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► **To cite this version:**

Houda Brahimi, Pierre Lacroix, Olivier Llopis. Optimization of a microwave frequency discriminator based on an optical delay line. International Topical Meeting on Microwave Photonics, Oct 2009, Valence, Spain. pp.4. hal-00410793

HAL Id: hal-00410793

<https://hal.science/hal-00410793>

Submitted on 24 Aug 2009

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Optimization of a microwave frequency discriminator based on an optical delay line

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Abstract—A microwave frequency discriminator based on an optical delay line is studied. This system features a noise floor below -150 dBc/Hz at 10 kHz offset. The noise mechanisms are studied in order to determine the main noise contributors.

I. INTRODUCTION

Optical delay lines or resonators are ideal devices to get an ultra high Q factor at microwave and millimeter wave frequencies. As an example, optical microwave oscillators [1] take benefit of these devices, to reach an ultra high spectral purity. Another application example is the microwave frequency discriminator based on an optical delay line [2,3], which can be used to characterize ultra high spectral purity oscillators, such as optical microwave oscillators. Also, a high spectral purity oscillator can be realized with such a system, simply by locking on it a conventional microwave oscillator. In this case, the source phase noise becomes the phase noise floor of the discriminator. The advantage of this approach rely in the fact that this system does not require a loop gain higher than unity at microwave frequencies, which means that a microwave amplifier is not absolutely necessary in the system. Indeed, the microwave amplifier is, very often, the main phase noise source in microwave optical systems [3].

In this paper, a microwave frequency discriminator based on a 4 km fiber optics delay line is studied. After a brief description of the system, which uses a classical topology, the measurement of its noise floor is performed using an ultra low phase noise source : a sapphire oscillator. Then, the noise contribution of each element of the system is investigated.

II. OPTICAL DELAY LINE MICROWAVE FREQUENCY DISCRIMINATOR : SYSTEM DESCRIPTION

The optical delay line frequency discriminator is a classical microwave delay line discriminator in which the microwave delay line is replaced by a long optical delay line. The system is depicted in Figure 1 : a low phase noise mixer compares the signal coming from a reference path to the one coming from the delay line, in which the oscillator under test frequency noise has been converted into phase fluctuations. A phase shifter, in the reference path, allows a 90° average

phase between the two signals in order for the mixer to perform in phase detection mode. Then, the output signal is amplified and analyzed on a FFT spectrum analyzer.

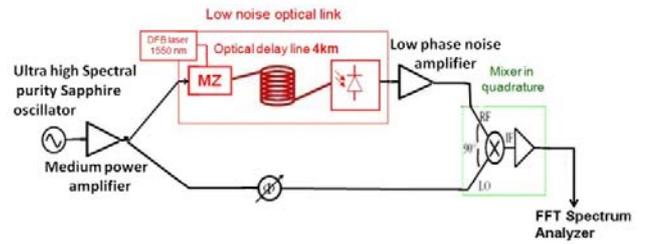


Figure 1. Optical-microwave frequency discriminator test configuration

The discriminator sensitivity being proportional to the time delay, the improvement resulting from the use of optics in place of a microwave coaxial cable is in the range of a few hundred to one thousand. This would lead to an improvement of the phase noise floor between 40 dB to 60 dB, if the other elements of the system were unchanged. Unfortunately, the use of optics adds some extra noise, both at low offset frequencies (modulation 1/f noise) and at higher offset frequencies (microwave additive noise).

The additive microwave phase noise is the degradation of the signal to noise ratio due to the losses in the optical link. This noise contribution can be estimated using the following formula [3,4] :

$$L(f)_{additive} = \frac{P_{opt}^2 S^2 RIN + \frac{4kT}{R_d} + 2qSP_{opt}}{P_{opt}^2 S^2 m^2}$$

where P_{opt} is the optical power on the photodiode, S is the photodiode sensitivity, RIN is the laser relative amplitude noise (natural value), k is the Boltzman constant, T the absolute temperature, R_d the photodiode load, q the electron charge and m the modulation index. Generally, the losses in the optical fiber spool are lower than the modulator losses (0.2 dB/km, with a total length of 4 km). This means that the laser RIN dominates in this equation and that it is mandatory to choose a laser with an extremely low RIN . For this reason, we use an EM4 DFB laser, featuring a 60 mW optical output power and a measured microwave RIN lower than

-160 dB/Hz at 10 GHz. We also try to maintain a high modulation index using a medium power amplifier (25 dBm output) which does not impact on the phase noise performance for two reasons : it is located before the splitting of the two path and its additive phase noise is very low (AML amplifier specified for low phase noise).

In most systems of this type, the photodiode output is amplified before performing the phase detection. This second amplifier is located at a very critical point of the system and its phase noise can be directly detected by the mixer. In a preceding version of our system, we have used a microwave carrier cancellation approach in order to cancel the $1/f$ noise of this amplifier [3], but this result in a system which is difficult to use and which is also very sensitive to vibrations. In this new system, a simpler configuration has been used : this amplifier has been removed and the photodiode is directly connected to the mixer RF port. This reduces of course the mixer phase detection factor K_ϕ , but our K_ϕ is still relatively high (~ 100 mV/rad) thanks to the high modulation index of the optical link.

III. SYSTEM EVALUATION WITH A MICROWAVE OSCILLATOR BASED ON A 5 GHz SAPPHIRE RESONATOR

The phase noise floor measurement of a delay line discriminator is quite difficult. The classical approach suppresses the delay, in order to cancel the sensitivity of the system to the source phase noise. This technique is valid for classical microwave frequency discriminators. However, in the case of the microwave-optical frequency discriminator, some noise processes may occur in the optical delay line itself, and it is thus important to characterize the system including this long delay line.

The only technique in this case is to use an ultra high spectral purity source, such as a sapphire microwave oscillator, to check the ability of the microwave-optical measurement bench to characterize such a source. An oscillator of this type at 4.87 GHz is available in our laboratory. It had been realized with a low phase noise SiGe amplifier and a WGM sapphire resonator ($Q_L \approx 60,000$) [5].

The phase noise of this oscillator has been measured close to the carrier using an Agilent E5052 phase noise measurement bench. Although the E5052 is based on conventional microwave sources, it uses a full cross correlation approach (two reference sources) which allows the measurement of ultra low phase noise sources at offset frequencies lower than 1 kHz.

Then the oscillator has been connected to the microwave optical frequency discriminator and the result is plotted in Fig. 2. As shown, the sapphire oscillator is effectively measured by the microwave-optical discriminator, with a better precision and on a wider range of baseband frequencies than with the Agilent system, although the first spurious peak of the 4 km delay line is clearly visible on this plot around 53 kHz, and prevents phase noise measurement in its vicinity.

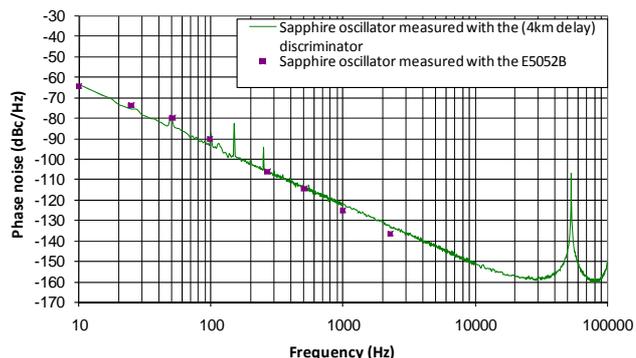


Figure 2. Phase noise of a 4.87 GHz sapphire oscillator measured with the optical delay line frequency discriminator, and using an Agilent E5052 cross-correlation phase noise measurement bench

As shown on this graph, the measured phase noise is -151 dBc/Hz at 10 kHz. It is difficult to know if this value corresponds to the oscillator under test phase noise or to the frequency discriminator noise floor, but it is already very low and beyond to the state of the art of these systems [3]. Our goal now is to understand which device still limits this performance, particularly in the $1/f$ region.

IV. ANALYSIS OF THE DIFFERENT NOISE CONTRIBUTIONS

The noise contributions in such a system comes from either the optical devices or the microwave devices, and is different whether the devices are located between the two arms of the phase detector or at the system input. The phase noise due to the optical to electrical conversions can be measured using the residual phase noise approach, just like for the measurement of the additive phase noise of a microwave amplifier.

Optical noise (short delay) compared to amplifier noise :

Figure 3 depicts the measured residual phase noise of two microwave amplifiers, measured with a -25 dBm input signal, which is compared to the residual phase noise of the optical link with short delay. One of the amplifiers is a conventional 30 dB gain wide bandwidth amplifier (2-18 GHz), while the other one is a low phase noise AML 25 dB gain amplifier. The optical link phase noise is relatively low, and is a little lower than the AML phase noise. This means that the use of an amplifier at the optical link output would degrade the phase noise performance, and that a better performance can be obtained without any amplifier, providing that the output signal is high enough to get a sufficient phase detection coefficient K_ϕ on the mixer. This is the reason why no output RF amplifier is used in our experiment.

Optical noise (long delay) :

Another interesting point is to investigate on a possible noise contribution coming from the long optical delay line. This contribution may arise from optical interferometric processes in the delay line, such as Rayleigh scattering.

We found experimentally an increase of the overall noise at high optical power in the delay line (> 10 mW), and an optical attenuator has been added to reduce this power down to a few mW in the 4 km fiber.

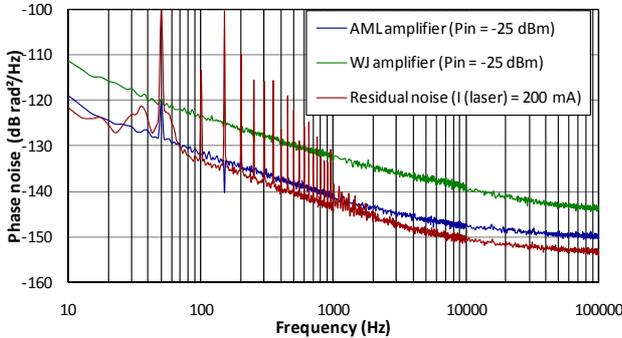


Figure 3. Residual phase noise of two microwave amplifiers (including a low phase noise AML amplifier), and of a MZ based optical link without any amplification at the photodiode output

1/f noise contributors in the optoelectronics devices :

Every electronic or optoelectronic device sustaining a current features a low frequency 1/f type fluctuation of this current, which can be converted into phase noise by the system nonlinearities. This is the case of laser diodes and photodiodes.

The conversion of these noise contributors in a nonlinear system is a complex process, which can only be described using a specific CAD approach (such as the conversion matrices in harmonic balance) and a precise model of the devices. We have developed such a model for a microwave optical link using Agilent ADS platform [6,7], but the approach presented in this paper will be more experimentally based. It will be connected later on to the model of ref. [6,7].

One of the results obtained with our nonlinear model shows that the direct conversion of the photodiode 1/f noise into phase noise should be relatively weak [7], because the capacitance of a reverse biased photodiode is almost constant and there is no way for this current fluctuation to affect the phase of the RF signal. We have therefore focused our experimental investigations on the laser 1/f noise, and the way it may be converted into a phase fluctuation of the RF modulation. Like any frequency source, laser noise can be split into two components : amplitude noise and frequency (or phase) noise.

Laser amplitude noise is easy to measure with a photodiode. In case of any doubt on the type of 1/f noise measured, it is possible to split the optical signal on two identical photodiodes, and to perform a cross spectrum analysis in order to reject the uncorrelated photodiodes noises.

The EM4 laser relative intensity noise has been measured, and is plotted in Figure 4. The measurement is performed in a Faraday's shielded room, and both the laser and the photodiode are battery biased.

As it is shown in Figure 4, the laser RIN improves at high optical power (or high bias current), both for the noise floor and the 1/f components.

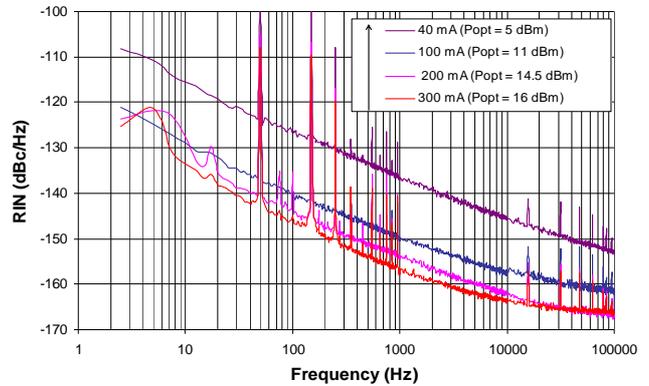


Figure 4. EM4 DFB laser RIN, measured at different bias current

The measurement of the laser frequency noise at low offset frequencies is more difficult. Indeed, in optics, the classically measured parameter is the laser spectral width, which is obtained either by mixing the laser signal to the one of a reference laser, or by using a long delay line and a homodyne approach. However, the spectral width measurement gives very little information on the laser frequency fluctuations, particularly at low offset frequencies. In order to investigate on this parameter, a measurement bench very similar to the microwave frequency discriminator has to be set up in the optical domain : a short (coherent) optical delay line ($L = 1$ m) is used to convert the laser frequency fluctuations into phase fluctuations, and these phase fluctuations are detected by a photodiode acting as a mixer [8]. It is also possible to use a pair of photodiodes (see Figure 5) arranged to get opposite output currents, in order to cancel the contribution of the laser amplitude noise (equivalent device of a microwave balanced mixer).

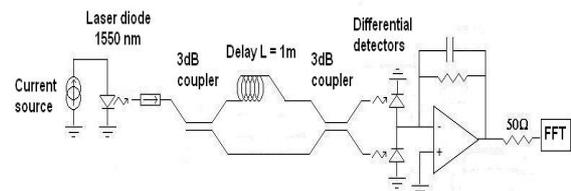


Figure 5. Laser frequency noise measurement bench

The most difficult step in this experiment is the system calibration. This is performed in our case by carefully modifying the laser bias current and detecting the corresponding shift in the output voltage, the laser wavelength sensitivity to its bias current being previously measured on an optical spectrum analyzer.

The measurement of the EM4 laser frequency noise is presented in Figure 6. Contrarily to the RIN data, the 1/f frequency noise is lower at low bias current. This means that the choice of a bias current level is difficult and cannot be based only on these two measurements: we have to determine if the main component in the 1/f phase noise observed on the

microwave signal going through the optical link is related to a conversion of the laser amplitude noise or of the laser frequency noise.

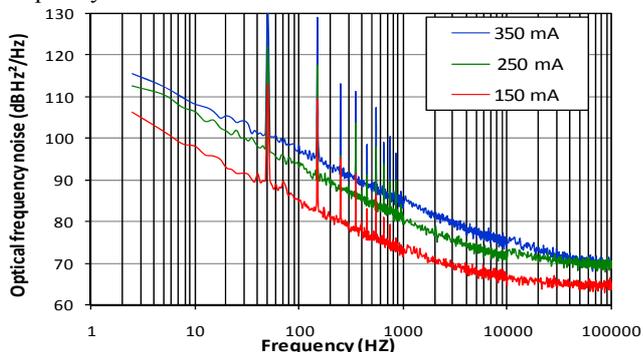


Figure 6. EM4 DFB laser frequency noise, at different bias currents

To this purpose, various experiments have been performed using a microwave network analyzer, with a similar approach as the one described in ref. [9] for microwave optical oscillators. The sensitivity of the microwave phase to a variation of the optical power has been studied, using an optical attenuator to modify the laser power, but the variation in RF phase has been found to be almost constant in our case versus this parameter (contrarily to [9]). The same experiment has thus been tried again with a variation of the laser wavelength, obtained by varying the laser bias. This time, a strong and almost linear variation of the RF phase has been observed, with a slope of $125^\circ/\text{nm}$.

This RF phase sensitivity factor has then been used together with the laser frequency noise data (Figure 6) to calculate the contribution of the laser frequency noise to the RF phase noise. In Figure 7, this contribution is represented, together with two others contributions to the microwave optical frequency discriminator noise floor : the input amplifier additive phase noise and the mixer phase noise. As it is clearly shown on this graph, the contribution of the laser frequency fluctuations is the dominant contribution to the system noise floor. Also plotted is the experimental data for the frequency discriminator noise measured with the sapphire oscillator. As shown, the phase noise calculated from the laser frequency noise conversion is pessimistic compare to the measured noise floor. The difference can be due either to calibration uncertainties in the laser frequency noise measurement or to a small change in the system configuration when the RF phase sensitivity to the variation of the laser wavelength has been measured. However, this study demonstrates the influence of the laser frequency noise, and open the way to an improvement of the experiment. Further system optimization will require to be able to find a compromise between the constraints on the additive phase noise floor, which is mainly related to the signal to noise ratio in the optical link and thus requires the laser to work at high current, and the constraints on the $1/f$ phase noise, which supposes a low laser $1/f$ frequency noise, and thus a relatively low laser bias current.

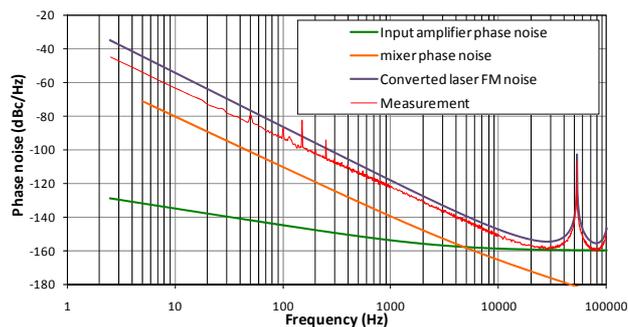


Figure 7. Contributions to the microwave discriminator noise floor

V. CONCLUSION

A microwave phase noise measurement bench based on an optical delay line has been studied. This measurement bench features state of the art performance, and its performance can still be improved if the main noise conversion processes involved in the system are fully understood. In this paper, the importance of the laser noise (both AM and FM noise), has been demonstrated through an experimental approach. Further improvements in performance are thus foreseen in a near future.

ACKNOWLEDGMENT

We wish to thank the French National Space Center (CNES) and the Midi Pyrénées Regional Council for their contribution to this study.

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