# LOW PHASE NOISE FIBER OPTICS LINKS
# FOR SPACE APPLICATIONS

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ABSTRACT

This paper summarises the results obtained on different systems dedicated to the optical distribution of high spectral purity RF and microwave signals in a satellite payload or towards the elements of an active antenna.

First, the interest of the photo-oscillator receiver for these applications in the RF frequency range is pointed out. Then, different emitter configurations are investigated in the microwave range. Finally, an application of these low phase noise microwave links in the field of time-frequency metrology i.e. an ultra high sensitivity microwave frequency discriminator, is addressed.

## 1 – INTRODUCTION

Fiber optics constitute a good alternative to conventional wiring in the distribution of high spectral purity RF signals because despite of added power consumption, they assess a drastic reduction in mass and suppress all problems of EMC/EMI.

Actually, in a microwave-optical antenna (for which a high quality signal has to be distributed on each radiating element) or in future large broadband satellite payloads, the LO (Local Oscillator) distribution network becomes a critical subsystem in terms of mass, complexity, reliability and electromagnetic compatibility issues.

In each of these applications, optical noise can be the limiting parameter to the system performances. Other parameters like optical link losses (that are closely related to the signal to noise ratio) or/and optical link nonlinearities must be also considered.

The present paper focuses on the optical transmission of Local Oscillators. For such an application, the nonlinear behaviour is not of a great importance because it only affects the harmonics of the signal that can easily be filtered. So, in the following, only noise problem is addressed.

Noise in the optical distribution of a frequency reference is divided in two parts: phase noise close to the carrier and an additive noise floor. Both noise contributions must be calculated (or evaluated) prior to the system design. Phase noise close to the carrier is related to the conversion of Low Frequency (LF) fluctuations by the system nonlinearities. A first example is the laser LF amplitude fluctuations that are converted into phase fluctuations of the RF modulating signal. Another one is the phase noise generated by the output RF amplifier, that also results from a conversion of the active device 1/f noise. The additive noise floor is mainly related to the receiver noises, (thermal and shot noise) for a passive optical link with a large number N of receivers (N>20). Contrarily to the conversion noise, this contribution to the phase noise can be easily calculated from the optical link carrier to noise ratio (CNR) [1,2].

The system optimisation requires a reduction of these two noise contributions both at the emitter and at the receiver. The optical transmitter can be directly modulated or externally modulated thanks to an intensity modulator. The receiver is either a pre-amplified photodiode or a sub-system including a phase noise filtering function like a PLL or an injection locked oscillator [2-5]. Choice of components and modulation type are largely dependent on the distributed signal frequency and phase noise requirements. At RF frequencies (under 1 GHz) and in the microwave range up to 5 GHz, direct modulation is generally more efficient. At higher frequencies, a Mach-Zehnder (MZ) modulator or an Electro-Absorption (EA) modulator must be used. In this paper, different low phase noise optical links are described, at 10 MHz, 875 MHz and 9.6 GHz. The system configuration is different in each case, and noise investigations have been performed both theoretically and experimentally. The 10 MHz system is dedicated to the distribution of an Ultra-Stable Reference Oscillator (USRO) used for the LO generation in the frequency converters of a satellite payload. Phase noise specifications are, in this case, particularly stringent. The 875 MHz system is related to the distribution of a Master Local Oscillator (MLO) that is directly used for frequency mixing in a satellite payload. Phase noise specifications are

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less stringent than for the in the 10 MHz distribution. However, same configuration of link is chosen in the two cases. So, direct laser modulation is used and, concerning the receiver, focus is put on a photo-oscillator. Various systems using different modulators are studied in the microwave range. In this case, main efforts are reported on the emitter, and an application of these low phase noise optical links at high frequencies is proposed: an ultra high sensitivity microwave delay line frequency discriminator.

2 – THE OPTICAL EMITTER

The optical source may have a strong influence on the overall noise performance, and must be carefully chosen. Thanks to the large commercial offering in the field of telecommunications laser modules, a laser diode emitting at 1.55 µm is an attractive solution. Moreover, these modules include an optical isolator and a thermal regulation to avoid optical power fluctuations and, consequently, an increase of the Relative Intensity Noise (RIN). Generally, device manufacturers do not specify the laser 1/f noise. Only the high frequency laser noise is specified through the RIN value. RIN determines the absolute limit of the carrier to noise ratio i.e. phase noise floor in the optical link. So, for this type of application a laser featuring a low RIN is required.

In our experiments, the optical emitter is a medium power single mode DFB laser from Mitsubishi at 1.55 µm, with an optical output power of about 13 dBm, a typical high frequency RIN about -160 dB/Hz and a 1/f noise corner frequency in the range of 10 kHz as shown in Fig. 1. The laser is directly modulated for RF applications at 10 MHz and 875 MHz. A link gain about –17 dB is thus provided (at low microwave power) for an optical point to point link with direct detection (photodiode loaded on 50 O). At frequencies higher than 5 GHz, an electro-optic MZM modulator from JDS Uniphase is set at the output of the laser. Another laser module from Mitsubishi that includes an EA modulator with a 3 dB bandwidth above 10 GHz is also used.
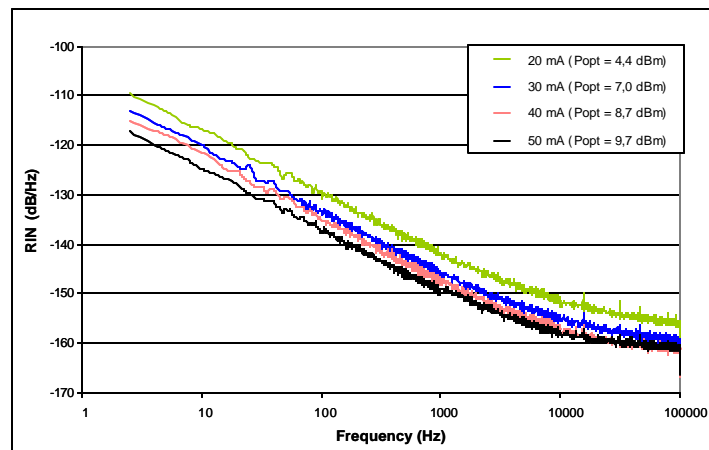


*Fig. 1: Experimental Low Frequency RIN of a Mitsubishi DFB laser*

3 – THE OPTICAL RECEIVER

Classically, an optical receiver is realised with a photodiode followed by an appropriate amplifier. This configuration is used in wideband transmissions, and is well fitted for the distribution of a set of various frequency reference signals. However, the choice of the output amplifier is not easy in a low phase noise application. Generally, because of the losses inherent to the electrical to optic (E/O) and optical to electric (O/E) conversions, a high gain amplifier is used. These high gain amplifiers, and particularly in the microwave range, feature a high level of 1/f phase noise which is added to the signal and which can be the main source of 1/f noise of the system. Moreover, the impedance matching between the photodiode and the amplifier is very often realized in a simple way, by keeping an amplifier 50 Ω input. This is clearly not the best match for the photodiode output impedance, but does not degrade the wideband properties of the photodiode. Only in the RF range, a higher input impedance can be used, providing the noise parameters (and particularly the amplifier phase noise) are under control.

These classical receivers are well fitted for a point to point transmission on a short distance. In this case, the optical losses are weak and the signal to noise ratio is good enough for a low phase noise application, at least for classical specifications (which may already exclude the case of the transmission of an ultra high spectrally pure signal at 10MHz). However, when the signal has to be distributed on several receivers, the optical power received becomes weak and the signal to noise ratio degrades rapidly. A solution in this case can be found in the photo-oscillator approach. The classical receiver is replaced by an oscillator, which naturally locks itself on the incoming RF signal. The output amplifier can be maintained in some cases, between the photodiode and the oscillator input, depending on the power required to efficiently lock the oscillator.

The advantages of the injection locked oscillator are the following : 1) for large offset frequencies phase noise, outside the locking bandwidth, is close to one of the free running oscillator (this phase noise is very low, providing the injection locked oscillator has been optimised versus this parameter) 2) phase noise close to the carrier, inside the locking bandwidth, is the copy of the incoming signal noise 3) the output RF power is kept at a constant level (ex : +10 dBm) at the output of the distribution network.

This approach has been chosen, in our systems, for the 10 MHz and the 875 MHz applications, which will be described in the next paragraph.

## 4 – 10 MHz AND 875 MHz PHOTO-OSCILLATORS

The drawbacks of the optical distribution at 10 MHz are clearly shown in Fig. 2. Actually, for a point to point transmission (one receiver) without any optical losses, phase noise specifications are not met. Moreover, a degradation of the phase noise floor is observed when the signal is distributed over an increasing number of receivers. The injection locked oscillator allows to maintain a phase noise floor at low level close to -165 dBc/Hz above 10 kHz offset, while keeping synchronisation at low offset frequencies (1 Hz or 10 Hz). However, in the 10 Hz to 100 Hz offset range, corresponding to the transition between the two types of noise (injection locked oscillator free running noise and source noise), an increase of phase noise occurs.
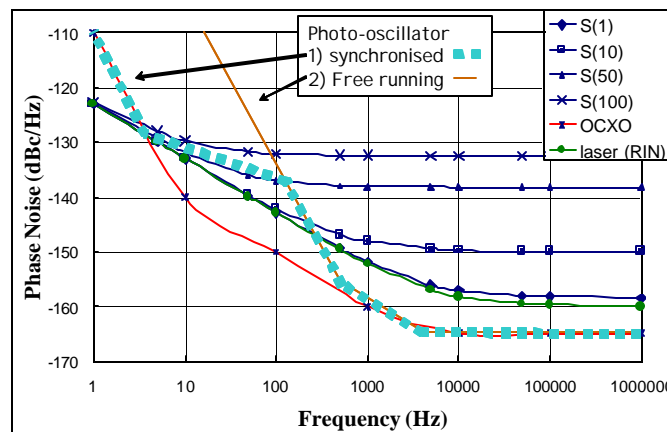


*Fig. 2 : Theoretical phase noise of a 10 MHz optical link. Optical link noise is prohibitive without photo-oscillator for distribution on a high number of outputs (50 or 100). The photo-oscillator allows to recover the USRO phase noise floor by keeping the RF output power at a constant level.*
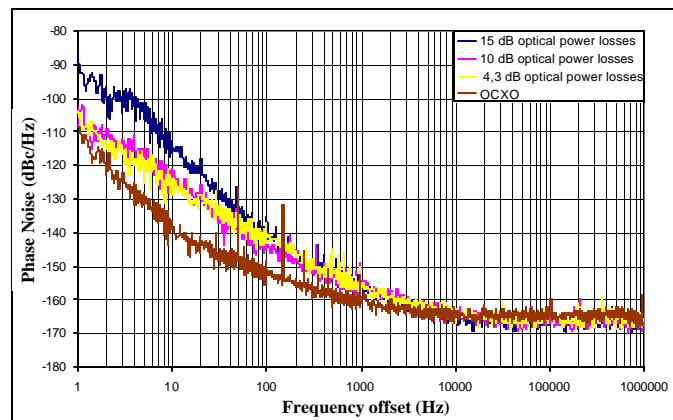


*Fig. 3 : Phase noise measurement of a 10 MHz optical link using an injection locked oscillator in detection chain. The output phase noise is close to the RF input signal phase noise up to 10 dB optical losses. Only a small degradation is observed between 10 Hz and 100 Hz offset. With 15 dB optical losses (distribution on 30 receivers), phase noise increases at 10 Hz, but the performances remain very good.*

The noise levels shown in Fig. 2 have been computed using analytical models [2,3]. These theoretical results have been confirmed experimentally, as shown on Fig. 3 where the phase noise measurement of a 10 MHz optical link using a photo-oscillator is performed and compared to the USRO signal for various optical loss budgets (simulating different distribution numbers).

Such performances have been obtained using a receiver circuit similar to the one given in Fig. 4. It is composed of a two stages circuit including an amplifier and a synchronised oscillator. The oscillator is based on

a low cost AT-cut quartz crystal resonator (designed to operate near 25°C). It has been optimised versus its free running phase noise and injection locking parameters thanks to a CAD approach and Agilent ADS software. Details on design and optimisation of such a circuit, are given in [2] and [6]. Direct calculation of the injection locking bandwidth or of the injection locked oscillator noise is not possible by using ADS. Therefore, a special technique has been implemented for the first parameter [2,6,7] and the injection locking noise has been computed from the free running noise and the locking bandwidth parameters using Kurokawa's equations [2,3,8].



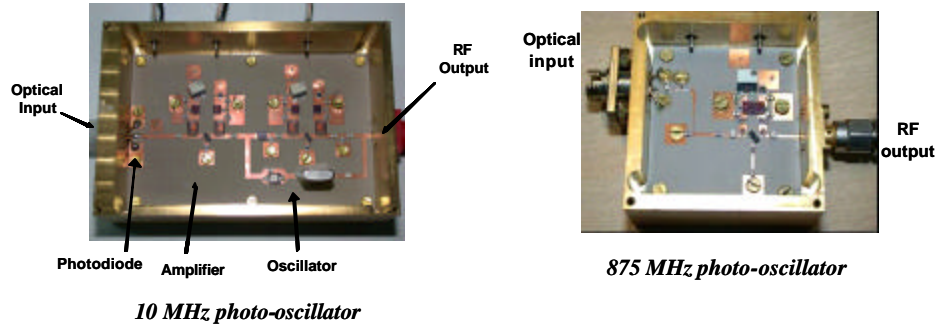10 MHz photo-oscillator      875 MHz photo-oscillator

*Fig. 4: Receiver circuits designed for the 10 MHz ultra low phase noise distribution system (left) and the 875 MHz LO distribution system (right) – realised on Teflon substrate using discrete elements*

The photo-oscillator is the only device that allows to provide phase noise performances compliant with the requirements for the 10 MHz optical distribution system. At higher frequencies, the requirements on the noise floor are not so stringent and a conventional approach (photo-receiver) may be sufficient. A 875 MHz photo-oscillator has however been designed, in order to take advantage of the second interesting feature of a photo-oscillator: the constant RF output power. Contrarily to the last one, the 875 MHz photo-oscillator is not stabilised by using a resonator (most resonators in this frequency range have prohibitive dimensions and/or are difficult to trim) but on the natural resonance of microstrip lines and discrete inductive and capacitive elements. In spite of its low Q factor, this circuit is able to filter the noise far from the carrier (above 200 kHz offset), as shown in Fig. 5.
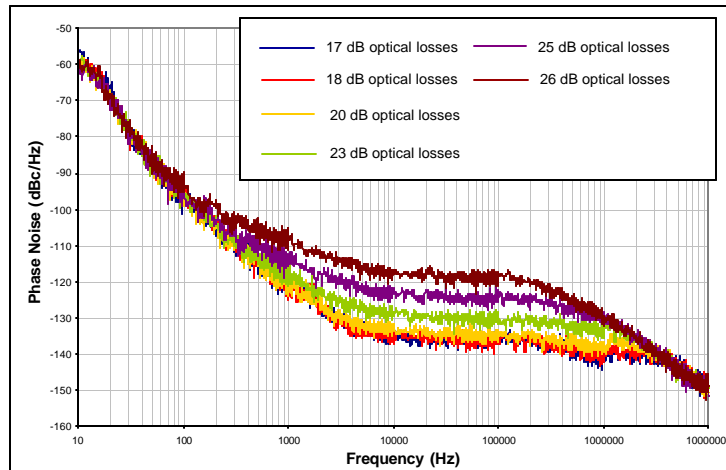


*Fig. 5: Phase noise of the output signal of a 875 MHz optical link using a photo-oscillator*

5 – MICROWAVE OPTICAL LINKS

In our investigations performed at X-band, the optical links emitter is a DFB laser diode followed by a Mach-Zehnder Modulator (MZM) biased at the quadrature. On the receiver side, a wideband photodiode (from Discovery co.) is loaded by a low noise 50 Ω microwave amplifier. The phase-noise floor of this optical link is given by:

$$S_j = \frac{1}{2CNR} \quad \text{(dBc/Hz)}$$

CNR is the optical link carrier to noise ratio.

By neglecting the laser RIN (-160 dB/Hz at 9.6 GHz for our DFB laser), the optical link theoretical phase noise floor is given by:

$$Sj = \frac{2kT + qI_oR_d}{P_{out}}$$

$I_0$ is the measured continuous photocurrent (A), $R_d$ the photodiode load impedance ($\Omega$) and $P_{out}$ the microwave output power (W).

As shown in Fig. 6, an optimisation of this last parameter requires to feed the modulator with a relatively high microwave power in the range of 20 dBm.

Apart from this white noise contribution, a 1/f noise is added to the system. This noise is particularly difficult to simulate, and the experimental approach has been preferred. In the first experiments, the phase noise of our system was close to the phase noise of the high gain amplifier at photodiode output. This device was a commercial amplifier, not optimised for phase noise applications, and could be improved through a specific design. In order to investigate the residual phase noise of the optical link alone, a microwave carrier rejection technique has been used in order to cancel the 1/f phase noise of this output amplifier [9] (Fig. 7,8).
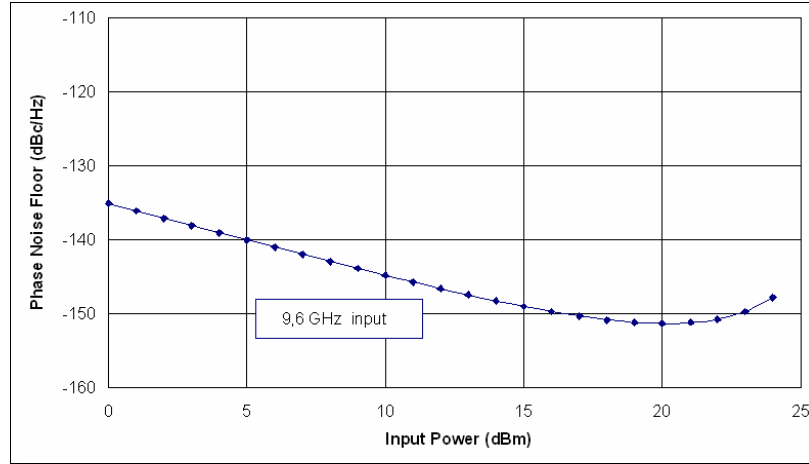


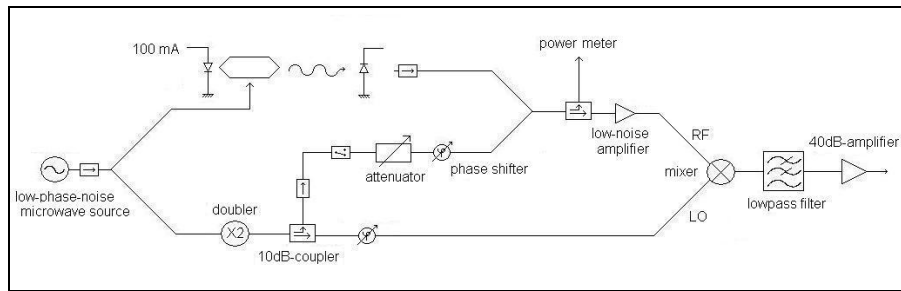*Fig. 6: Theoretical phase noise floor of a 9.6 GHz-optical-link*



*Fig. 7: Phase noise measurement of the microwave optical link, including an interferometer path that cancels the 1/f phase noise of the output microwave amplifier*

The measurement results are shown in Fig. 8 for two different optical links using two different modulation techniques : MZM and EA modulators. The white phase noise floor is correctly predicted by the equation given above. It could be easily improved thanks to an increase of the signal power level on the modulator. Taking into account only the white noise floor, the MZ modulator should be preferred to the EA modulator because of an improved gain performance (and CNR) of about 9 dB. On the contrary, the EA modulator will be preferred if the system integration is mandatory.

The excess phase noise starts at very low frequency offset (about 100 Hz) and a $1/f^2$ shape is observed for this noise instead of a 1/f one. The origin of this last noise contribution is not clear. The conversion of the laser LF RIN should have lead to a 1/f noise (or close to 1/f). We rather suspect some temperature related fluctuations, or even vibrations. Because of its low corner frequency, this last noise contribution can be neglected for many applications, and the improvement of the optical link phase noise will mainly rely on the improvement of the microwave output amplifier phase noise. The design of a high gain and low phase noise amplifier could be the solution for the development of a low phase noise microwave optical link, but this is not an easy task [6]. There

is however one specific application in which the amplifier phase noise can be cancelled and in which the LF excess noise of the optical link will determine the performances of the system: the optical delay line frequency discriminator.
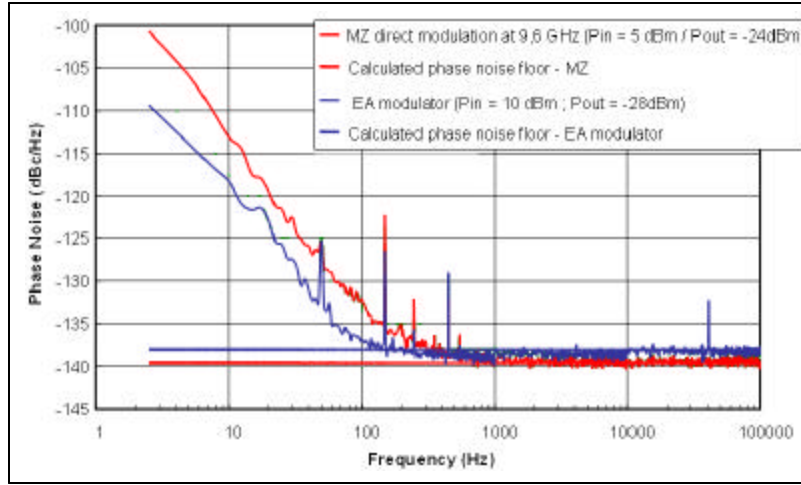


*Fig. 8: Noise measurement of a 9.6 GHz-optical-link using two different modulators (MZ and EA)*

6 – MICROWAVE PHASE NOISE MEASUREMENT USING AN OPTICAL DELAY LINE

The measurement of the phase (or frequency) fluctuations of low phase noise microwave sources has always been a difficult problem. Two different techniques can be used : the active technique, that requires a reference source, and the passive technique, in which the reference is a passive element such as a resonator or a delay line. The problem of the active technique is due to the availability of a tunable high spectral purity reference source, and is generally limited to the performance of the best commercially available synthesisers. The passive technique does not require any external oscillator and is broadband if implemented with a delay line. However, the sensitivity of this last technique is poor, and it is generally used to characterise low stability sources such as VCOs (it is less sensitive to a source drift during the measurement, compare d to the active technique). The moderate sensitivity of the microwave delay line discriminator is due to the use of microwave delay lines, in which the losses increase rapidly with the delay. Because of these losses, the classical length of a delay line at X band is in the range of 10 m. By replacing the microwave delay line by an optical delay line, the line length up is increased up to a few kilometres (Fig. 9). The measurement bench sensitivity is increased in the same proportions . So, the only problem remains the same than the one addressed in paragraph 5: losses and noise caused by the E/O and O/E conversions. With such a measurement bench, the characterisation of any type of microwave source should be possible, including the ultra high spectral purity sources developed for time-frequency metrology.
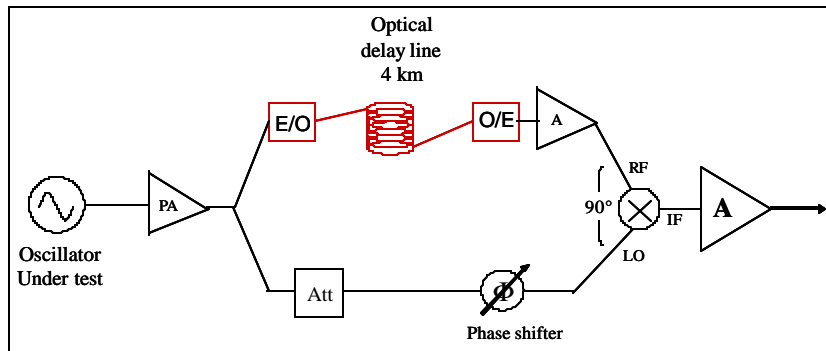


*Fig. 9: Optical delay-line frequency discriminator for phase-noise measurement of microwave sources ; simplified configuration (no interferometry)*

We have realised such a high performance frequency discriminator adding to the measurement bench used to characterise our optical links (Fig. 7) an optical delay line of 2 km or 4 km. By keeping the microwave interferometer path, we should be able to cancel the 1/f noise of the amplifier, and to reach an ultimate performance close to the carrier.

This system is sensitive to the source frequency fluctuations. The sensitivity factor $K_m$ is directly proportional to the delay $\tau$ and is given by:

$$K_m = 2\boldsymbol{p\,t}\;Kj$$

$K_\phi$ is the mixer phase detection sensitivity factor

The source under test phase noise can then be calculated as following:

$$Sj = \frac{S_{\Delta f}}{f_m^2} = \frac{S_{V_{out}}}{(2\boldsymbol{pt}\;Kj\;f_m)^2}$$

with $S_{?f}$ oscillator frequency noise, $S_{V_{out}}$ the measured output voltage noise and $f_m$ the frequency offset (Hz).

The phase-noise floor of such a system can be calculated, assuming that the dominating phase noise is the optical link phase noise described in paragraph 5 (Fig. 8):

$$S_{j\;min} = \left(\frac{1}{2\boldsymbol{pt}\;fm}\right)^2 .S_{j\;optical}$$

However, the close-to-carrier measurement bandwidth is reduced, because the overall measurement bench sensitivity is affected by a $\sin(p.f_m.t)/p.f_m.t$ response which is generally neglected in the case of an electrical line, but which becomes non-negligible in the case of optical delay lines.

The first results obtained with such a phase noise measurement bench are very promising, and compare well with the literature [10]. As shown in Fig. 10, phase noise about -95 dBc/Hz at 100 Hz offset, or -143 dBc/Hz at 10 kHz offset has been effectively measured, using as a test source a 100 MHz ultra high spectral purity quartz crystal oscillator (Wenzel co., premium SC) directly multiplied up to the measurement frequency (4 GHz). It is interesting to point out that the measurement bench performs in the same way at higher frequencies and should give the same performances. It will be only limited by the MZM bandwidth (close to 15 GHz).
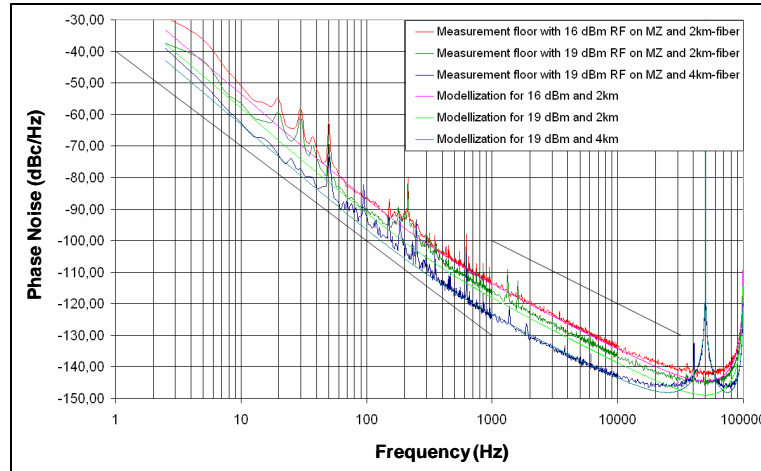


Fig.10: Theoretical and experimental and measured phase-noise floors for the microwave optical delay line discriminator. The measurement is performed at 4 GHz with an ultra high spectral purity quartz source

7 – NEW APPLICATIONS OF LOW PHASE NOISE MICROWAVE LINKS

Apart from the signal distribution applications, described in paragraph 1, or the metrology application in paragraph 6, new perspectives are today opened by the availability of ultra high Q optical resonators with reduced dimensions, such as spherical or toroidal microresonators [10]. These devices could be used in place of the fibre optic delay line in a frequency discriminator, or directly as the frequency reference device in an optical-microwave-oscillator, while keeping reduced dimensions for the system. However, these applications require the development of a specific technology allowing the hybrid integration of the optical resonator, the optical coupling lines and the microwave active devices.

## 8 – CONCLUSION

Photonics technologies offer major benefits in development of future communication equipment in satellite payloads, with high performance and low mass/size requirements. They could also help, in a near future, to reach a higher level of performance in terms of phase noise for the microwave sources. These developments are only possible if the phase noise of the optical links is under control.

In this paper, various optimised phase noise optical systems have been presented both at RF and microwave frequencies. The photo-oscillator receiver has been chosen in order to optimise the phase noise floor of the RF links, and to ensure a constant power level at the output of the reference frequency distribution network. As an example, a phase noise floor of -165 dBc/Hz has been reached at the output of a 10 MHz receiver using low cost devices. At microwave frequencies, investigations have been performed with two different emitters and the conditions to reach high phase noise performances have been explained. Finally, an application in the field of time-frequency metrology has been described, and an ultra low phase noise microwave source has been successfully measured in such a configuration.

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