

# CAD OF MICROWAVE OPTICAL SYSTEMS FOR TIME&FREQUENCY APPLICATIONS

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## BIOGRAPHY

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## I- INTRODUCTION

Optical devices are more and more involved in time and frequency applications. They may be used for frequency reference signal distribution in a system, taking benefit of the low losses of the optical fibers, and of their small size and their immunity to electrical parasitic signals. They may also be used to realize high quality resonators and delay lines, leading to equivalent Q factors which are difficult to reach with classical RF or microwave techniques. An example is the optical delay line frequency discriminator, which is able to characterize microwave sources with a phase noise floor lower than -140 dBc/Hz at 10 kHz offset [1]. Another example is the microwave optical oscillator, either based on optical resonators or delay lines, which can deliver ultra high spectral purity signals [2].

However, the performance of these systems is dependent on the performance of the devices used for the electrical to optical or optical to electrical conversions, on the chosen optical modulation technique, on the necessary microwave amplifiers, on the devices biasing circuits, on the quality of the optical fiber and, above all, on the topology chosen to build the whole system. It is thus important to be able to compute the system phase noise using an appropriate modeling approach. This analysis will allow us to understand where are located the main noise sources in the system, and how to improve the system performance by reducing these noise sources or their impact on the phase noise.

## II- SIMULATION OF AN MZ BASED OPTICAL LINK: RF GAIN

Microwave circuit design software was optimized in the 90s to take into account frequency conversion phenomena between noise sidebands. They are very useful to simulate the microwave elements used in a microwave optical system. The main drawback is that they generally do not include any model for the optical devices. However, various approaches can be used to describe an optical device with an equivalent electrical circuit, or simply with a mathematical model, and to include this model in the chosen CAD tool.

In a first approach, we began simulating a Mach Zehnder modulator (MZ) based optical link, and more specially the RF gain. Indeed, MZ modulator is the most common modulation technique used in high quality microwave optical links, the other techniques being direct laser current modulation (generally limited to a few GHz in frequency), electro-absorption modulator (of smaller size, but not as efficient as MZ modulator) and dual frequency laser (mainly for very high frequencies applications, i.e. above 40 GHz).

First, we have focused our approach on the power response of the modulator, or more exactly on the simulation of a complete optical link using this modulator taking into account the effect of the system non-linearity on the transmission of the RF signal. The main nonlinearity in a MZ modulator is due to the  $1+\cos(x)$  curve of the modulator (due to the interference of the signals in the modulator arms), which leads to a saturation phenomenon which depends on the parameters of this curve: maximum optical power and maximum power voltage  $V_0$  and extinction voltage  $V_\pi$  (see Figure 1).

This type of system has been studied many times in the literature; using analytical approaches based on the Bessel's functions calculations [1], [8], [9]. However, because of the use of Bessel's function, a computer approach is always required with these approaches (ex : Matlab computation), and it is difficult to take into account on the same model the specific behaviour of the microwave electronic devices located before the modulator or after the photodiode. Therefore, a CAD approach is highly interesting for this system.

We have worked with Agilent ADS microwave simulation software. Because ADS do not include optical devices or signals, the laser source is described just like if it was a microwave source, using the system models of microwave sources which take into accounts their FM and AM noises. This makes a system with three main frequencies: DC, microwave frequency and optical frequency, and their possible harmonics. Normally, the harmonics of the optical signal are not of importance in the system, with the exception of course of the DC signal which corresponds to the detection of the laser amplitude. On the contrary, because of the nonlinear response of the system to the RF signal, some harmonics of the microwave signal have to be taken into account (we generally use 4 harmonics of this signal). Depending on the type of simulation used in ADS, the optical frequency can be the real optical frequency (in the THz range), or has to be replaced by a lower frequency in order to simplify the computation. As an example, a 200 GHz frequency is sufficiently high compared to a transmission of an RF signal at 10 GHz to avoid any interaction between the two signals, and there is no fundamental difference in a computation made with such a frequency and the actual optical frequency (the real value of the optical frequency as no influence on the simulation result).

The input parameters of our CAD model are the MZ modulator optical insertion losses  $L_{ins}$  and the voltages  $V_0$  and  $V_\pi$ , as well as its frequency response which is modelled using a low pass filter on the modulator RF input port. On the other side of the optical link, the photodiode is described by a quadratic detector (nonlinear voltage controlled current source) and, once again, a low pass filter to take into account its frequency response.

Concerning the nonlinear model of the MZ modulator, two different techniques have been implemented. A first technique describes the optical interference inside the MZ modulator using an electrical phase modulator available in ADS library (Figure 2). The main drawback of this technique comes from this circuit element: it may only be used together with an envelope simulation approach. The envelope simulation is dedicated to the simulation of a slow varying signal superimposed to a fast signal. This is exactly the case of the RF signal compared to the optical signal, and the power response can be efficiently computed with this approach. However, in terms of noise, we will need the description of the noise conversions between the system three main frequencies: DC, RF and optical. Using the envelope approach, the noise is considered only around two frequencies: the carrier frequency (optical in this case) and the modulation frequency (RF in this case). Thus, using this approach, it is impossible to take into account the effect of the low frequency noise ( $1/f$  noise), which is an important parameter of the system. We have thus implemented on ADS a second approach, in which the optical interference is no more described using circuits' elements but using an equivalent black box nonlinear equation (Symbolically Defined Device). In this approach, only the harmonic balance simulator is used, and there are no more

fundamental differences between the system three main frequencies.

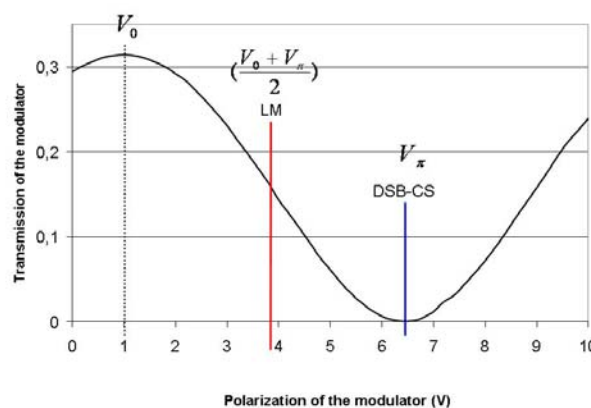


Figure 1: MZ modulator optical power response versus bias voltage

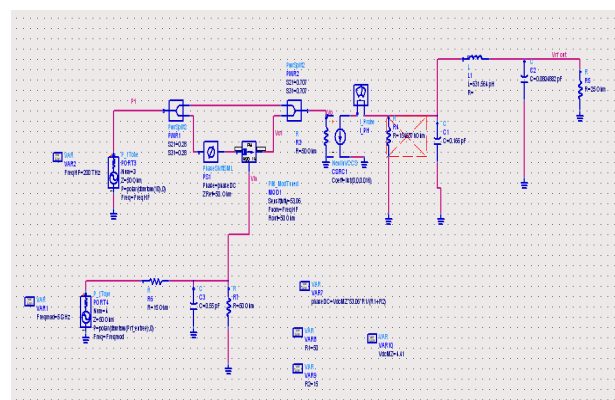


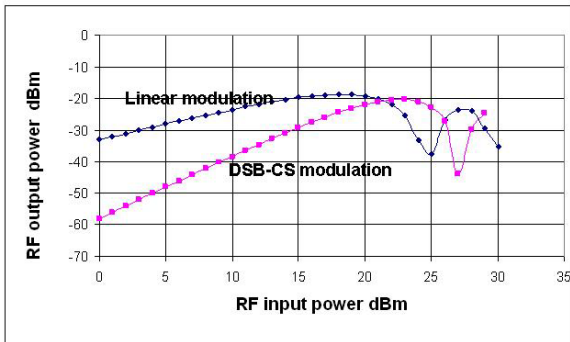
Figure 2: Circuit for the computation of the optical link RF power transmission using the envelope simulation technique on ADS.

In this case, the model is no more a circuit equivalent model of the optical link, rather a mixed between an analytical model and a circuit model. However, the analytical part of the model is very simple (there are no more Bessel functions) and the complexity of the electronic part can be as complex as required by the model user.

In our MZ based systems, we use two different types of modulation: the classical linear modulation (LM) and the optical carrier suppression (double sideband carrier suppression, or DSB-CS), which results in a frequency doubling of the RF signal. The last modulation type requires a high level of RF input power (typically, in the range of 20 dBm), but is more efficient in terms of signal to noise ratio if such an RF power is available [1], [3]. In the classical linear modulation, the MZ modulator is biased at  $(V_0+V_\pi)/2$ , while in the optical carrier rejection mode, it is biased at  $V_\pi$ .

Figure 3 shows the result of an ADS simulation concerning the RF output power versus the RF input power for this optical link. Both types of modulation are

studied (LM and DSB-CS). The input RF signal frequency is 10 GHz for the linear modulation and 5 GHz for the carrier suppression case (frequency doubling), and in both cases, the output is at 10 GHz. The laser power is 10 dBm, which corresponds to a classical medium power telecommunications laser. As shown in Figure 3, at low RF power, the linear modulation results in a much better gain, but a high level of output power can also be reached with the DSB-CS modulation, if an RF signal higher than 20 dBm is available to drive the modulator input. These results are close to the ones obtained with analytical models for a similar system [1].



**Figure 3:** ADS simulation of the optical link with MZ modulator for two types of bias of the modulator: linear  $(V_0 + V_\pi)/2$  and frequency's doubling  $(V_\pi)$ .

However, at very high level (above 25 dBm), and in the particular case of the DSB-CS modulation, some differences appeared. These differences are probably related to the approximations made in the analytical model in the truncation of the Bessels series development, and in this CAD approach, in the harmonic number chosen for each frequency. These problems are still under study at this time, but they correspond to an RF power range which is above the one which is effectively implemented in our application.

### III- NOISE SIMULATION OF AN MZ BASED OPTICAL LINK: RF NOISE AND PHASE NOISE

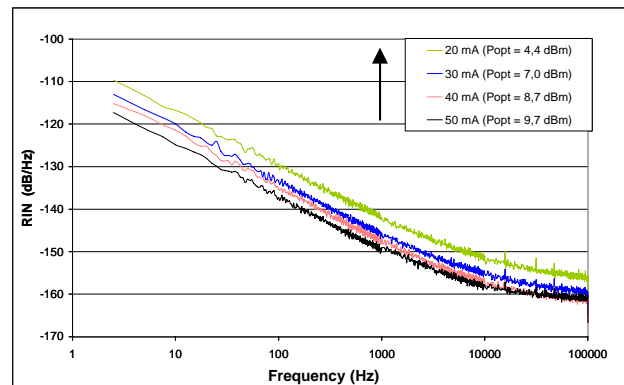
It was essential to introduce the noise parameters into this simulation, the ultimate purpose of this work being the simulation of an opto-electric oscillator and of all of its noise components.

The interest of our approach lies mainly in the capabilities of the Agilent ADS software to describe the noise conversions in non-linear regime (between the different carriers: DC, RF and optical). Indeed, special techniques have been developed in this software for the simulation of phase noise in oscillators or mixers. These techniques are based on the computation of the system Jacobian matrix, which is required in the harmonic balance approach for the computation of the system nonlinear steady state, and on the use of this matrix to compute the conversion of a small perturbation at one

frequency towards another frequency. This technique is known as the conversion matrices technique for nonlinear noise computation [4].

Up to now, the laser was simply described by a sinusoidal source. We now add to the model the fluctuations in amplitude (AM) and in frequency (FM) of this source. The laser frequency noise can be estimated from laser linewidth measurements, which are performed using a self-heterodyne measurement bench. The laser relative amplitude noise (RIN) is also measured on a dedicated measurement bench, which includes two different set-up: one for the measurement of the laser 1/f noise, which works between DC and 100 kHz, and another one for the measurement of the laser microwave RIN, which uses a fast photodiode and a low noise microwave amplifier up to approximately 15 GHz. The laser FM noise is added to the CAD model by using a system model of the source (directly available in ADS) which includes the phase noise. The laser RIN is described using an amplitude modulator at the laser output. Figure 4 represents the RIN measurement data obtained on a Mitsubishi medium power DFB laser at low frequency; these data have been used for the model implementation.

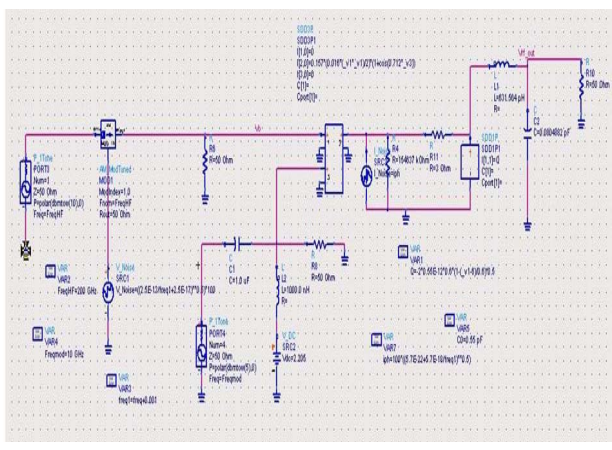
As previously explained, the MZ modulator is described using an equivalent black box nonlinear equation and the photodiode is described using a quadratic detection followed by an equivalent electrical circuit.



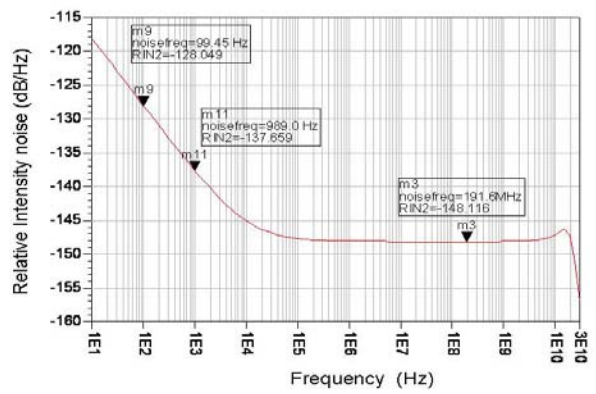
**Figure 4:** DFB laser 1/f relative amplitude noise (RIN), at different bias current. Device FU68PDF from Mitsubishi. Measurement performed in a Faraday's shield, using a battery bias for the laser, and a low noise PIN photodiode + amplifier.

Figure 5 depicts this optical link, with all its noise components. The MZ modulator receives the optical signal from the laser, the RF signal and also the DC bias. At the output, a photodiode realizes the signal quadratic detection and delivers the RF power on a load resistance. This photodiode also includes a noise source, in which the main contribution at RF frequencies and high optical power is the schottky noise  $S_{\text{schottky}} = 2qI_0$  ( $q$  being the electron charge and  $I_0$  the photodiode output DC current). At low frequencies (below 10 kHz), this photodiode may also exhibit a 1/f noise. However, it is difficult to estimate this noise, because it is generally masked at high optical power by the laser 1/f amplitude

noise. Indeed, correlation measurements have been performed to be sure of the noise origin in the measurement presented in Figure 4: at high optical level, the laser noise dominates the optical link noise, even at low frequencies (1/f noise). However, it is clear that this 1/f noise component of the photodiode exists, and it is possible to include such a noise source in the model, even if it is still difficult to measure it (at least in order to check its possible effect on the system phase noise).



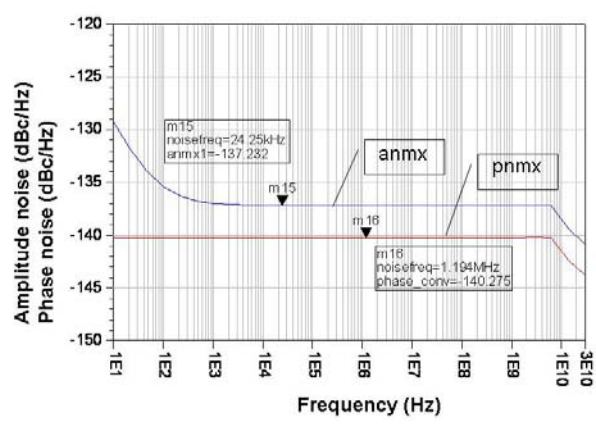
**Figure 5:** ADS noise simulation of the optical link, which uses an SDD model of the MZ modulator and two main noise sources: laser noise (AM and FM) and photodiode noise (white noise and 1/f noise).



**Figure 6:** ADS simulation of the noise to DC carrier ratio at the output of the optical link.

Figure 6 represents the result of a simulation of the noise component around the DC for this optical link, divided by the amplitude of the DC carrier. The interest of this simulation is in finding the phase noise floor, which is related to the carrier to noise ratio at the RF modulation frequency. For this simulation, the laser RIN noise floor has been chosen a little bit higher than the one depicted in Figure 4 (which corresponds to an high quality device), and the noise floor observed at the optical link output is close to the chosen RIN value. The 1/f RIN is also clearly visible, and the noise cut-off above 10 GHz is due to the low pass filter associated to the photodiode.

Figure 7 depicts the phase noise and amplitude noise simulations around the RF carrier at 10 GHz, obtained with the “pnmx” and “anmx” outputs of ADS software. Contrary to the result presented in Figure 6 at baseband, no 1/f phase noise has been computed. Only a relatively small 1/f AM noise is visible around the 10 GHz RF carrier. The computed phase noise is thus restricted to the noise/signal ratio, which can be computed from the RIN value at 10 GHz and the RF output power at 10 GHz.



**Figure 7:** Simulated optical link phase noise and amplitude noise around the RF carrier (10 GHz).

**IV- DISCUSSION ON THE 1/F NOISE**

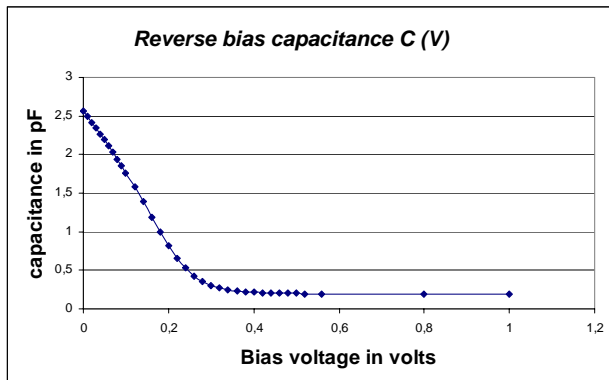
The absence of the 1/f phase noise was unexpected. Such a noise would come from noise conversions trough the nonlinear elements of the system. One possibility is that we had not included all the 1/f noise sources of the physical system, or not all the nonlinearities.

At first, the model included only the laser’s 1/f amplitude noise and the nonlinearity of the MZ modulator. This results in a relatively high level of 1/f amplitude noise around the DC output (this is normal, because the optical link is based on amplitude modulation), but no 1/f phase noise around the RF carrier. We have then added a noise component associated to the photodiode. Direct conversion of low frequency noise into phase noise in this component is possible, but such a process requires a reactive element in the photodiode model to generate the phase modulation by the baseband 1/f noise. Such a conversion could be performed by the diode nonlinear capacitance.

Following published models of photodiodes [5], as well as our own measurements (Figure 8), we have added to our model this nonlinear capacitance. The problem is that the diode’s capacitance is almost constant, in the working zone to be used in photodetection behaviour (large reverse bias: -6 V in our case).

This explains why adding this nonlinearity to the model, together with a 1/f noise source, has not generated any 1/f phase noise contribution on the RF output.

We are pursuing our investigations, because  $1/f$  phase noise has been measured in optical links and it is necessary to be able to model it accurately [1], [6], [7]. However, we think today that this phase noise contribution has little chance to be generated by the photodiode, or at least that the phenomenon will not be described by classical electrical models of photodiodes.



**Figure 8:** Measurement on a probe test set of an InGaAs photodiode capacitance (Optospeed), versus reverse bias. Capacitance nonlinear behaviour is clearly limited to the 0 V bias region.

## V- CONCLUSION

A Mach Zehnder based optical link has been implemented on a microwave circuit simulator. The model is able to describe the parameters of the RF or microwave transmission through the optical link, such as the power gain or the signal to noise ratio. The simulation of the optical link additive phase noise has also been performed, but the result obtained can only be related at this time to the signal to noise ratio. No significant  $1/f$  phase noise has been simulated, and the  $1/f$  component of the spectra around the RF carrier was only related to the amplitude noise. Further investigations on noise conversion are in progress, as well as the description of more complex systems such as a microwave-optical frequency discriminator or a microwave-optical oscillator.

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