Performance of Interferometric Systems for Optical Processing of Microwave Signals: Influence of Laser- and Microwave-Phase Noises

Yannis Le Guennec, G. Maury, B. Cabon

Performance of interferometric systems for optical processing of microwave signals: influence of laser and microwave phase noises

Y. Le Guennec , G. Maury, B. Cabon
IMEP, UMR CNRS 5130, 23 rue des Martyrs, BP 257, 38016 Grenoble Cedex 1, France
email: leguenne@enserg.fr, cabon@enserg.fr, maury@enserg.fr , fax : +33 (0)4 76 85 60 80

Abstract:
An unbalanced Mach-Zehnder interferometer (UMZ) is used to convert microwave (MW) frequency modulation (FM) of a laser diode into intensity modulation (IM). In coherent interference regime, it is shown that parasite FM, induced by laser-phase noise and the MW-phase noise of the modulation source, causes negligible intensity noise but significant phase noise in the photo-detected intensity at the output of the UMZ. Theoretical study is realized in linear- and nonlinear-interference regimes. Results are validated experimentally.

Index terms: Intensity modulation (IM), laser-phase noise, microwave (MW) phase noise, optical telecommunications, unbalanced Mach-Zehnder (UMZ) interferometer.

I. Introduction

Optical processing of MW signals, like MW mixing for up/down-conversions, is very interesting for a wide range of applications including fiber-radio and radar systems [1]. In these systems, the MW phase noise and intensity noise detected by the photo-detector at the end of the optical link may be of drastic importance [2].

It has already been demonstrated the use of a UMZ to generate conversion of MW subcarriers of digital signals when UMZ operates respectively in non-linear interference regime [3], [4]. The basic principle of this system is based on the conversion of the FM of the light emitted by a laser diode into IM (FM/IM conversion). The optical phase noise of the laser source as well as the phase noise of the MW modulation signal are also converted into IM. These phase noises may have a significant influence on the phase noise and on the amplitude noise of the photo-detected intensity at the output of the UMZ. In this article, we have developed a theoretical approach, confirmed by experiments, to show the influence of the laser and MW phase noises through the FM/IM conversion with the UMZ interferometer. To quantify this impact, we consider a LD directly modulated by a single RF signal, followed by an UMZ working in coherent regime, like in the case of optical MW mixing. In section II, the general expression of the photo-detected intensity at the output of the UMZ is established with optical and MW phase noises. In section III, the influence of the laser phase noise is considered. In section IV, the effect of the phase noise of the MW subcarrier on the FM/IM conversion is studied. Experimental results are then discussed in section V and successfully compared to the theory.

II. General expression of the intensity at the output of the UMZ

The optical field E(t) at the output of a laser diode is directly modulated by a RF signal at frequency f_{RF}. If we take into account phase noises, the expression of E(t) can be written as:

$$
\begin{aligned}
&E(t)=m(t)\cdot r(t)\cdot \exp\left(j2\pi\nu_0 t\right)\times E_0 \\
&\text{with}\quad m(t)=\sqrt{1+m_{RF}\cos(2\pi f_{RF}t+\phi_{RF}(t))}\times\exp\left\{j\left[\beta_{RF}\sin(2\pi f_{RF}t+\phi_{RF}(t))\right]\right\} \\
&\text{and}\quad r(t)=\exp\left(i\phi(t)\right)
\end{aligned}
\tag{1}
$$

where E_0 is the amplitude of the optical field, ν_0 is the optical carrier frequency, m_{RF} and β_{RF} are the amplitude and frequency modulation index at f_{RF} respectively. The phase term ϕ_{RF} is the MW random phase fluctuation leading to the broadening of the MW spectral line. The multiplicative term r(t) includes random variations of the optical field phase $\phi(t)$ which leads to the broadening of the optical spectral line of the laser.

The optical field is coupled into an integrated glass substrate UMZ interferometer as shown on Fig.1. The delay between the two arms of the UMZ is τ. The detected instantaneous intensity at the output of the UMZ is given by :

$$
I_{inst}(t)=\frac{1}{4}\left(E(t)+E(t+\tau)\right).\left(E(t)+E(t+\tau)\right)^{*} \tag{2}
$$

We consider that the amplitude modulation index is low (m_{RF}<<1) and that FM is dominant over AM. As the optical receiver is not fast enough to follow the variations of optical phase, the detected intensity I(t) is the average of the instantaneous intensity (2) over several optical periods. Since the

MW random phase fluctuation and the optical phase random fluctuation are independent random variables, it can be derived that:

$$I(t)=\frac{E_0^{\,2}}{2}\left[\begin{array}{l}1+\langle\cos\Phi(t,\tau)\rangle\left\langle\cos\left(2\pi\nu_0 t+\beta_{RF}\sin(2\pi f_{RF}(t+\tau)+\varphi_{RF}(t+\tau))-\beta_{RF}\sin(2\pi f_{RF}t+\varphi_{RF}(t))\right)\right\rangle\\ -\langle sin\Phi(t,\tau)\rangle\left\langle\sin\left(2\pi\nu_0 t+\beta_{RF}\sin(2\pi f_{RF}(t+\tau)+\varphi_{RF}(t+\tau))-\beta_{RF}\sin(2\pi f_{RF}t+\varphi_{RF}(t))\right)\right\rangle\end{array}\right] \quad (5)$$

where $\Phi(t,\tau)=\varphi(t+\tau)-\varphi(t)$ is the optical phase fluctuation that relates to the random optical phase change between t and t+τ.

III. Influence of laser phase noise

The optical phase fluctuation $\Phi(\tau)$ is usually a zero-mean stationary random Gaussian process [5]. If the frequency fluctuation random process is a white noise, it can be shown that [6]:

$$\langle\exp j\Phi(t,\tau)\rangle=\exp\left(-\frac{\tau}{\tau_{opt}}\right) \quad (7)$$

where τ_{opt} is the coherent time of the source, this coherent time is linked to the spectral linewidth $\Delta\nu_{opt}$ of the optical source as:

$$\tau_{opt}=\frac{1}{\pi\Delta\nu_{opt}} \quad (8)$$

In the case of DFB laser diodes, the optical spectral linewidth is usually smaller than 10 MHz. For our DFB laser, τ_{opt}=32 ns. The delay τ of the longest arm of our integrated UMZ is about 0,33 ns that corresponds to a free spectral range (FSR) of the UMZ of 3GHz. $\tau \ll \tau_{opt}$ means that we work in a strong coherent regime. We can conclude from (7) that in a very good approximation:

$$\langle\cos(\Phi(t,\tau))\rangle\approx 1 \quad and \quad \langle\sin(\Phi(t,\tau))\rangle\approx 0 \quad (9)$$

hanges of optical phase between t and t+τ are negligible because of the very long coherence time of the source compared to τ.

The frequency-noise spectrum of a laser diode under free running conditions is composed of white noise and flicker noise. It has been already demonstrated that in a very coherent regime, contribution of the flicker noise in the photo-detected phase noise at the output of a UMZ is dominant over the contribution of white noise but these contributions are both very low [6]. Equation (9) is then still perfectly valid.

The expression of I(t) (5) can be simplified as:

$$I(t)=\frac{E_0^{\,2}}{2}\left[1+\left\langle\cos\left(2\pi\nu_0\tau+\beta_{RF}\sin(2\pi\ f_{RF}(t+\tau)+\varphi_{RF}(t+\tau))-\beta_{RF}\sin(2\pi\ f_{RF}t+\varphi_{RF}(t))\right)\right\rangle\right] \tag{10}$$

It can then be concluded that, in the coherent regime, the photo-detected intensity does not hold any terms induced by laser phase noise.

IV. Influence of microwave phase noise

A. Linear regime

In linear regime of interference $2\pi\nu_0\tau=(2p+1)\pi/2$, $k\in Z$ [3]. The detected intensity (10) can be rewritten as:

$$I(t)=\frac{E_0^{\,2}}{2}\left[1+(-1)^p\left\langle\sin\left(\beta_{RF}\sin(2\pi\ f_{RF}(t+\tau)+\varphi_{RF}(t+\tau))-\beta_{RF}\sin(2\pi\ f_{RF}t+\varphi_{RF}(t))\right)\right\rangle\right] \tag{11}$$

We introduce instantaneous frequency fluctuations $\Delta f_{RF}(t)$ defined by:

$$\varphi_{RF}(t)=2\pi\Delta f_{RF}(t)\tau \tag{12}$$

After a Bessel expansion of equation (11), it is shown that only odd harmonics of f_{RF} are photo-detected. We also see that the amplitude of the spectral line at frequency f_{RF} depends on the value of f_{RF}, meaning that the UMZ acts as a linear filter. Frequency f_{RF} has to check a relation depending of the FSR of the UMZ to maximise the power detected at f_{RF} [3]:

$$f_{RF}=(2k+1)\frac{FSR}{2},\ k\in N \tag{14}$$

The spectral line at frequency f_{RF} can be approximated by the dominant terms of (13) expressed as:

$$I_{f_{RF}}(t)=2E_0^{\,2}(-1)^p J_0\left(\beta_{RF}\right)J_1\left(\beta_{RF}\right)\left\langle\sin\left(2\pi f_{RF}t+\frac{\psi_{RF}(t,\tau)}{2}\right)\cos\left(\frac{\Phi_{RF}(t,\tau)}{2}\right)\right\rangle \tag{15}$$

$$\text{where}\ \begin{cases}\Phi_{RF}(t,\tau)=\varphi_{RF}(t+\tau)-\varphi_{RF}(t)\\ \psi_{RF}(t,\tau)=\varphi_{RF}(t+\tau)+\varphi_{RF}(t)\end{cases}$$

$\Psi_{RF}(t,\tau)$ is the MW phase fluctuation that expresses the random MW phase change between t and t+τ.

In the case of MW synthesiser, spectral linewidth of the MW subcarrier is typically smaller than 10 kHz which corresponds to a coherence time of the MW source of τ_{MW}>33 μs>>τ_{opt}>>τ. This inequality means that the fluctuation of MW phase is even slower than optical phase fluctuation. In these conditions, MW phase fluctuation between t and t+τ is also negligible and Eq. (15) can be written as:

$$I_{f_{RF}}(t)=2E_0^{\ 2}(-1)^p J_0\left(b_{RF}\right)J_1\left(b_{RF}\right)\left\langle\sin\left(2pf_{RF}\,t+f_{RF}(t)\right)\right\rangle \qquad (16)$$

Finally, in conditions of coherent and linear regime, after photo-detection, the detected intensity holds the term of MW phase noise from the source but no terms of parasite IM induced by MW phase noise.

B. Non-linear regime

In the non-linear regime of interference (maximum or minimum), $2\pi\nu_0\tau=q\pi$, k∈ Z. Detected intensity (10) can be expressed as:

$$I(t)=\frac{E_0^{\ 2}}{2}\left[1+(-1)^q\left\langle\cos\left(b_{RF}\sin(2p\ f_{RF}(t+t)+f_{RF}(t+t))-b_{RF}\sin(2p\ f_{RF}t+f_{RF}(t))\right)\right\rangle\ \right] \qquad (17)$$

After a Bessel expansion, we note that only even harmonics are present in the MW spectrum. Considering that changes of MW phase between t and t+τ are again negligible, the dominant term detected at harmonic 2n at frequency $2nf_{RF}$ is expressed by:

$$I_{2nf_{RF}}(t)=2E_0^{\ 2}(-1)^q J_{2n}^{\ 2}\left(b_{RF}\right)\left\langle\cos\left(2p2nf_{RF}t+2nf_{RF}(t)\right)\right\rangle \qquad (18)$$

Under coherent interference and at maximum or minimum of interference, the detected intensity holds a MW phase noise term $2n\phi_{RF}$ depending of the source and of the the rank of the harmonic, but no term of parasite IM induced by MW phase noise appears.

V. Experimental validation

In this paragraph, we first define the theoretical expressions of the power spectral density (PSD) that have been measured after photo-detection in linear and non-linear regimes.

A. Expression of the PSD of the MW phase noise at f_{RF} in the linear regime

In linear regime, assuming that the fluctuation of random phase is very low, detected intensity at f_{RF} (17) can be simplified as:

$$I_{f_{RF}}(t)=A_0 \sin\left(2\pi f_{RF}t+\varphi_{RF}(t)\right) \tag{19}$$

where A_0 is the amplitude of the detected intensity at f_{RF} depending on E_0, β_{RF} and p according to (16).

The PSD $S_{f_{RF}}(f)$ of the photo-detected intensity $I_{f_{RF}}(t)$ is then expressed by [7]:

$$S_{f_{RF}}(f)=\frac{A_0^2}{4}\left[\left(\delta(f-f_{RF})+\delta(f+f_{RF})\right)+S_{\varphi_{RF}}\left(f-f_{RF}\right)+S_{\varphi_{RF}}\left(f+f_{RF}\right)\right] \tag{20}$$

Sidebands of the signal detected at frequency f_{RF} are induced by the random fluctuation of the MW phase. We typically define $S^{\varphi}_{f_{RF}}(f)\,(unit\ dB_c/Hz)$ as the ratio between the phase noise PSD per unit bandwidth and at a frequency f from the carrier and the power of the signal at f_{RF}:

$$S^{\varphi}_{f_{RF}}(f)=10.\log\left[\frac{1}{2}\left(S_{\varphi_{RF}}\left(f-f_{RF}\right)+S_{\varphi_{RF}}\left(f+f_{RF}\right)\right)\right] \tag{21}$$

Expression (21) directly shows that the PSD of the detected phase noise $S^{\varphi}_{f_{RF}}(f)(dB_c/Hz)$ in linear regime is the same as the PSD of the phase noise of the MW subcarrier that modulates the laser source.

B. Expression of MW phase noise PSD at $2nf_{RF}$ $n\in N$ in the non-linear regime

In non-linear regime, if B_{2n} is the amplitude of the detected intensity at the harmonic $2nf_{RF}$, we can define the PSD $S_{2nf_{RF}}(f)$ as follows:

$$S_{2nf_{RF}}(f)=\frac{B_{2n}^2}{4}\left[\left(\delta(f-2nf_{RF})+\delta(f+2nf_{RF})\right)+S_{2n\varphi_{RF}}\left(f-2nf_{RF}\right)+S_{2n\varphi_{RF}}\left(f+2nf_{RF}\right)\right] \tag{22}$$

As previously, we can also define $S^f_{2nf_{RF}}(f)(dBc/Hz)$ as:

$$S^f_{2nf_{RF}}(f) = 10.\log\left[\frac{1}{2}(2n)^2.\left(S_{2nf_{RF}}\left(f-2nf_{RF}\right)+S_{2nf_{RF}}\left(f+2nf_{RF}\right)\right)\right] \quad (23)$$

Equation (23) shows that the PSD of the detected phase noise is increased by 20.log(2n) in non-linear regime, when compared to linear regime (21).

C. Experimental results

Experimental measurements of the phase noise PSD of the MW signal detected at the output of the UMZ have been carried out to check previous theoretical results (21) (23). These measurements have been realized as shown on Fig. 1 using a spectrum analyzer with a very low phase noise. Interference regime is controlled fixing temperatures of the laser diode and of the glass substrate of the UMZ and adjusting the bias current of the laser diode in order to change slightly the optical wavelength. Amplitude modulation index at f_{RF} is m_{RF}=0,05. Results are presented on Fig. 2. Single sideband PSD have been measured at a frequency offset up to 10 kHz from the carrier frequency f_{RF}. Error bars due to the analyzer noise have been added to all measured points. Fig. 2 shows measured points for phase noise PSD of the photo-detected intensity at f_{RF} , at the output of UMZ in linear regime, and for phase noise PSD measured for the MW source independently. Both measurements are equal as expected by theory (21). Fig. 2 also shows measured points for the phase noise PSD of the photo-detected intensity at $2f_{RF}$ at the output of the UMZ in non-linear regime. The values are about 6dB higher than the same PSD measured in the linear regime at f_{RF}. This result is in agreement with theory, (23) with n=1.

VI. Conclusion

The influence of both optical and MW phase noise on the photo-detected microwave signal at the output of an interferometer has been investigated theoretically and experimentally. It was shown that, in coherent interference regime, no terms of parasite amplitude noise exist, neither induced by laser phase noise nor by the MW phase noise, after FM/IM conversion.

Considering the phase noise of the photo-detected microwave signal, the theoretical approach has shown also that, in the linear regime, the PSD at frequency f_{RF} is equal to the PSD of MW phase noise of the source used to modulate the laser diode. In non-linear regime, the PSD of the phase noise at harmonic number 2n detected at the output of the UMZ, is increased by 20.log(2n).

Both conclusions are confirmed by measurements of the phase noise PSD detected at UMZ output, in linear and non-linear regimes.

VII. References

[1] R. Helkey, J.C. Twichell and C. Cox, "A down Conversion Optical Link with RF Gain", J. Lightwave Technol., vol. 15, pp.956-961, 1997.

[2] K. Kitayama, "Ultimate performance of Optical DSB Signal Based Millimeter-Wave Fiber Radio System: Effect of Laser Phase Noise", J. Lightwave Technol., vol. 17, pp.1774-1781, 1999.

[3] G. Maury, A Hilt, T. Berceli, B. Cabon, A. Vilcot, "Microwave-frequency conversion methods by optical interferometer and photodiode," IEEE Trans. on Microwave Theory and Techniques, Volume: 45 Issue: 8, Aug. 1997, pp 1481 -1485

[4] Y. Le Guennec, G. Maury, B. Cabon, "BER Performance Comparison Between Active Mach-Zehnder Modulator and Passive Mach-Zehnder Interferometer for Conversion of Microwave Subcarriers of BPSK Signals," Microwave and Optical Technology Letters, vol. 36, no. 6, pp 496-498, Mar. 2003.

[5] P.B. Gallion, G. Debarge, "Quantum Phase Noise and Field Correlation in Single Frequency Semiconductor Laser Systems," IEEE Journal of Quantum Electronics, vol. 20, no. 4, pp. 343-349, Apr. 1984.

[6] Y. Salvadé, R. Dändliker, "Limitations of interferometry due to flicker noise of laser diodes," Journal of Optical Society of America, vol. 17, no. 5, pp. 927-932, May 2000.

[7] Aeroflex, PN9000 Automated Phase Noise Measurement System Application Note #1, pp.5-7.

Figures

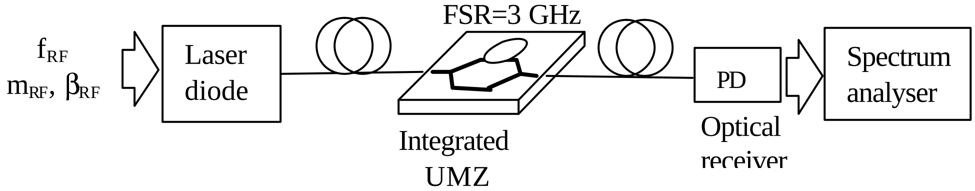

Fig. 1 Experimental set-up for measurement of intensity converted phase noise using a UMZ

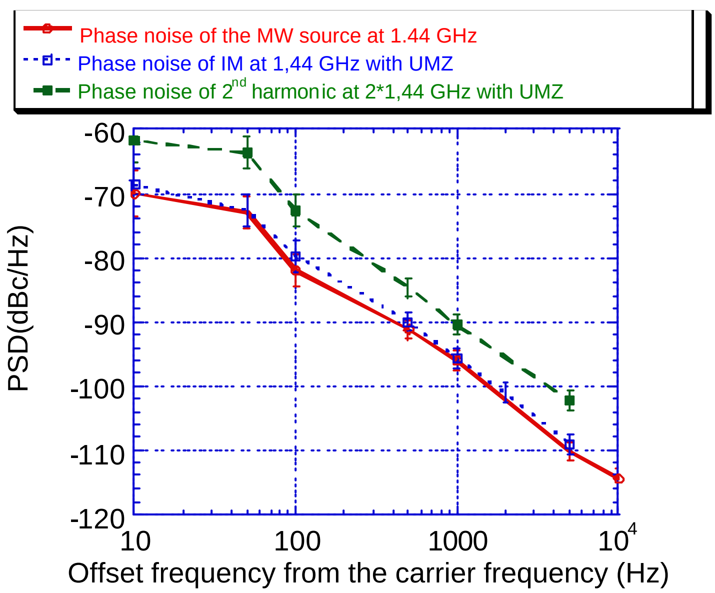

Fig. 2 Measurements of the photo-detected phase noise PSD, at the output of the UMZ, in linear and non-linear regimes (2nd harmonic). Comparison with the phase noise PSD of the MW source.