Proceedings of the 2003 IEEE International Frequency Control Symposium and PDA Exhibition
Jointly with the 17th European Frequency and Time Forum

A LOW PHASE NOISE OPTICAL LINK FOR REFERENCE OSCILLATOR SIGNAL DISTRIBUTION

G. Quadri[1], H. Martinez-Reyes[1], B. Benazet[2], O. Llopis[1]
[1]LAAS-CNRS, 7 Avenue du Colonel Roche, 31077 Toulouse, Cedex 04, France
[2]Alcatel Space Industries, 26 Avenue J. F. Champollion, B.P. 1187, 31037 Toulouse, France

Abstract – **Various circuits dedicated to high spectral purity signal transmission over fiber optics are presented. The main application investigated is the 10 MHz reference frequency distribution in various subsystems of a satellite payload. Our work has been focused on the receiver and more particularly on the RF signal conditioning at the receiver level, in order to minimize the phase noise degradation due to the optoelectronics elements. The advantage of the photo-oscillator solution has been emphasized.**
***Keywords* - Optical link, Synchronized Oscillator, Photo-Oscillator, OCXO, phase noise, Optic fiber.**

I. INTRODUCTION

Optic fibers constitute an attractive alternative to conventional wiring for numerous analog applications [1,2]. Indeed, in addition to its small size and low mass, the fiber does not interfere with electronic devices and provides an excellent isolation of the transmitted signal. One of the targeted applications of our work is the reference frequency signal distribution to various subsystems of a telecommunications satellite (see Fig. 1). Another application could be remote synchronization and control of antennas.

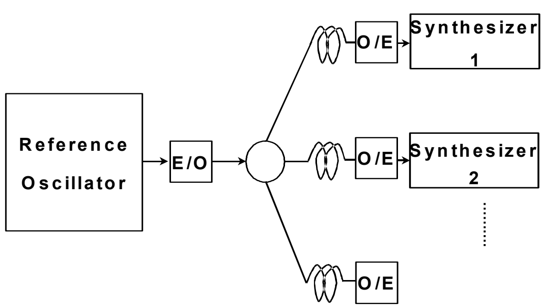

Fig. 1: Optical link for Reference Oscillator signal distribution

However, to meet the system requirements of our project, the fiber optics link should not degrade the spectral purity of the signal (i.e. its phase noise). To this purpose, the Injection Locked Photo-Oscillator (I.L.P.O.) [3,4] is an efficient approach which naturally filters the signal far from the carrier, thus removing the additional noise due to the optical link. Moreover, an optically controlled oscillator delivers a constant output power, which is an interesting feature for a clock or reference frequency delivering network.

The application goal for the 10 MHz link is the reference frequency distribution in a telecommunications satellite. The signal from the ultra stable quartz crystal oscillator should be transmitted with no degradation of its phase noise, and this is a very stringent requirement.

II. PHOTO-OSCILLATOR; THEORY

The indirect optical injection locking can be efficiently described by combining the classical noise modeling of an optical link [5,6] with the theory of injection locked oscillators [7,8,9]. The only questionable point is probably in the interaction between the two systems: has the photodiode an effect on the oscillator noise? But if the two systems are isolated in some way from one to another, this approach should apply. The following equation (1) (from Kurokawa's theory [7]), is an expression of the output phase noise spectral density of an injection locked oscillator (I.L.O.), versus the input signal phase noise $S_{\varphi\ input}$, the free running oscillator phase noise $S_{\varphi\ free}$, the locking bandwidth f_{lock} and the offset from the carrier f_m.

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

The phase noise spectral density at the oscillator input is composed of the phase noise contribution of the signal to be transmitted (not considered here) and of the optoelectronic noise. The later is mainly due to the laser noise and to the photodiode noise. A simple model to describe this input phase noise is represented by equation (2)

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

RIN_{LF} being the relative intensity noise at 1 Hz, K the 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 at the input of the photodiode P_{det}, the photodiode sensitivity S, the dark current i_{obs}, the laser modulation index m, the relative intensity noise RIN at high frequency and the electron charge q. Its expression is given by

$$CNR = \frac{P_{\det}^2\, S^2\, m^2}{2\,(P_{\det}^2\, S^2\, RIN + 2\,q\,(S\,P_{\det} + i_{obs}))} \quad (3)$$

The other input parameters required to compute the phase noise using equation (1) are the I.L.O. locking bandwidth f_{lock} and the I.L.O. free running phase noise $S_{\varphi\ free}$.

The I.L.O. free running oscillator phase noise spectral density $S_{\varphi\ free}$ is calculated using equation (4) and the following parameters: the transistor residual phase noise $S_{\varphi\ transistor}$, the quartz resonator residual phase noise $S_{\varphi\ quartz}$, the quartz resonator loaded Q_L quality factor, the free running oscillation frequency f_0 and the offset frequency from the carrier f_m. All these parameters are obtained experimentally. This expression is similar to Leeson's [8] approach.

$$S_{\phi\ free} = \left[S_{\phi\ transistor} + S_{\phi\ quartz}\right] \cdot \left[1 + \frac{f_0^2}{4Q_L^2} \cdot \frac{1}{f_m^2}\right] \qquad (4)$$

The I.L.O. locking bandwidth f_{lock} is calculated using Adler's [9] expression (equation (5)) from the RF signal power P_{in} at the input of the oscillator and the RF signal power P_{out} at the output of the oscillator.

$$f_{lock} = \frac{f_0}{2 \cdot Q_L} \cdot \sqrt{\frac{P_{in}}{P_{out}}} \qquad (5)$$

The I.L.O. input power P_{in} is obtained from an RF model of the optical link (including the optical losses, the photodiode sensitivity, the optical power delivered by the laser and the photodiode load impedance). The I.L.O. output power P_{out} is either simulated (using a nonlinear model of the RF oscillator) or simply measured on the free running oscillator.

In order to optimize the phase noise of such a circuit, it is essential to optimize the second term of the equation (1), which corresponds to the synchronized oscillator residual phase noise. This can be done by optimizing the free running oscillator phase noise and the locking bandwidth. Both parameters are difficult to simulate, but a CAD approach can lead to interesting results providing a precise enough model is available of the oscillator active device. Another efficient approach, which may be used complementarily with CAD, is to implement a device selection procedure using a residual phase noise test bench which will help in choosing the transistor and eventually the resonator.

The above described modeling approach has been used to design our receivers, and to analyze the phase noise results. However, a prior requirement to design such an optical link is to choose the light source.

III. Optical-link; the emitter

The optical source has a strong influence on the overall noise performance, and must be chosen carefully. 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 RIN. The RF or microwave signal can then be applied directly to the laser diode (direct modulation) or to a Mach-Zehnder modulator (indirect modulation). In our study, the direct modulation configuration has been chosen, mainly because it is simpler and cheaper than the indirect modulation.

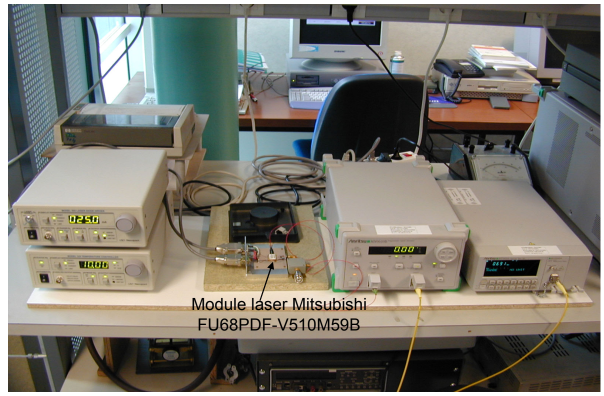

Fig. 2: View of the emitter

The device manufacturers do not specify the laser 1/f noise, and only the high frequency laser noise is specified through the relative intensity noise parameter (RIN). However, it is this RIN which may determine the phase noise far from the carrier, and a laser featuring a low RIN value should be chosen. This has led us towards a medium power single mode DFB laser: a Mitsubishi 1.55 µm laser module, with an optical output power of about +10 dBm and a typical RIN of -155 dBc/Hz (0.5 GHz to 3 GHz). Another laser module, Alcatel 1905 LMI, with an higher maximum output power of 15 dBm, has been also used in a second time.

III. Optical-link; the RF receivers

The 10 MHz signal of an oven controlled crystal oscillator features very good spectral characteristics. The goal is to transmit such a signal with almost no degradation of its SSB phase noise. The laser RIN already prevent this transmission by creating a noise floor already higher than the reference OCXO noise floor.

We have evaluated three different configurations for the receiver in order to obtain the best possible conditioning of the RF signal: photodiode + amplifier, photodiode + amplifier + filter and the I.L.P.O. (see Fig. 3, 4, 5).

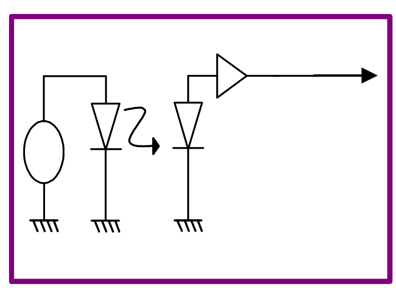

Fig. 3: Analog optical link with amplifier

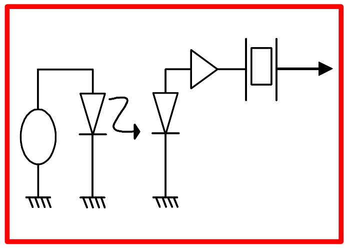

Fig. 4: Analog optical link with RF amplifier and quartz filter

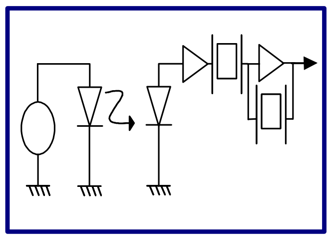

Fig. 5: Analog optical link with RF amplifier, quartz filter and photo-oscillator

Several topologies have been studied for the injection locked oscillator and the circuits that, if necessary, could precede it. But the circuit topology is not the only problem. A low phase noise design must be based on low noise devices and a procedure has to be implemented for devices selection. In our case, residual phase noise measurements have been carried out to this purpose, using the 10 MHz reference source Wenzel Premium SC 501-04609. Then, a silicon BJT transistor has been chosen for the oscillator active element. This transistor, with specific polarization techniques [10], features a very low 1/f noise level and a very low phase noise floor. Concerning the feedback loop resonator, an AT-cut quartz crystal resonator has been chosen.

Both devices feature an excellent residual phase noise level, and particularly far from the carrier (see Fig. 6 and Fig. 7). The AT-cut quartz crystal resonator loaded Q_L factor is about 14000 with 1,5 dB of power transmission loss. Higher loaded Q_L factor is available with SC cut resonators. However, these resonators have to be temperature controlled and the receiver cost, size and consumption increase would be prohibitive in this case. Using such a device is undesirable for spatial applications.

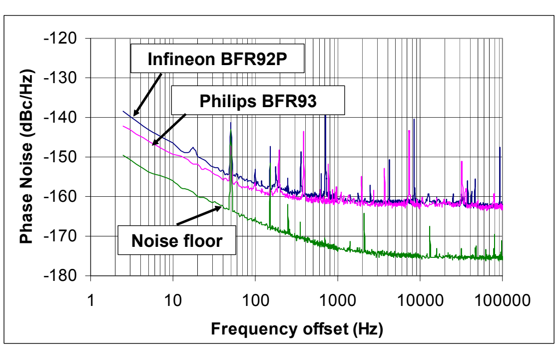

Fig. 6: 10 MHz residual phase noise measurement for two Si BJT transistors

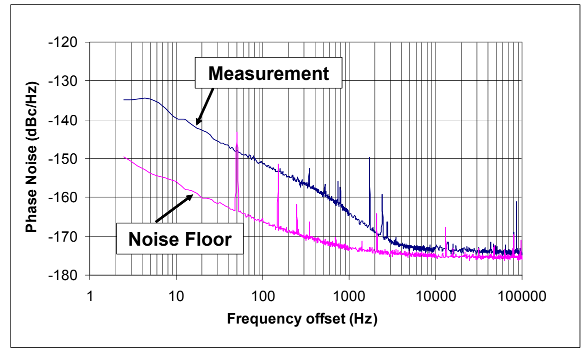

Fig. 7: 10 MHz residual phase noise measurement of the AT-cut quartz resonator measured with two identical resonators

The optical link preliminaries characterizations have shown a constant frequency response from few MHz to 1 GHz: This corresponds to the photodiode bandwidth (Thorlabs FGA04). The optical link RF gain is about -16 dB with no optical loss and loaded onto 50 Ω. To increase the RF signal power at the receiver output, an amplifier has been added directly after the photodiode. Such an amplified RF optical link has been measured and a residual phase noise floor of about -140 dBc/Hz has been observed (see Fig. 8). This phase noise floor is prohibitive for our application. It is probably related to the laser RIN, which is a little bit degraded in this experiment by the temperature control of the laser. In order to reduce this phase noise floor, in addition to improve the laser performance, the solution at receiver level consists in the output signal filtering. This can be simply performed by adding a resonator at the output or using the synchronized oscillator approach.

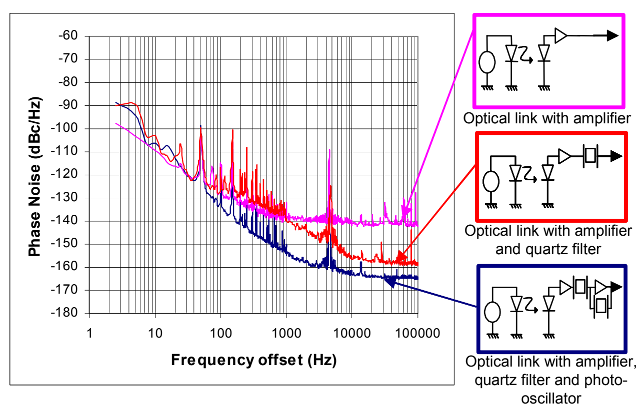

Fig. 8: 10 MHz optical link preliminary residual phase noise measurements for different receiver configurations. These measurements have been realized with the Mitsubishi Laser Module and with optical losses about 3 dB.

As shown in Fig. 8, the improvement due to the quartz filter is already important compare to the conventional receiver, but the best result is obtained with a synchronized oscillator placed at the end of the link.

Another concern is the increase of the optical link SSB phase noise with the increase of the optical losses or the optical distribution factor (number of receiver modules to be synchronized). Once again, the I.L.P.O. approach is the most interesting because the phase noise floor is kept despite the increasing of the optical losses. Moreover, the RF output is also held at a constant level.

The fiber optic link with the I.L.P.O. configuration features a constant output power of +9 dBm and a phase noise floor (above 10 kHz offset) of about -165 dBc/Hz

IV. THE 10 MHZ OPTICAL LINK FINAL TEST

An oscillator phase noise measurement bench using a PLL technique and two high spectral purity 10 MHz OCXO has been selected for the final characterization of the optical link. This characterization has been performed with another laser module and another photodiode followed by a Trans-Impedance Amplifier (T.I.A). The optical output power is +7.3 dBm and the modulation index of about 0,8.

The 10 MHz optical link phase noise measurements for the three different receiver configurations have been performed (see Fig. 9).

Moreover, in the case of the third configuration (I.L.P.O. circuit), the phase noise measurements have been performed versus different optical power losses which simulate the RF signal distribution over a different number of receivers (see Fig. 10). 10 dB optical losses are equivalent to a distribution on 10 receivers and 15 dB, on about 30 receivers.

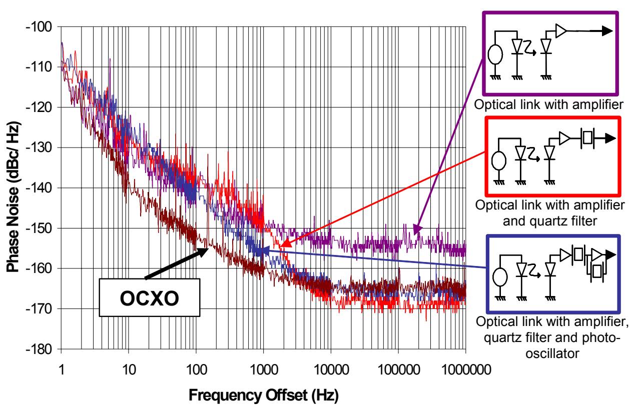

Fig. 9: 10 MHz optical link phase noise measurement for different receiver configurations using the PLL technique. These measurements have been realized with the Alcatel Laser Module and with 4.3 dB optical losses in the link.

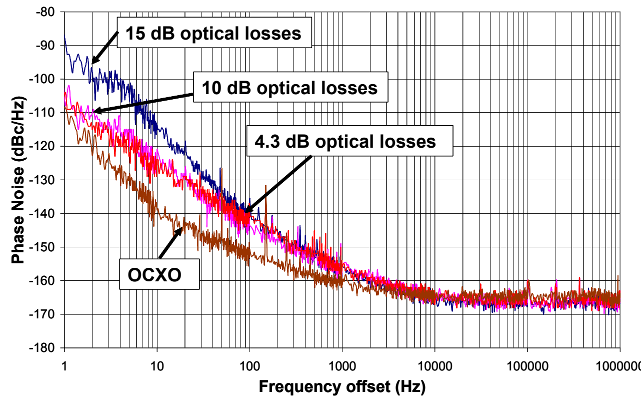

Fig. 10: 10 MHz I.L.P.O. optical link phase noise measurements versus the optical losses. These measurements have been realized with the Alcatel Laser Module.

The results obtained for the 10 MHz I.L.P.O. optical link have shown a phase noise floor of about -165 dBc/Hz, above 10 kHz offset, which remains constant for any optical loss used in the experimental set up. At lower offset frequencies, the phase noise behavior relies on all the phase fluctuations sources (reference OCXO, laser, photo-diode, amplifier, quartz filter) in the link and on the I.L.O. synchronization bandwidth.

V. THE 10 MHz I.L.P.O. OPTICAL LINK: MODEL TO EXPERIMENT COMPARISON

The modeling approach described in section II has been implemented using Mathcad software to compare the phase noise experimental results obtained in the measurement tests with the synchronized oscillator phase noise theory.

The theoretical calculations agree with the measurement results for any optical loss budget used in the tests (see Fig. 11 to Fig. 13).

Many phase fluctuations sources are presents in the optical RF link and they have been considered in the model in order to accurately determine the close to carrier phase noise behavior of the optical link.

The model and the experimental results are in good agreement and show that the 10 MHz I.L.P.O. optical link phase noise only depends on the free running oscillator phase noise behavior.

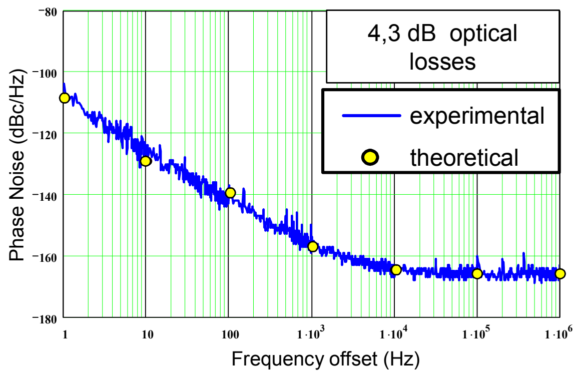

Fig. 11: 10 MHz I.L.P.O. optical link phase noise simulations versus measurements with 4,3 dB optical losses.

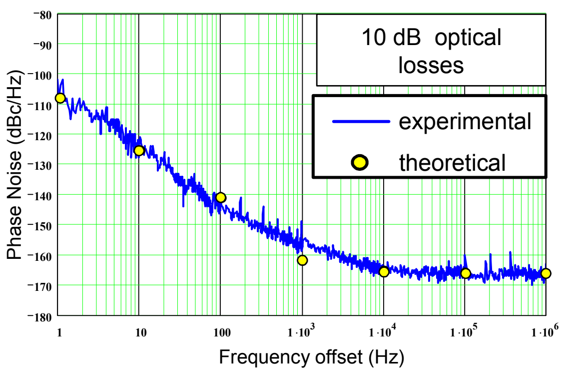

Fig. 12: 10 MHz I.L.P.O. optical link phase noise simulations versus measurements with 10 dB optical losses.

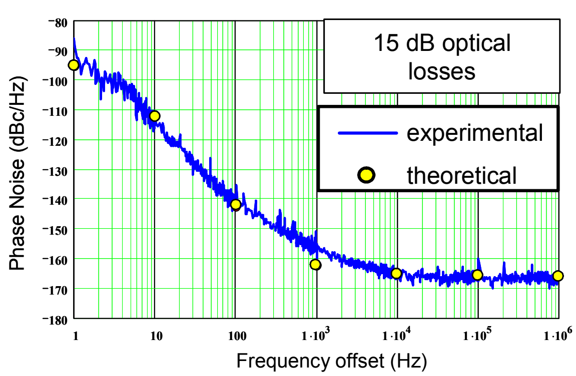

Fig. 13: 10 MHz I.L.P.O. optical link phase noise simulations versus measurements with 15 dB optical losses

VI. Conclusion

Many different receiver configurations have been studied for 10 MHz reference signal distribution with an optical link. The most interesting solution is represented by the I.L.P.O. optical link that provides a phase noise floor of about -165 dBc/Hz and an RF signal output of about +9 dBm. Both characteristics remain constants for any optical loss in the link.

A theoretical model of the I.L.P.O. optical link has been developed and a good agreement has been observed between this model and the experimental data.

Acknowledgment

This work has been partly supported by the French National Space Agency (CNES).

References

[1] G. F. Lutes, R.T Logan *« Status of frequency and timing reference signal transmission by fiber optics »* 1991 IEEE Int. Freq. Control. Symp, pp. 679-686.

[2] R.T Logan, G. F. Lutes *« High stability microwave fiber optic systems»* 1992 IEEE Int. Freq. Control. Symp, pp. 310-316.

[3] A. S. Daryoush, *« Optical synchronization of millimetre-wave oscillators for distributed architectures»* IEEE trans. on MTT, vol 38, n° 5, may 1990, pp. 467-476.

[4] R. D. Esman, L. Goldberg, J. F. Weller, *"Optical phase control of an optically injection locked FET microwave oscillator"* IEEE trans. on MTT, vol 37, n° 10, oct. 1989, pp. 1512-1518.

[5] A. J. Seeds, *"Microwave Photonics"*, IEEE trans on MTT, vol 50, n° 3, march 2002, pp. 877-887.

[6] G. P. Agraval, *"Fiber optic communication systems"*, Wiley Edition, 1997.

[7] K. Kurokawa, *"Noise in synchronized oscillators"*, IEEE Trans. on Microwave Theory and Tech., vol 16, n° 4, april 1968, pp. 234-240.

[8] D.B. Leeson, *"A simple model of feedback oscillator noise spectrum"*, Proc. Of the IEEE, vol n°54, n° 2, feb. 1966, pp. 329-330.

[9] R. Adler, *"A study of locking phenomena in oscillator"*, Proc. IRE, vol. 34, n° 6, june 1946, pp. 351-357.

[10] O. Llopis, G. Cibiel, Y. Kersale, M. Regis, M. Chaubet, V. Giordano *« Ultra low phase noise sapphire SiGe HBT oscillator »* IEEE Microwave and Wireless Components Letters, vol.12, n°5, may 2002, pp.157-159