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PHASE NOISE CHARACTERISTICS OF LOCAL OSCILLATORS FOR SATELLITE COMMUNICATIONS EARTH STATIONS

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ABSTRACT

In this article we discuss the general characteristics of local oscillators for down conversion applications in satellite communications earth stations. We study the basic properties of phase noise and their implications in the local oscillator global performance. Our analysis is focussed on the characteristics of oscillators with bipolar and GaAsFET solid state devices. We also describe the role of the main oscillator parameters in relation to the general performance of the sat-link radio frequency front end.

RESUMEN

En este artículo se discuten las características generales de osciladores locales de conversores de bajada, utilizados en estaciones terrenas para comunicaciones vía satélite. Se estudian las propiedades básicas del ruido de fase y sus implicaciones en el funcionamiento global del oscilador. El análisis se enfoca a dispositivos de estado sólido de tipo bipolar y GaAsFET. Se describe también el papel que los parámetros del oscilador juegan en relación al equipo receptor de radio frecuencia del enlace vía satélite.

1. INTRODUCTION

Microwave solid state oscillators have an important function as local oscillators in satellite communications earth stations frequency conversion subsystems. The main function of the local oscillator is to provide a reference signal which associated to the input signal determines the intermediate frequency (IF) of the reception system. This IF signal is obtained through the mixing process of the reference local oscillator signal (LO) and the down link input signal (RF), that is to say: IF = LO ± RF. In conventional TVRO (television receive only) systems the typical IF is 70 MHz. The local oscillator reference frequency is determined then by Eq. (1):

$$\mathrm{LO} = \mathrm{RF} \pm 70\ \mathrm{MHz} \quad . \tag{1}$$

In the mixing process, spurious intermodulation products are also generated. This is due to the non-linear characteristics of the mixer which has a transfer function described by Eq. (2):

$$I = f(V) = a_0 + a_1 V + a_2 V^2 + \ldots + a_n V^n \quad . \tag{2}$$

The applied voltage V, consists of the local oscillator signal and the RF signal at the input of the mixer. The mixer output current is given by Eq. (3):

$$I = f(V) = a_0 + a_1(V_{LO}\,\mathrm{sen}\omega_{LO}t + V_{RF}\,\mathrm{sen}\omega_{RF}\,t) + \\ + a_2(V_{LO}\,\mathrm{sen}\omega_{LO}\,t + V_{RF}\,\mathrm{sen}\omega_{RF}\,t)^2 + \ldots \qquad (3)$$

The two components of Eq. (3) show that a DC level as well as the original signals will be present at the mixer output. The frequency products $\omega_{LO} - \omega_{RF} = \omega_{IF}$ are obtained from the second order term and their amplitude is proportional to a_2. The third and higher order terms of Eq. (3) generate intermodulation products of the form $n\omega_{LO} + m\omega_{RF}$. These terms can be frequency allocated inside the desired IF range and can be processed as noise. The amplitude level of such products are influenced by the local oscillator power level. According to Henderson$^{(1)}$, the local oscillator power level is 20 dbm higher than the RF input level, but lower than the maximum dynamic range of the mixer. If the local oscillator central frequency changes in small time intervals around its nominal value, the mixer will process these changes as spurious signals creating undersirable signals located in the neighborhood of the intermediate frequency. An analysis of the influence of the frequency variations is described in this paper with emphasis to satellite communications down converters.

2. PHASE NOISE CHARACTERISTICS OF MICROWAVE OSCILLATORS

Phase noise is defined in function of the short term frequency stability as any phase or frequency random fluctuation around the oscillator nominal frequency of operation ocurred in time intervals of the order of seconds or less.

There are different ways to represent and measure phase noise. Time domain representation of phase noise is shown in Fig. 1.

Equation (4) describes the behavior of an ideal local oscillator signal:

$$V(t) = V_s \mathrm{COS}(\omega_{LO}\ t) \quad . \qquad (4)$$

Actual behavior of the signal including random phase fluctuations is described by Eq. (5):

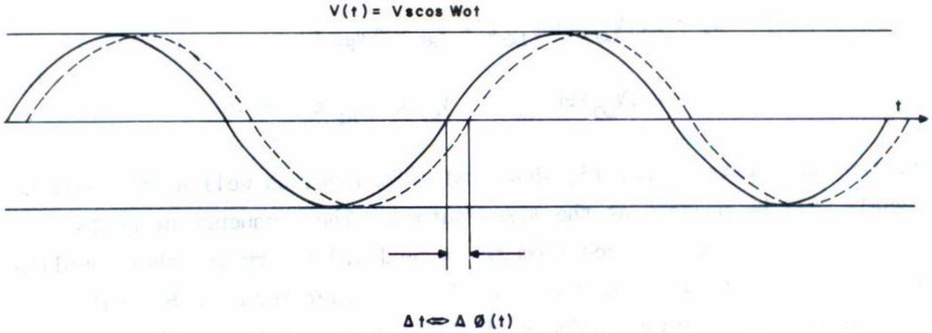

Fig. 1. Time domain phase fluctuations.

$$V(t) = V_s COS\omega_{LO}\ t + \Delta\phi(t) \qquad , \tag{5}$$

where V_s is the amplitude signal, ω_{LO} is the nominal oscillation frequency and $\Delta\phi(t)$ represents the random phase fluctuations of the signal. Phase and frequency fluctuations are related by Eq. (6):

$$f(t) = \frac{1}{2\pi}\frac{d\phi(t)}{dt} \tag{6}$$

The effect of $\Delta\phi(t)$ in the output of an earth station down converter is described in time domain in Fig. 2.

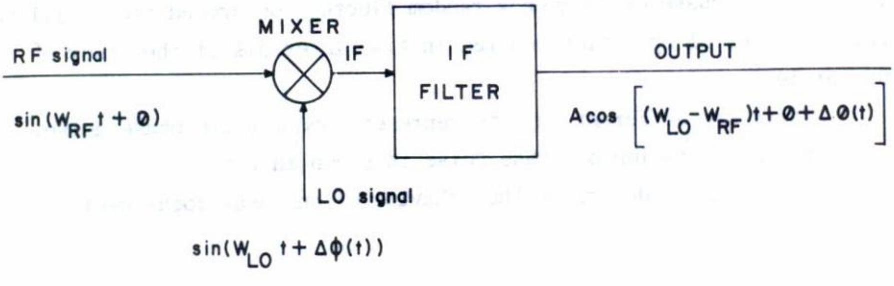

Fig. 2. Effect of $\Delta\phi(t)$ in the IF output signal.

As can be seen from Fig. 2 an intermediate frequency IF is modulated by $\Delta\phi(t)$ which is the local oscillator phase noise contribution.

This noise will be added to the video and audio output signals provoking information distortion.

Noise phase fluctuations are conveniently represented in frequency domain. The terms involved in frequency domain representation are $S_{\Delta\phi}(fm)$ and $S_{\Delta f}(fm)$ which are respectively the power spectral density of phase and frequency fluctuation.

Phase fluctuations in time domain $\Delta\phi(t)$ are related to frequency domain phase fluctuations as shown in Eq. (7):

$$\Delta\phi(fm) = \S\{\Delta\phi(t)\} \quad , \tag{7}$$

where § is the Fourier transform operator and fm is the Fourier frequency (sideband-offset-modulation, base band frequency). The spectral density of phase noise $S_{\Delta\phi}(fm)$ is defined as the mean square value of phase fluctuations in frequency domain:

$$S_{\Delta\phi}(fm) = \Delta\phi^2 \text{rms in } (\text{rad}^2/\text{Hz}) \quad . \tag{8}$$

Equation (8) is in turn related to the spectral density frequency fluctuations by Eq. (9):

$$S_{\Delta f}(fm) = \Delta f^2 \text{rms} = f^2 \Delta\phi \text{ rms} = f^2 S_{\Delta\phi}(fm) \text{ in } \left(\frac{\text{Hz}^2}{\text{Hz}}\right) \quad . \tag{9}$$

A common way to represent phase noise in frequency domain is in terms of sideband signal to noise ratio. L{fm} is defined as the ratio of single sideband phase noise power (P_{SSB}) to total signal power (P_S) in a 1 Hz bandwith fm hertz from the carrier:

$$L\{fm\} = \frac{P_{SSB} \text{ fm Hz off the carrier (in a 1 Hz Bandwidth)}}{\text{Carrier Power Level}} \quad . \tag{10}$$

L{fm} is related to $S_{\Delta\phi}(fm)$ and $S_{\Delta f}(fm)$ in the following way$^{(2)}$:

$$L\{fm\} = \frac{1}{2} S_{\Delta\phi}(fm) = \frac{1}{2f^2} S_{\Delta f}(fm) \quad . \tag{11}$$

Under the assumption that total phase deviation is less than 1 radian, a graphic representation of L{fm} is shown in Fig. 3.

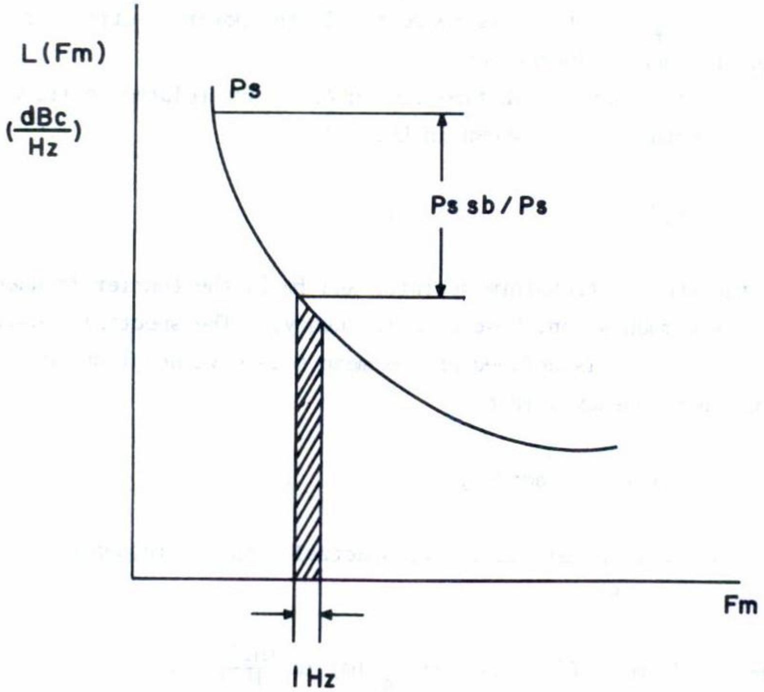

Fig. 3. Frequency domain representation of oscillator phase noise.

One of the most common problems in earth stations is the signal to noise ratio limitation imposed by local oscillator phase noise. Due to the fact that the noise phase characteristic of the local oscillator are transferred through the mixer to the IF signal, $S_{\Delta\phi}(fm)$ appears as a constant noise power at the demodulator output. Figure 4 shows a simplified block diagram of a FM down link earth station. The signal to noise ratio shown for the system shown in Fig. 4 is given by$^{(3)}$

$$\frac{S}{N} = \frac{P_s}{P_r} = \frac{K_f^2}{2} \frac{\int_{fa}^{fb} Sv(f)\, df}{\int_{fa}^{fb} L\{fm\}\, df} \quad . \tag{12}$$

Where K_f is the modulation gain constant, Sv(f) is the demodulated instantaneous voltage spectral density, fa and fb are the cut-off frequencies of the band-pass filter. It can be seen from Eq. (12) the important influence of the value of L{fm} on the receivers S/N level.

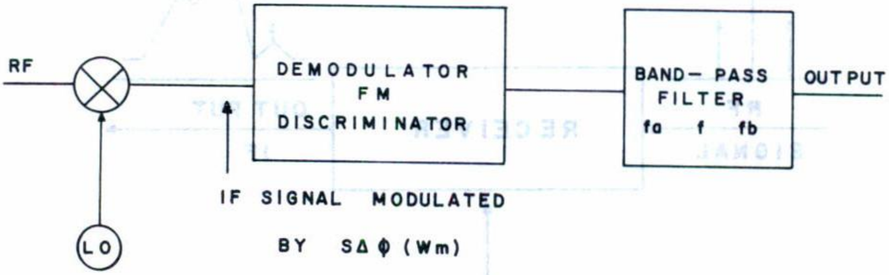

Fig. 4. Earth station down conversion simplified block diagram.

Another effect of local oscillator phase noise is depicted in Fig. 5. In this case there is a loss of sensitivity in the receiver system caused by the apparent increase in floor noise level. Equation (13) provides information about the increase of floor noise (FN) in function of L{fm}(3):

$$\text{FN apparent (dB/Hz)} = 10 \log \left[F + KT - \text{Psin} + L\{fm\}\right] \quad , \qquad (13)$$

where F is the receiver noise figure, Psin is the power at which the receiver is tunned.

3. LOCAL OSCILLATOR PHASE NOISE PARAMETERS

An analysis of those parameters that determine the local oscillator phase noise level has been described in an important paper by Lesson(4). In this paper an oscillator phase noise model which is shown in Fig. 6b is proposed. The oscillator is considered as a feedback amplifier associated to a band-pass filter circuit. A general expression of the output phase noise spectral density $S_{\phi_1}(\omega m)$ of Fig. 6b is given by(5)

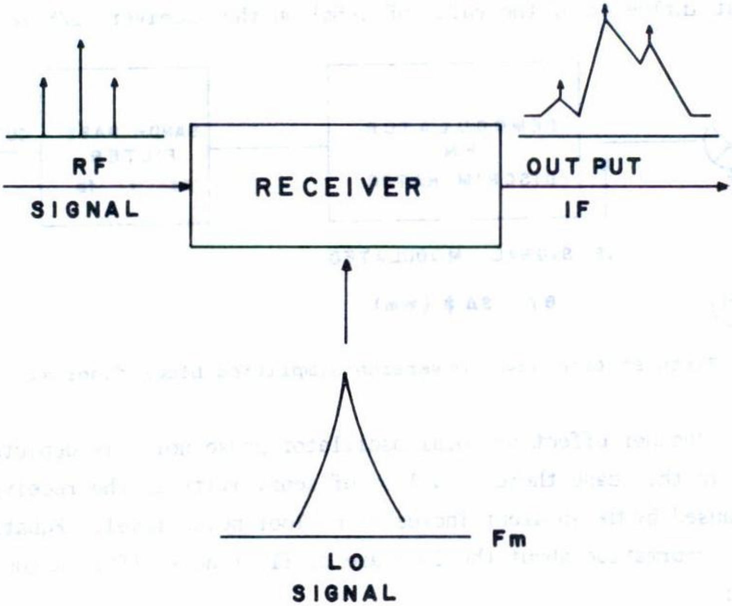

Fig. 5. Effect of phase noise oscillator on the earth station signal-noise ratio.

$$S_{\phi_1}(\omega m) = S_{\phi_0}(\omega m)\ \left|\left(H(j\omega) - 1\right) H^*(j\omega)\right|^{-1} \quad , \tag{14}$$

where $S_{\phi_0}(\omega m)$ is the phase noise spectral density contribution of the active device. $H(j\omega)$ is the equivalent band-pass filter (or resonator) transfer function which is given as follows:

$$H(j\omega) = \frac{1}{1 + j\dfrac{2\omega m\, Q_L}{\omega_0}} , \tag{15}$$

where $\omega_0/2\,Q_L$ is the half power Bandwidth of the resonator, Q_L is the loaded quality factor and ω_0 is the resonance frequency.

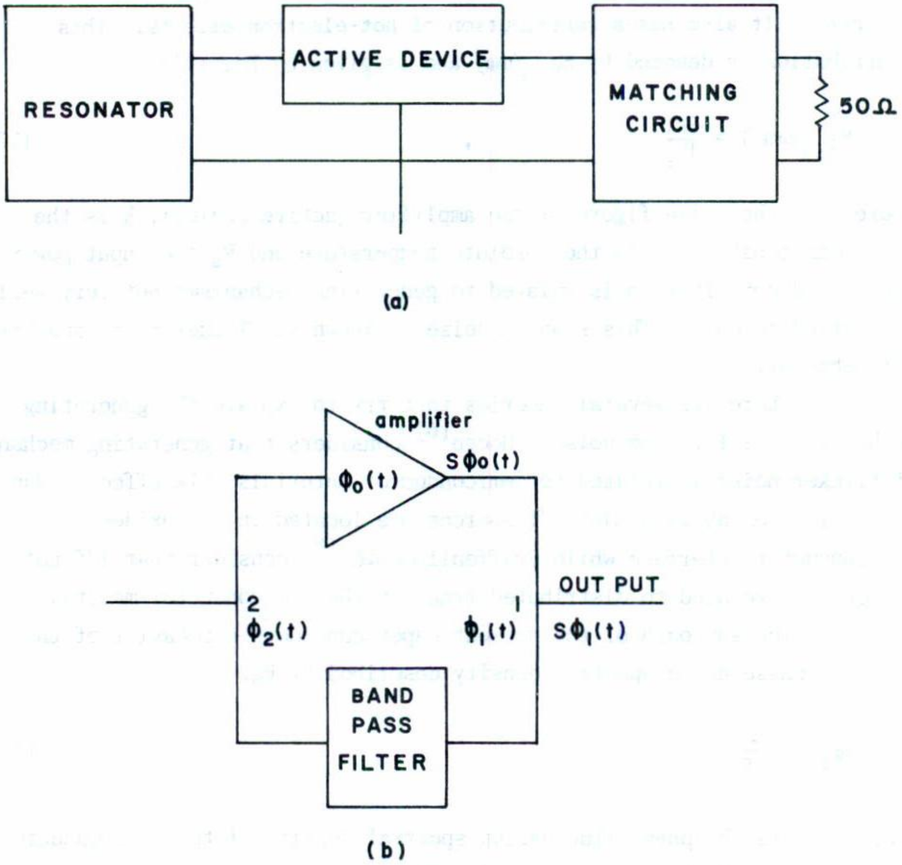

Fig. 6. Circuit oscillator model (a). Noise oscillator model (b).

Substituting Eq. (15) in Eq. (14) the following equation is obtained:

$$S\phi_1(\omega m) = S\phi_0(\omega m)\left|1+\left(\frac{\omega_0}{2Q_L\omega m}\right)^2\right| \quad . \qquad (16)$$

The phase noise spectral density of the active device has two main contributions. One is related to additive white noise with flat frequency response. In GaAsFET microwave devices this noise is associated with the noise generated in the channel and induced via capacitance through the gate. It also has a contribution of hot-electron effects. This contribution is denoted by $S\phi_{0a}(\omega m)$ and is given by Eq. (17):

$$S\phi_{0a}(\omega m) = \frac{FkT}{P_s} \quad , \tag{17}$$

where F is the noise figure of the amplifier (active device), k is the Boltzmann constant, T is the absolute temperature and P_s the input power. The second contribution is related to generating mechanisms not very well understood to date. This kind of noise in known as flicker noise and has 1/f behavior.

There are several theories that try to explain the generating mechanism of 1/f random noise. Hooge$^{(6)}$ considers that generating mechanism of flicker noise is related to semiconductor materials bulk effect. Van der Ziel$^{(7)}$ establishes that 1/f sources are located in the oxide-semiconductor interface while Graffeuil *et al.*$^{(8)}$ consider that 1/f noise sources are related to distributed traps in the semiconductor material.

The approach of the present paper considers a behavior of the device's phase noise spectral density described by Eq. (18)$^{(9)}$:

$$S\phi_{0b} = \frac{\alpha}{\omega m} \quad , \tag{18}$$

where $S\phi_{0b}$ is the phase fluctuation spectral density of the semiconductor device due to flicker noise, α is the flicker noise parameter (intensity of flicker noise) that has an average value$^{(8)}$ of around 10^{-4}.

The total spectral density of phase fluctuation is given as the sum of the white and flicker contributions:

$$S\phi_0(\omega m) = S\phi_{0a}(\omega m) + S\phi_{0b}(\omega m) \quad , \tag{19}$$

$$S\phi_0(\omega m) = \frac{FkT}{P} + \frac{\alpha}{\omega m} \quad . \tag{20}$$

Behavior of Eq. (20) is shown in Fig. 7, where ω_c is the crossing frequency between thermal and flicker noise for the active device. It is obvious to note from Fig. 7 that for frequencies lower than ω_c the basic noise contribution is due to flicker noise while for frequencies higher than ω_c the main contribution is due to thermal noise.

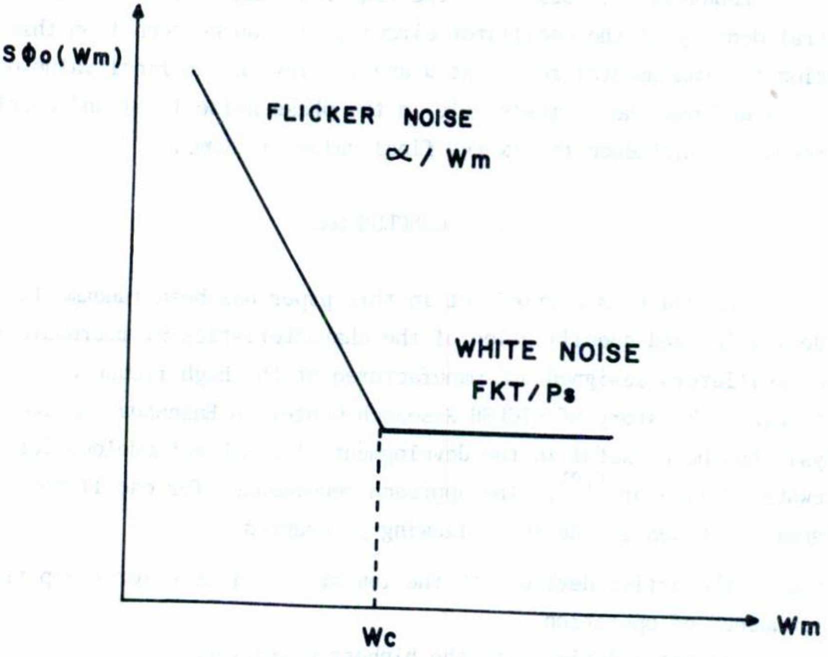

Fig. 7. Noise spectrum of the active device.

It has been shown that for GaAsFET devices the flicker contribution is considerably higher than in bipolar devices. This means that for GaAsFET devices ω_c is higher than for bipolar devices$^{(9)}$.

With the total oscillator circuit, the phase fluctuations of the active device are related to the resonator transfer function resulting the following important expression:

$$S_{\phi_1}(\omega m) = \left(\frac{\alpha}{\omega m} + \frac{FkT}{P_s}\right)\left(1 + \left(\frac{\omega_0}{2Q_L\omega m}\right)\right) , \tag{21}$$

and due to the relation L{fm} = $\frac{1}{2}$ S$\phi(\omega)$ we obtain finally

$$L\{\omega m\} = \frac{1}{2}\left(\frac{\alpha}{\omega m} + \frac{FkT}{Ps}\right)\left(\frac{\omega_0}{2Q_L\omega m}\right) \quad . \tag{22}$$

Equation (22) describes the required single sideband phase noise spectral density of the oscillator circuit. It can be seen from this equation the fundamental role that α and Q_L play in the final value of $L\{\omega m\}$. α defines the device's role in the phase noise level and Q defines the resonator influence to fix the final value of $L\{\omega m\}$.

4. CONCLUSIONS

The analysis carried out in this paper has been fundamental in the definition and specification of the characteristics of microwave solid state oscillators designed and manufactured at the high frequency electronics laboratory of CICESE Research Center in Ensenada, Mexico. The analysis has been useful in the development of a CAD methodology for microwave oscillators(10). The approach recommended for oscillator designers is based in the two following procedures:

1. Choose the active device with the lowest α available for the particular frequency of operation.
2. Use a resonator device with the highest Q available.

The consensus among researchers is that the oscillator noise spectrum is generated not at microwave frequencies, but instead is a result of an up-conversion of low-frequency noise mixing with the carrier frequency in non-linear elements of the active device.

According to Rohdin(11), besides steps (1) and (2) above mentioned, a large signal design instead of Leeson's model would improve the oscillator noise performance. Bianchini(12) and Riddle(13) have proposed methods for reducing phase noise level from its nominal value through frequency-locked loop and optimization of oscillation impedance respectively. The specific source of phase noise has not been defined precissely to date. However, it is beleived that low frequency noise source is related to charge fluctuation in the gate depletion layer. This effect could be neutralized by proper device design and choosing the optimum terminal structure.

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