IMPACT OF PHASE TO AMPLITUDE NOISE CONVERSION IN ANALOGUE OPTICAL LINKS

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ABSTRACT

In optical fiber links, optical phase noise is converted into amplitude noise which is detected by the photodiode by the way of undesired multiple reflections (cavity effect) or by the use of unbalanced Mach Zender interferometers (UMZ) inserted in the link for purposes of microwave optical processing.
In this paper, the linewidth of a laser diode is extracted from noise measurements together with the 1/f contribution to the detected noise. Since it is shown that the linewidth enhancement factor α of a laser diode is determinant for microwave mixing performances using a passive UMZ, the influence of α in the detected noise at the output of the UMZ is modelled.

INTRODUCTION

In recent years, optical fiber links for microwave signals have an and increasing number of applications. Quality of the transported information is crucial as for instance, for the close-to-carrier phase noise of a local oscillator. Indeed, the phase noise of the local oscillator must be preserved to match the requirements during mixing operations and more generally during signal processing operations.
Noise is generally broken down into two components in the Fresnel representation: the amplitude noise and the phase noise. As the conversion from the optical modulated signal to the microwave signal is made by quadratic detection, the optical phase noise does not contribute directly to the microwave noise. The optical phase noise will nevertheless be detected, owing to any phase to amplitude conversion processes. Some of these conversion processes are analysed below.
As the optical phase noise is converted into optical amplitude noise, the characterisation of the optical phase noise becomes relevant. The optical phase noise of the laser is due to the fluctuation of photon density, and results in the broadening of the laser linewidth. The measurement of the laser linewidth is obtained by self-delayed homodyne mixing technique. The phase noise spectra is then deduced from the intensity fluctuation spectra due to interference.
Among the phase-to-amplitude noise conversion processes in microwave optical link, we focus our attention on self-delayed interference due to insertion of either an optical cavity or an interferometric structure like the Unbalanced Mach-Zender Interferometer [1].
First, we present the laser linewidth measurement by self-delayed interference theoretically and experimentally, in order to then study the chirp influence on noise density detected at the output of the Unbalanced Mach-Zender Interferometer.

INTERFEROMETRIC NOISE AND LASER LINEWIDTH

Theory

The laser linewidth is due to a photon density fluctuation. In order to measure the laser linewidth, self-delayed interference are achieved (Fig. 1).

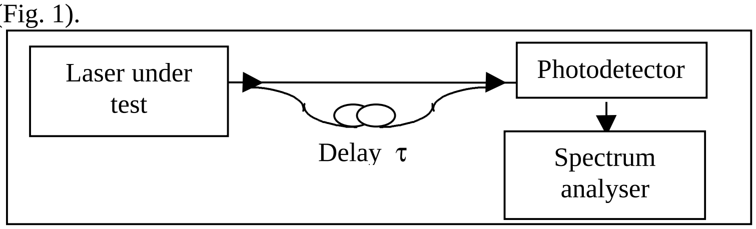

Fig. 1 : Self-delayed interference method.

The wave issued from the laser is divided into two beams of equal amplitude. The first is delayed and recombined with the second. The resulting detected intensity is analysed with a spectrum analyser.
The detected intensity is equal to:

$$I(t) = \left| \left(\frac{E_o^2}{2} \cdot \exp\left(jwo(t) + \Phi(t) \right) + \frac{E_o^2}{2} \cdot \exp\left(jwo(t-t) + \Phi(t-t) \right) \right) \right|^2 \tag{1}$$
$$= \frac{E_o^2}{2} \cdot \left[1 + \cos(wo \cdot t + \Delta\Phi(t)) \right] \quad \textit{where } \Delta\Phi(t) = \Phi(t) - \Phi(t-t)$$

with $\Phi(t)$, being the phase fluctuation of the laser, ωo, being the laser frequency and τ being the delay between the two beams.
In local network or radar systems, as well as with the Unbalanced Mach-Zenhder Interferometer , the delay induced in the cavity is shorter than laser coherence time τ_c or at least equivalent to it. Consequently, only $\tau << \tau_c$ will be studied here. Note that long cavity effects have been extensively published in the past mainly for telecommunications applications [2],[3],[4].
Assuming that $\Delta\Phi(t) << 1$, i.e. $\tau << \tau_c$ (coherent interference regime), the detected intensity can be simplified as:

$$I(t) = \frac{E_o^2}{2} \cdot \left[1 + \Delta\Phi(t) \right] \tag{2}$$

The spectral density of intensity fluctuations $S_I(f)$ is equal to

$$S_I(f) = \frac{1}{\pi} \int_{-\infty}^{+\infty} < \Delta\Phi(t)\Delta\Phi(t+\theta) > \cdot e^{-j \cdot 2 \cdot \pi \cdot f \cdot \theta} . d\theta \cdot \cdot \tag{3}$$

After some calculations, we obtain at quadrature :

$$S_I(f) = 4 \cdot \frac{\sin^2(\pi \cdot f \cdot \tau)}{f^2} \cdot S_{\Delta f_{opt}}(f) \tag{4}$$

where $S_{\Delta fopt}$ (f) represents the spectral density of frequency noise of the laser. The spectral density of the laser phase, deduced from the spectral density of detected intensity fluctuations, can be expressed by:

$$S_{\Delta f_{opt}}(f) = C_1 + \frac{C_2}{f} \quad \text{where } C_1 \text{ and } C_2 \text{ are constants} \tag{5}$$

From C_1 and C_2 , two usual parameters, the linewidth B of the laser and the coherence time $\tau_{1/f}$ of the 1/f noise are expressed as : $B=\pi.C_1$, et $\tau_{1/f} = (4\pi^2.C_2)^{-1/2}$ (6)

Measurement

An experimental bench with software facilities permits us to obtain the phase noise parameters of the laser through the deviation of C_1 and C_2. The noise power is measured in a bandwidth from 1kHz to 1GHz, with a spectrum analyser.
Two curves are presented in Fig. 2 :

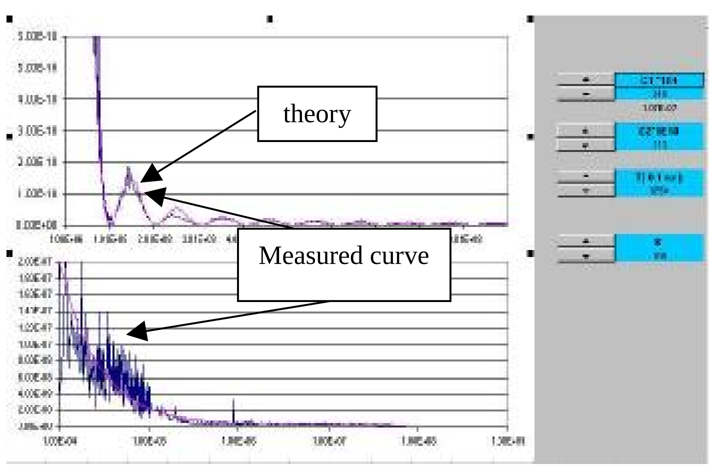

Fig. 2 : Experimental results and theoretical fit for parameter's extraction

The result is obtained by computing C1 and C2 coefficients in expression (5) to fit with the experimental result. The first graph represents the interferometric noise in a bandwidth from 1 MHz to 1GHz in linear scale. The period and the level of noise density are related to the delay τ and to C_1.
The second graph represents the interferometric noise with a logarithmic scale. It permits to extract C_2.

Results

Two lasers have been tested following the previous method with two delays: τ=10ns and τ=20ns.
We used a Alcatel 1905 LMI laser, at 180 mA of bias current at 25°C and a Lucent laser, at 90mA of bias current at 25°C.

laser	C_1 (MHz)	B (MHz)	$C_2.10^{11}$ Hz²	$\tau_{1/f}$ (ns)
Alcatel	3.6	11	22	210
Lucent	5.5	17.4	3	530

We estimate the margin of error reached by this method to be around 20%, mainly limited by spectrum analyser performances.

UNBALANCED MACH-ZENDER

This model of phase-to-amplitude optical noise conversion is helpful to characterise some specific degradations occurring along a microwave optical link. Some of the component requirements can be deduced from this theoretical model.

Intensity noise resulting from phase to intensity modulation conversion can cause severe problems in non linear fiber-optics systems [5] or interferometric systems. Degradation in BER performance and in spectral purity or signal to noise ratio can be observed in direct detection systems. The influence of the linewidth enhancement factor α of the directly modulated laser diode is examined here, by evaluating the intensity noise in the detected optical power. Indeed, as explained in the last section, passive interferometric optical systems can be used for performing original microwave functions like filtering and mixing in the incoherent or coherent regime of interference for these two applications respectively. For purpose of optimising the optical network topology, we calculated the increase in noise power spectral density S_{out} (f) for different values of α as a function of frequency and for different interference regimes.

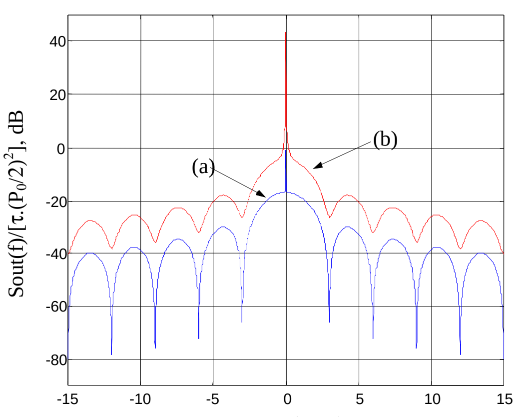

Fig. 3 : Coherent regime of interference and the two fields in quadrature of phase, for α=0 (a) and α=5 (b).

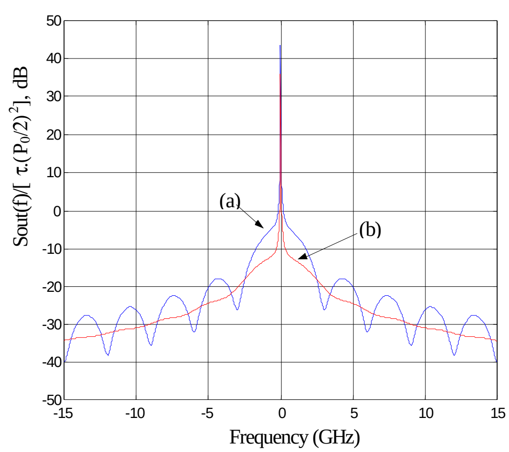

Fig. 4 : Coherent regime and the two fields in quadrature of phase (a), and maximum/minimum of transmission (b), with α=5.

The case of coherent regime is shown here in Fig. 3 and in Fig. 4, the interfering fields are in quadrature of phase. The laser of coherence time τ_c= $31.8.10^{-9}$ s is followed by an interferometer with a delay between the two arms τ= $3.33.10^{-10}$ s (unbalanced Mach Zehnder integrated on a glass substrate with a free spectral range FSR of 3 GHz). The instantaneous optical power of the laser is P_0.

From Fig. 3, it can be shown that a laser diode with an enhancement factor of 5 causes an 11 dB increase in the detected noise intensity at frequencies $f>(\tau_{1/f})^{-1}$.
In Fig. 4, the noise power spectral density is calculated for two interference regimes, i) maximum or minimum of detected optical intensity at the output of the interferometer, and ii) quadrature regime of interference. It is shown that noise density is about 8 dB lower at moderate frequencies f ($f>(\tau_{1/f})^{-1}$and f <FSR) when the maximum/minimum regime of interference is used.
In conclusion, this noise contribution can be reduced by an appropriate choice of both the laser (i.e., the linewidth) and the regime of interference, in order to respect to the phase spectral purity requirements. It has been shown that passive interferometers working in the coherent regime can perform microwave mixing functions when combined with a directly modulated laser diode, and with a mixing conversion gain proportional to α^2 [1]. The FM modulation due to the chirp effect can cause noise degradation in the detected intensity at the output of the interferometer, as shown here. However, the regime of interference that leads to an enhanced mixing conversion gain corresponds to the maximum non-linearity. Therefore, the regime of interference is theoretically the maximum or minimum of transmission. This is confirmed by experiments. In the case presented here, we used a distributed Feed Back Laser Diode (DFB LD) with a linewidth enhancement factor α of 5, modulated by two CW signals at frequencies 1.5 GHz and 4.5 GHz. The FSR of the unbalanced Mach-Zender interferometer was equal to 3 GHz. We simultaneously measured the mixing response in the Photo Diode (PD) current at mixing frequencies sum and difference 6 and 3 GHz respectively with the average optical power at the output of the interferometer. As expected and shown in Fig. 5, mixing is optimal for both maximum and minimum of transmission. Finally, optimal mixing conditions in this example coincides advantageously with the regime causing the maximum noise reduction.

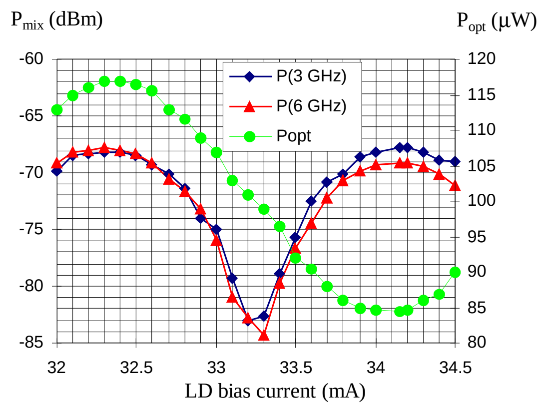

Fig. 5 : Effect of the interference regime on the mixing response.

CONCLUSION

This model of phase-to-amplitude optical noise conversion is helpful to characterise some specific degradations occurring along an optical link. Some of the component requirements can be deduced from this theoretical model. An appropriate choice of the laser used reduces noise effect. Indeed, the laser phase noise, i.e. its linewidth has to be chosen taking into account both the phase spectral purity requirements and the optical networks topology, especially regarding the cavity delay.

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