Influence of the Chirp Effect of DFB Laser in Phase-to-Intensity Noise Conversion in RF-Modulated Optical Links

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Abstract — **The power spectral density of the optical intensity in RF modulated optical links is investigated theoretically and experimentally in interferometric systems. The influence of the Henry factor α of directly modulated DFB laser diodes is shown on the conversion of phase noise into intensity noise, for the first time.**

I. INTRODUCTION

The semiconductor laser is one of the most important light sources in fiber-optical and integrated optical systems [1]. This is due to its high efficiency, simplicity of modulation and compact size. DFB (Distributed Feedback) lasers are fast becoming the transmitters of choice in most optical communication systems today. In optical communication systems many types of impairments (e.g. noises) are added to the signal [2, 3]. These impairments result in a fluctuation to the signal. Thus, the statistical properties of the signal are changed and therefore, they can degrade the system performance.

Laser phase noise results from fluctuations in the difference between the phases of two identical waves separated in time. The phase noise is very important in designing optical fiber communication systems. The dynamic range of many optical signal processing and sensing devices incorporating two-beam interferometers, such as Mach-Zehnder, can be limited by random phase fluctuations of the optical source emission field [4, 5].

The analysis of the fluctuations of the optical power is essential to understand the degradation of the phase noise of an optical link. Quality of the transported information is crucial as for instance, the close-to-carrier phase noise of a local oscillator. The phase noise of the local oscillator must be preserved to match the requirements during signal processing and analysis, for example in radar applications.

Several authors have considered the effects of phase-to-intensity noise conversion on noisy light without modulation [3]-[7]. We, and other authors have considered optical processing of microwave subcarriers, with conversion of frequency modulation (FM) into intensity modulation (IM) on modulated pure carriers by interferometers like Mach-Zehnder (MZ) modulators [8, 9]. But the conversion of FM-noise (due to chirp of diodes) into intensity noise in these interferometric systems has never been considered before.

The problem addressed here of phase-to-intensity noise conversion process in microwave optical link is general. It occurs whenever self-delayed interference exist, either due to insertion of an optical cavity or an interferometric structure like an Unbalanced Mach-Zender Interferometer.

In previous works, we have considered this system for microwave-photonics signal processing. We demonstrated that an unbalanced passive MZ can generate frequency conversion of analogue microwave subcarriers, with or without digital modulation [9, 10], where a directly modulated laser diode with a large chirp is used for FM to IM conversion at the output of the MZ. The higher the chirp is, the higher the FM index β is, and the larger the mixing conversion gain is. In this paper we consider the conversion of FM-noise and the influence of β.

Section II presents phase to intensity noise conversion with the MZ interferometer without modulation of the laser diode. Section III deals with FM to intensity noise conversion with direct modulation of a laser diode, and the effect of laser chirp coefficient α. Different frequency-modulation indexes (β) values are investigated and their effects on the noise power spectra is demonstrated. Both white noise and 1/f noise are considered. The objective is to characterize noise in analogue RF modulated optical links, under direct modulation. Investigations are made on both experimental and theoretical points of view.

It is shown that the low frequency noise is reduced by proper choice of the FM index β. Section IV presents experimental results with excellent agreement with theory.

II. CONVERSION OF PHASE-TO-INTENSITY NOISE IN AN INTERFEROMETER, WITHOUT MODULATION

In this case, the input optical field into the interferometer is :

$$E(t) = E_o \exp(j(\omega_o t + \phi_{in} + \phi(t)))$$

where E_o is the field amplitude, ω_o is the center angular optical frequency, ϕ_{in} is the constant phase of laser and $\phi(t)$

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is the instantaneous phase and represents the laser phase noise.

The schematic diagram of a fiber-optic system using an Unbalanced Mach-Zehnder (UMZ) is shown in Fig. 1, with a delay τ_d between the two arms, with $\tau_d = n\Delta L/c$, where n is the effective index of fiber, c is the light velocity and ΔL is the length difference.

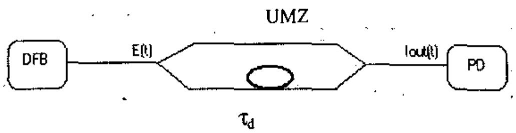

Fig. 1. Fiber-optic Mach-Zehnder. DFB: Distributed Feedback Laser, PD: Photodetector.

All modeling data obtained down here are related to an experimental DFB laser emitting at 1550 nm, that has been used in combination with the UMZ for signal processing purposes [9].

The light intensity $I_{out}(t)$, detected by the optical receiver placed at the output of the interferometer of delay τ_d between the two arms, is expressed as:

$$I_{out}(t) = \frac{1}{4}\left|E(t) + E(t-\tau_d)\right|^2$$

$$= \frac{1}{4}\left|E(t)\right|^2 + \frac{1}{4}\left|E(t-\tau_d)\right|^2 + \frac{1}{2}Re[E(t).E^*(t-\tau_d)]$$

The interference term $I_{N,out}(t)$ is:

$$I_{N,out}(t) = \frac{1}{2}Re[E(t).E^*(t-\tau_d)] \qquad (1)$$

Equation (1) can be written as:

$$I_{N,out}(t,\tau_d,\Delta\phi) = Re\left\{\frac{I_o}{2}\exp[j(\omega\tau_d + \Delta\phi(t))]\right\}$$

where $I_o = E_o^2$ is the average optical intensity and the phase noise variable $\Delta\phi(t)$ is defined as:

$$\Delta\phi(t) = \phi(t) - \phi(t-\tau_d)$$

The noise power spectral density (NPSD) can be calculated from the normalized Fourier transform of the autocorrelation function R(t) of the interference term $I_{N,out}(t)$. The autocorrelation function R(t) is:

$$R(t) = \langle I_{N,out}^*(t',\tau_d,\Delta\phi(t')).I_{N,out}(t'+t,\tau_d,\Delta\phi(t'+t))\rangle$$

At quadrature operation of the interferometer, R(t) can be written as [5]:

$$R(t) = \frac{I_o^2}{4}\exp[-8\int_0^\infty S_F(f)\frac{\sin^2(\pi t f)}{f^2}\sin^2(\pi\tau_d f)df]$$

where $S_F(f)$ is the spectrum of the instantaneous frequency fluctuation (FM-noise spectrum). The FM-noise consists of a white noise component (C_1) and a 1/f noise component (C_2/f) and we have:

$$S_F(f) = C_1 + \frac{C_2}{f}$$

where C_1 and C_2 are constants, $C_1 = 1/(\pi^2\tau_c)$, τ_c is the coherence time, $\tau_c = 1/(\pi\Delta\upsilon)$, $\Delta\upsilon$ is the laser linewidth and can be expressed as: $\Delta\upsilon = \Delta\upsilon_{ST}(1+\alpha^2)$, $\Delta\upsilon_{ST}$ is the linewidth predicted by the well-known Schawlow-Townes and α is the linewidth enhancement factor introduced by Henry, also called chirp factor. $C_2 = 1/(2\pi\tau_{1/f})^2$, $\tau_{1/f}$ is the coherence time of 1/f noise. The NPSD can be written as:

$$S_{I_{N,out}}(f,\tau_d) = FT[R(t)] \qquad (2)$$

where FT is the Fourier transform.

Simulation results fit very well experimental measurements. Constants C_1 and C_2 have been extracted from fitting our experimental data as well be shown in Fig. 4 (see section IV). We have then obtained:

$C_1 = 6.37\times 10^4$ Hz, $C_2 = 10^9$ Hz^2,

which leads to $\tau_c = 1.59\mu$ s.

III. INFLUENCE OF CHIRP ON INTENSITY NOISE IN MICROWAVE MODULATED INTERFEROMETRIC SYSTEMS

With considering the direct modulation of a laser, the optical field at the input of interferometer has both amplitude and frequency modulation. It is expressed as:

$$E(t) = E_o\sqrt{1 + m\cos(\omega_m t)}e^{j\beta\sin(\omega_m t)}e^{j(\omega_o t + \phi_{in} + \phi(t))}$$

where E_o is the field amplitude (it is not modulated), m is the intensity-modulation index, β is the frequency-modulation index (due to the laser diode chirp), f_m is the modulation frequency (microwave range), ϕ_{in} is the constant phase of laser and $\phi(t)$ is the instantaneous phase and represents the laser phase noise.

Under small sinusoidal signal modulation, β and m are correlated by [11]:

$$\frac{\beta}{m} = \frac{\alpha}{2}\sqrt{1+\left(\frac{f_g}{f_m}\right)^2} \qquad (3)$$

where f_g is a characteristic angular frequency depending on the laser diode and on its bias point. When f_m is high enough, but lower than f_R, α is approximated to:

$$\alpha \cong 2\beta/m \qquad (4)$$

Our experimental DFB laser diode has a resonant frequency f_R around 7 GHz at a bias point of 35mA, a threshold current I_{th}=9.3mA, a slope efficiency η=0.95mW/mA and $\alpha \cong 5$. In the case of a fixed intensity modulation index, m=0.4, then $f_g \approx 1.4$ GHz for our experimental laser, above which β is constant and equals 1. The effects of large frequency modulation with large β have been explored by investigating different modulation frequencies $f_m < f_g$, since β decreases with f_m (Eq. (3)).

The interference term $I_{N,out}$ can be written as:

$$I_{N,out}(t,\tau_d,\Delta\phi) = Re\Big\{ \frac{E_o^2}{4}\sqrt{1+2m\cos(\omega_m\tau_d/2)\cos(\omega_m(t-\tau_d/2))}\times$$
$$\times\exp\{j[\omega_o\tau_d + 2\beta\sin(\omega_m\tau_d/2)\cos(\omega_m(t-\tau_d/2))]\}\times$$
$$\times\exp(j\Delta\phi(t))\Big\} \qquad (5)$$

At quadrature operation of the interferometer, the autocorrelation function R(t) can be written as:

$$R(t) = \frac{I_o^2}{4}[1+4m\cos(\omega_m\tau_d/2)\cos(\omega_m t/2)$$
$$\times\cos(\omega_m(t-\tau_d/2)) + 4m^2\cos^3(\omega_m\tau_d/2)$$
$$\times\cos(\omega_m(t-\tau_d/2))]^{1/2}$$
$$\times\cos[4\beta\sin(\omega_m\tau_d/2)\sin(\omega_m t/2)\sin((\omega_m(t-\tau_d)/2))]$$
$$\times\exp[-8\int_0^\infty S_F(f)\frac{\sin^2(\pi t f)}{f^2}\sin^2(\pi\tau_d f)df] \qquad (6)$$

The noise power spectral density can be calculated as:

$$S_{I_{N,out}}(f,\tau_d) = FT[R(t)] \qquad (7)$$

The noise power spectral densities under various β and f_m ($f_m<f_g$, $\alpha=5$ and m=0.4 in Eq. (3)) are shown in Fig. 2 for the previous values of C_1, C_2 and $\tau_d=6.61\tau_c$ (to be compared with Fig. 5).

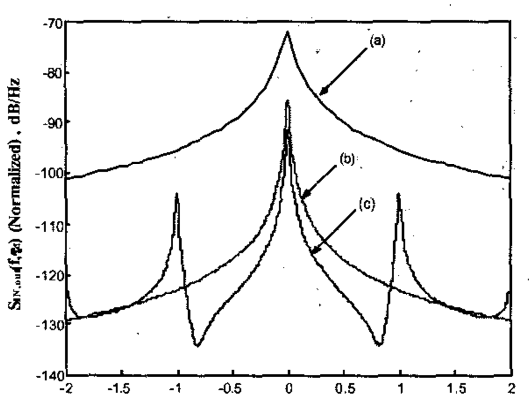

Fig. 2. NPSD normalized, in incoherent regime ($\tau_d=10\tau_c$) (a) $\beta=2$, $f_m=800$ MHz, (b) $\beta=28$, $f_m=50$ MHz, (c) $\beta=140$, $f_m=10$ MHz .

The modulation will move the low-frequency noise spectrum to harmonics of the modulation frequency f_m. For more simplicity, we have shown the noise power around f=0.

Figure 2 shows that the variations in the noise power spectral density with frequency depend strongly on β. The close-to carrier phase noise is reduced by proper choice of β (which depends on both f_m and α).

It is shown that, we have interest in increasing the frequency modulation index β, for both purpose of better frequency mixing of analogue microwave subcarriers [9] and noise reduction in interferometric systems with direct modulation.

IV. EXPRIMENTAL RESULTS

The experimental setup is shown in Fig. 3.

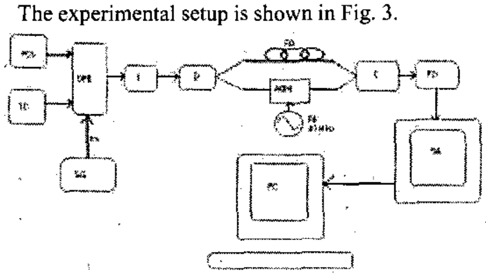

Fig. 3. Schematic experimental setup. TC: Temperature Controller, PCS: Precision Current Source, SG: Signal generator, DFB: Distributed Feedback laser, I: Isolator, D: Divisor, AOM: Acousto-Optic Modulator, PD: Photodetector, SA: Spectrum Analyzer.

The measured spectra are shown in Fig. 4a and 4b for the case of the coherent regime: $\tau_d/\tau_c=0.30$ ($\Delta L=96$m). Simulation data with $C_1=6.37\times10^4$Hz and $C_2=10^9$Hz^2 are plotted with measurement curves. As can be shown, a very good agreement is obtained.

The measurements of Fig. 5 show the influence of the modulation index β on noise power, for the incoherent regime ($\tau_d/\tau_c=6.61$ and $\Delta L=2102$m). It is shown that the higher β is, the lower the NPSD is. This confirm the simulation results of Fig. 2.

V. CONCLUSION

In this paper, we have presented theoretical calculations and experimental results of conversion of FM-noise to intensity noise in an RF-optical link which use UMZ interferometer and a directly modulated DFB laser diode. The calculations are valid for any regime of interference, coherent and incoherent. The influence of frequency modulation on intensity noise conversion is demonstrated, and it is shown that the linewidth enhancement factor has a strong influence on the noise power measured at the output of the unbalanced MZ interferometer.

A proper choice of the frequency modulation and of subsequent FM modulation index can reduce the noise conversion in self delayed interferometers. Experimental confirmations are shown in this paper.

These simulations of noise power spectral densities can be employed to estimate the laser phase noise performance and dynamic range of optical two-beam interferometer systems, as it can be used in optical radar signal processing where signal integrity is mandatory.

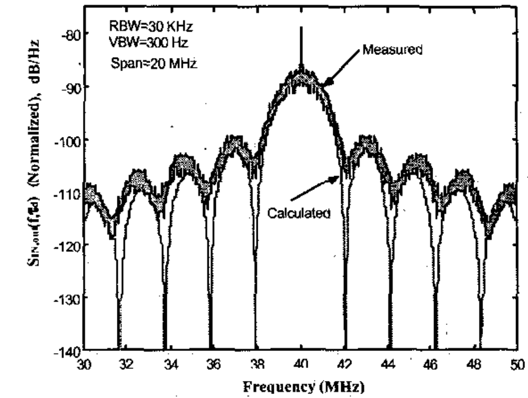

Fig. 4a

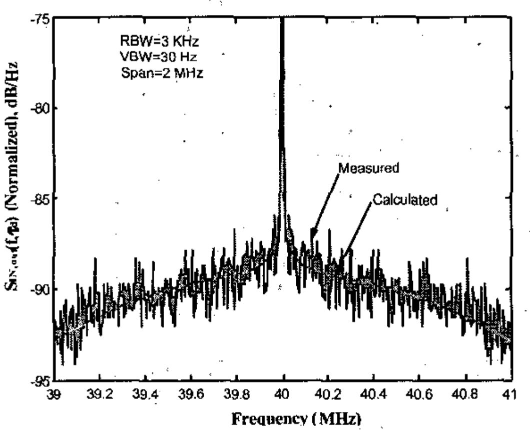

Fig. 4b

Fig. 4a and 4b. NPSD normalized, in the coherence regime and without modulation. Measurements and calculations are compared.

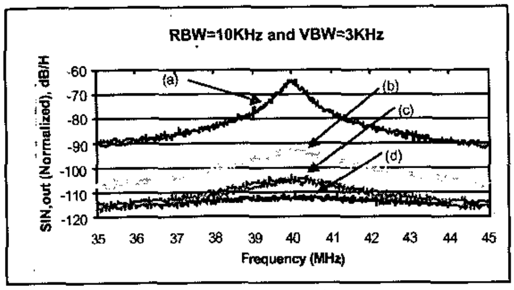

Fig. 5. NPSD measured in the incoherent regime (τ_d/τ_c=6.61) (a) f_m=800 MHz, β=2, (b) f_m=150 MHz, β=9.38, (c) f_m=100 MHz, β=14, and (a) f_m=50 MHz, β=28.

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