical distribution of microwave local oscillators at frequencies exceeding 20 GHz is described. Such a scheme paves the way to more advanced sub-systems involving optical frequency-mixing and optical transmission of microwave signals, with applications to multiple-beam active antennas.

## 1. INTRODUCTION

Satellite operators are anticipating the emergence of a new market based on broadband communications in the next five to ten years. Typically, broadband space systems should offer high data rate connections to very large numbers of low price terminals. The present generation of satellites is not really well suited for such broadband telecom missions involving millions of end users. Ku and C bands are getting more and more congested and do not offer enough bandwidth for growth. Receive performances of the satellite are not sized for the use of small and low-power terminals.

Multiple access schemes are not adapted, as there are, for managing thousands of simultaneous links. New satellites shall be designed to meet the next coming requirements. Lastly, to be economically viable, communication price shall be as low as possible. Only satellites with very large capacity in terms of bandwidth or numbers of circuits would enable to achieve low communication price.

Several options are being pursued to significantly enhance the satellite capabilities [1]. Broadband payloads will have complex multi-beam active antennas, hundreds of channels to receive, to route and to transmit, large on-board digital processors for switching and/or regenerating telecom signals.

Photonic technologies offer major benefits in the development of such future payloads with high performance and low mass/size requirements. These functions include the optical distribution of reference signals and local oscillators in various frequency ranges. Actually, in large broadband payloads, the LO distribution network is becoming a critical subsystem because of mass, complexity, reliability and electromagnetic compatibility issues. In this context, fibre optics links constitute an attractive alternative to conventional wiring because they may enable drastic mass savings, suppress all problems of EMC/EMI, simplify and thus shorten the integration phase, at the expense of some extra power consumption.

In the medium term, photonic solutions may also be used for distributing local oscillators in the microwave range in future multi-beam active antennas operating in Ka-band. In such applications, small size and low power dissipation at the antenna element side are critical requirements. Actually, each antenna receiver may be equipped with an electro-optic intensity modulator that

both receives a photonic local oscillator and is driven by the incoming microwave signal, so that frequency mixing with the LO can be achieved as well. As a matter of example, such a sub-system may find application in re-configurable, multi-beam active antennas where received microwave signals may be digitised and antenna beam forming performed within a centralised digital processor.

## 2. OPTICAL DISTRIBUTION OF RADIO-FREQUENCY REFERENCE OSCILLATORS

The distribution of radio-frequency (RF) reference oscillators via an optical fibre network may find application in future satellite payloads. Figure 1 shows a block diagram of a telecom repeater architecture based on a digital transparent processor that may require the distribution of several types of radio-frequency oscillators. Such a repeater architecture performs frequency down- and up-conversion, each in two consecutive steps, and thus needs both the distribution of an Ultra-Stable Reference Oscillator (USRO), typically at 10 MHz, for re-constructing local oscillators within some frequency-converters and the distribution of a Master Local Oscillators (MLO), typically around 1GHz, for direct use by other frequency-converters.

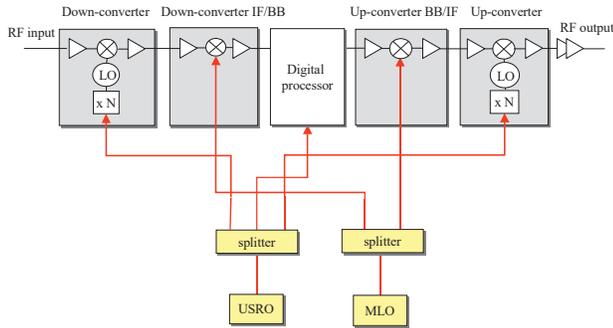


Fig. 1. Example of telecom repeater architecture requiring two types of reference oscillators

The following two cases have been considered: the distribution of an USRO at 10 MHz and the distribution of a MLO at 800 MHz. In both cases, the RF signal issued from the reference oscillator has to be delivered to tens of equipment.

A major requirement is that the optical distribution network shall not add phase noise degradation in the reference signal and shall guaranty a constant power

level to each converter. The requirements of phase noise degradation for the two cases are different. USRO distribution requires phase noise floor in the order of -160 dBc/Hz. MLO distribution is content with a higher noise floor around -130 dBc/Hz.

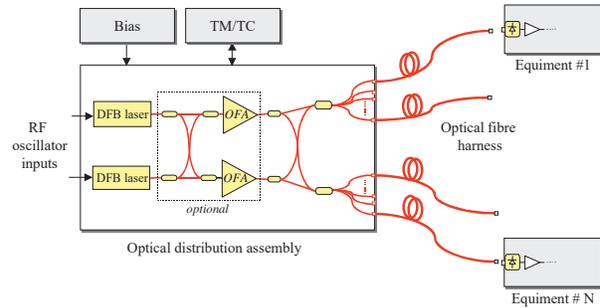


Fig. 2. General architecture for the optical distribution of RF reference oscillators

Fig. 2 show a general optical network architecture for the distribution of RF oscillators. Its consists of an optical distribution assembly and an optical fibre harness. The optical distribution assembly features RF inputs for direct modulation of the injection current of distributed feed-back (DFB) semiconductor lasers. This technique is regarded as the simplest and at the end the most efficient way to transfer an RF frequency signal onto an optical carrier. Active or passive optical networks may be considered, i.e. that incorporate or not Optical Fibre Amplifiers (OFA).

The optical signal is power divider through passive optical splitters and delivered to a number of RF equipment over an optical fibre harness. Each RF equipment incorporates a photo-receiver that converts the optical signal back into an RF one.

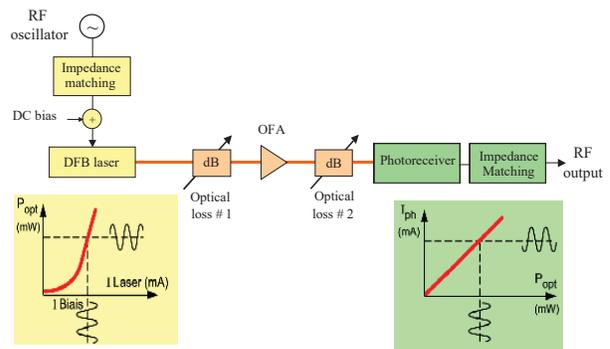


Fig. 3. Generic RF optical link model

The performances of each architecture were evaluated in terms of RF gain, carrier-to-noise ratio, phase noise performance, optical loss budget and achievable splitting ratio. A software tool was developed using the optical link model shown in Fig.3. It includes a DFB laser with appropriate impedance matching, an optical fibre amplifier, optical attenuators accounting for splitting losses and a photo-receiver typically made of a PIN diode and a trans-impedance amplifier.

The phase noise spectral density at the optical link output is composed of the phase noise of the RF signal to be transmitted (not considered here) and of the optical link noise. This latter is mainly due to the laser noise and to the photodiode noise. A simple expression of the link output phase noise is given by [2] :

$$S_{\phi_{input}} = K \cdot \frac{RIN_{LF}}{f_m} + \frac{1}{(2 \cdot CNR)} \quad (1)$$

where  $RIN_{LF}$  is the laser Relative Intensity Noise (RIN) at 1Hz,  $K$  its AM/FM noise conversion factor,  $CNR$  the carrier-to-noise ratio, and  $f_m$  the offset frequency from the carrier. The CNR depends on the optical power detected  $P_{det}$ , the photodiode sensitivity  $S$ , the dark current  $i_{obs}$ , the thermal noise  $i_{th}$ , the laser modulation index  $m$ , the laser  $RIN$  at high frequency, and the electron charge  $q$ . Its expression is as follows [3] :

$$CNR = \frac{P_{det}^2 \cdot S^2 \cdot m^2}{2 \cdot (S^2 \cdot P_{det}^2 \cdot \langle RIN \rangle + 2 \cdot e \cdot (S \cdot P_{det} + i_{obs}) + \langle i_{th}^2 \rangle) \cdot \Delta f} \quad (2)$$

The optical network architectures were first studied and compared in terms of achievable phase noise performance, as functions of key component parameters, for both USRO and MLO distributions.

The theoretical predictions were assessed and consolidated in the breadboard demonstrator implemented with optical COTS components that is shown in Fig. 4. The 1.55  $\mu\text{m}$  DFB laser was a commercial device delivering up to 40mW peak optical power with about -160 dBc/Hz relative intensity noise. By implementing impedance matching at the laser input, it was possible to get up to +13 dBm optical power from the laser with a modulation index close to 90%, with less than +10 dBm RF drive power. A commercial compact OFA providing up to +18 dBm output power was used as well. The photo-receivers were selected among products designed and marketed for analogue TV applications.

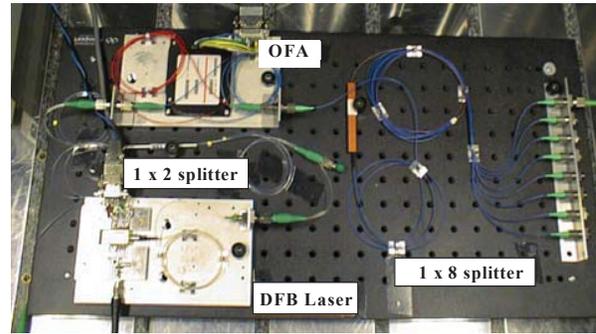


Fig. 4. Optical LO distribution breadboard demonstrator based on COTS components

The main outcomes of these experiments are as follows. The distribution of an Ultra-Stable Oscillator signal with a phase noise floor at -150 dBc/Hz can be achieved through an active optical network with optical splitting losses up to 21 dB. In practice, this would allow for the signal distribution to about 64 RF equipment. However, none of the architectures enables to meet the most stringent phase noise floors in the order of -160 dBc/Hz, as sometimes targeted for Ultra-Stable Oscillators. On the contrary, the phase noise floor performances required for the distribution of Master Local Oscillators, i.e. about -130 dBc/Hz, can be met with any of the architectures that were considered.

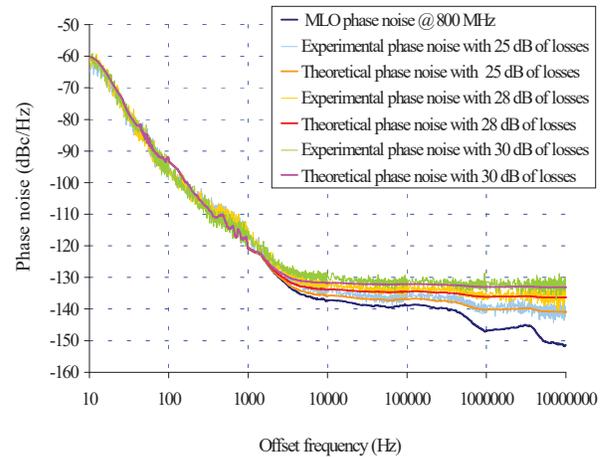


Fig. 5. Experimental and theoretical phase noise performance vs. optical splitting loss in an active MLO distribution

Fig. 5 gives the phase noise performance obtained with an active MLO distribution network. First, it is shown that a good agreement between calculations and

measurements was obtained, thus confirming the validity of our prediction model. Second, it is shown that up to 30 dB optical losses can be accommodated while keeping the phase noise level floor below -130 dBc/Hz. In practice, this would allow for the distribution to more than 256 equipment. Similar results obtained with a passive optical network have shown that up to 100 equipment could be fed from a single high-power DFB laser.

The different architectures were also compared in terms of mass, size, power consumption and reliability with conventional RF implementations. For both USRO and MLO distributions, savings of about 80% on harness mass were found, and of about 60% on the whole sub-system composed of the distributor and the harness. This figure takes the extra power consumption into account.

More advanced solutions were also investigated in order to improve the phase noise floor performance and to meet the most stringent requirements put to USRO distribution. It turns out that Injection-Locked Photo-Oscillators (ILPO) may be used in place of conventional photo-receivers. Actually, such a device naturally filters the signal far from the carrier, thus removing noise added by the optical link. In addition, an optically-controlled oscillator maintains the output RF power at a constant level. This is an interesting feature for the reference frequency delivery network. Equation (3) derived from Kurokawa's theory [4] gives an expression of the output phase noise spectral density of a synchronised oscillator, versus the input signal phase noise  $S_{\phi_{input}}$ , the free running oscillator phase noise  $S_{\phi_{free}}$ , the locking bandwidth  $f_{lock}$  and the offset from the carrier  $f_m$ .

$$S_{\phi_{sync}} = \frac{1}{1 + \left(\frac{f_m}{f_{lock}}\right)^2} \cdot S_{\phi_{input}} + \frac{\left(\frac{f_m}{f_{lock}}\right)^2}{1 + \left(\frac{f_m}{f_{lock}}\right)^2} \cdot S_{\phi_{free}} \quad (3)$$

Some preliminary experimental results obtained with a 10 MHz ILPO-based optical link are reported in Fig. 6. They show that a phase noise floor of about -165 dBc/Hz was obtained above 10 kHz offset, that remained constant for any optical loss used in the experimental set-up. At lower offset frequencies, the phase noise behaviour is related to the accumulation of all the phase fluctuation contributions in the link (respectively from the reference oscillator, the laser, the photodiode, the amplifier, the quartz filter) and to the ILPO synchronisation bandwidth.

The calculations based on the modelling approach given by Eq. (3) were found in agreement with the experimental results for any optical loss tested in the link [4] [5].

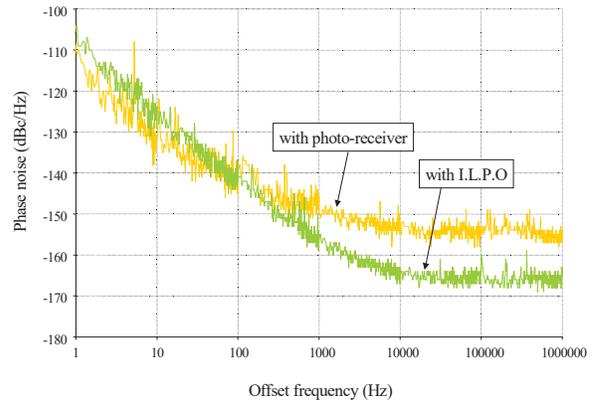


Fig. 6. Comparison of phase noise performance for USRO distributions using a photo-receiver (orange) or a photo-oscillator (green)

### 3. OPTICAL DISTRIBUTION OF MICROWAVE LOCAL OSCILLATORS

The optical distribution of local oscillators in the microwave frequency range will also find application in broadband telecommunication payloads.

As a matter of example, Fig. 7 shows the block diagram of an advanced receive antenna concept making use of digital beam-forming to provide re-configurable multiple-beam coverage. The up-link microwave signals received at each antenna array element need to be frequency down-converted and transmitted to centralised fast analogue-to-digital converters (ADC). Once digitised, the input signals may be processed appropriately so as to form any set of antenna beams on demand. This concept may be applied to various arrayed antenna architectures, but in any case, their implementation in Ka-band will impose to reduce the pitch of the receiver array down to the centimetre range.

In such conditions, it is clear that small size, low mass and low power dissipation at the antenna element side become critical requirements. Optical solutions are thus good candidates for distributing local oscillators directly in the microwave range. Well above LO distribution, frequency mixing with the microwave input signal can be performed as well, as it is shown in Fig.7. Each antenna receiver may include an electro-optic intensity

modulator that is fed by the photonic local oscillator on one hand, and driven by the received microwave signal on the other hand. First, the electro-optical modulator enables to transfer the microwave signal (e.g. in Ka-band) onto an optical carrier with minimum power required. Second, as the optical signal at the modulator output includes frequency compounds at intermediate frequencies, it performs frequency-down-conversion as well. Unwanted frequency compound are filtered out after detection at the optical link output.

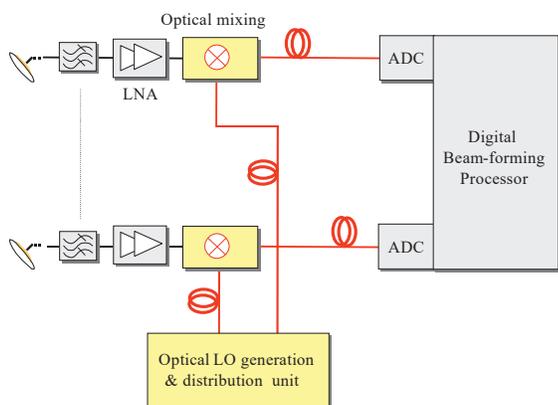


Fig. 7. Block diagram of an advanced multi-beam antenna concept with optical LO distribution, optical mixing and digital beam-forming

The LO generation and distribution unit required in such applications has to include the means to produce a microwave LO signal, in the 25-30 GHz range, under optical form, with high enough power and low phase noise, and to deliver it to a large number of antenna receivers.

The transfer of a microwave signal onto an optical carrier through direct current modulation of a laser diode is typically limited to frequencies below 15 GHz. In practice, it is even less, since the modulation depth decreases rapidly as the modulation frequency increases, thereby drastically reducing the carrier-to-noise ratio at the optical link output. At such high frequencies, one may make use of external electro-optical intensity modulators that have been developed up to 40 GHz for high bit-rate transmission on ground.

Optical heterodyning refers to a number of techniques, all based on the interference of two optical carriers onto a photodiode to generate a microwave or millimetre-wave frequency. For example, two optical carriers at

1550 nm with a wavelength spacing of 0.25 nm that fall on a high-bandwidth photo-detector generate a beat frequency of about 30 GHz. This technique is in principle only limited by the photodiode response. By implementing an optical phase-locked loop (OPLL), it is possible to lock the phase of one laser onto the phase of the other, and thus to drastically reduce the phase noise resulting from the laser beat linewidth. So-called dual-frequency lasers are diode-pumped solid-state lasers, emitting simultaneously two frequency modes (i.e. two wavelengths) that are exactly spaced by the LO frequency. An OPLL is also needed; an error signal may be produced by mixing the beat signal with a low-noise reference oscillator, and fed back to an electro-optical high-birefringence intra-cavity crystal, so as to make the phase of one of the modes track the phase of the other.

Optical double side-band modulation with carrier suppression (DSB-CS) is a very similar LO generation technique. Its principle is represented in Fig. 8. It makes use of a high-power CW laser and a Mach-Zehnder electro-optical intensity modulator that is biased ( $V_{\text{bias}}=V_{\pi}$ ) for minimum optical transmission.

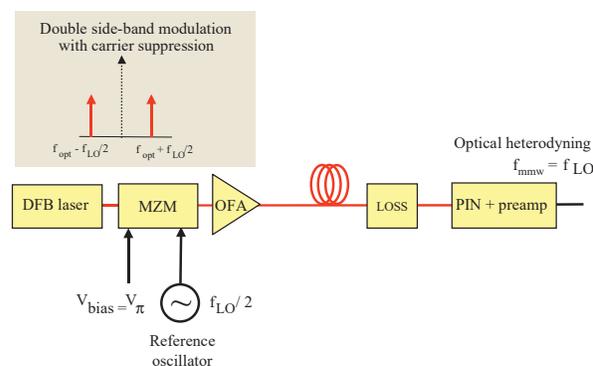


Fig. 8. Microwave LO generation using optical double side-band modulation with carrier suppression (DSB-CS)

In these conditions, when the Mach-Zehnder modulator (MZM) is driven by a low-amplitude signal, only the first two side-bands are present in the optical spectrum of the output signal. Operating the MZM at minimum transmission bias results in optical carrier suppression. If the MZM is driven by a high-purity microwave signal at  $f_{LO}/2$  frequency, then the two optical side-bands are separated by a frequency spacing equal to  $f_{LO}$ . Optical heterodyning at the photo-receiver generates a high-purity microwave signal at  $f_{LO}$  frequency.

Some preliminary experiments were carried out. As a matter of example, Fig. 9 shows the optical spectrum of a 25 GHz photonic LO that was obtained by double side-band modulation at 12.5 GHz of a high-power DFB laser emitting at 1553 nm wavelength.

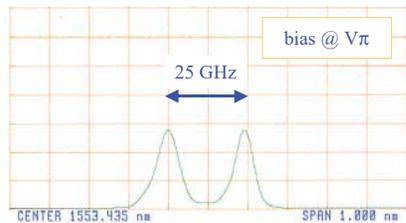


Fig. 9. Optical spectrum of microwave LO using optical double side-band modulation with carrier suppression

For the time being, these LO generation techniques still need a lot of developments but they are anticipated to be very attractive solutions for the upper frequency bands (e.g. Ka, Q and V bands).

#### 4. CONCLUSION

The distribution of high spectral purity signals over fibre optic assemblies and harnesses within future telecommunication payloads has been presented. Major benefits are to be drawn from using optical technologies in such intra-satellite applications : drastic mass and volume savings, suppression of EMC/EMI issues, simplification of cabling and integration steps ...

Theoretical predictions consolidated by experimental results show that master local oscillators in the 1 GHz range can be distributed through active optical fibre networks up to several hundreds of equipment, while exceeding usual phase noise performance requirements. Similarly, passive optical networks would support such a distribution up to one hundred equipment.

Ultra-stable reference oscillators, typically running at 10 MHz, may be distributed to several tens of equipment with phase noise floor below  $-150$  dBc/Hz. It was shown that significant improvements of the optical link phase noise performance could be obtained, if required, through the implementation of Injection Locked Photo-Oscillators.

Finally, an example of advanced antenna concept has been presented that requires the distribution of a high-frequency local oscillator. By performing not only LO distribution but also microwave signal frequency-

conversion and transmission, photonic technologies may bring more than substantial improvements: they just may constitute one of the enabling technologies allowing for the practical implementation of such advanced payload concepts.

#### 5. ACKNOWLEDGMENT

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