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Accurate Phase Measurements of Broadband Multitone Signals using a Specific Configuration of a Large Signal Network Analyzer

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Presented at the IEEE Microwave Theory and Techniques Symposium 2006

Accurate phase measurements of broadband Multitone signals using a specific configuration of a Large Signal Network Analyzer

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Abstract — **Accurate measurements of time domain waveforms at microwave frequencies are performed using the harmonic sampling principle[1]. This principle used in the Large Signal Network Analyzer (LSNA) enables to transform a measured RF spectrum into an IF spectrum which is then digitized by ADCs. Unfortunately in this principle IF spectrum bandwidth is limited to 10MHz due to the need of high dynamic range ADCs (14bits). In this paper, we propose a new method that enables to accurately measure the phase relationships and the amplitudes of the spectral components of broadband microwave signals. Measurements of a 62MHz bandwidth multitone signal at L Band have been performed and are shown. The extension of the proposed method to wider bandwidth is absolutely possible. Furthermore the application of the proposed technique to other harmonic samplers than those used in the LSNA is also possible.**

Index Terms — **. LSNA Phase measurement, Broadband multitone signal, Time domain waveform, Spectral Stitching.**

I. Introduction

In depth characterization of the behavior of non linear devices requires an accurate determination of input and output time domain waveforms.

In order to extract time domain waveforms both amplitude and phase of the spectral components of the signal driving the device under test must be measured. Furthermore, nowadays there is a crucial need for wideband characterization of non linear devices such as power transistors because such devices are driven by more and more broadband modulated signals in modern communication systems.

There is also a need for accurate multitone characterization of power transistors, because the characterization and the optimization of linearity versus power added efficiency is very important and crucial for power amplifiers operating under multitone stimuli.

In the field of microwave instrumentation, the time domain waveforms of microwave signals can be obtained thanks to the harmonic sampling principle. This technique performed by the LSNA is limited to narrowband modulated signals (i.e 10MHz). This is due to the required trade off between the dynamic range of ADCs (14bits) and the sampling speed (25MHz).

In the first part of this paper, the principle of harmonic sampling performed within the LSNA is recalled and its limitations concerning the bandwidth are highlighted. In a second part we explain the proposed technique which enables larger measurement bandwidth. In the last part, the validation of the new characterization method is proposed by measuring the group delay of a band pass filter at L Band by using a multitone signal.

II. Harmonic Sampling Principle Performed In The LSNA

A block diagram that illustrates the harmonic sampling principle performed within the LSNA is given in Figure 1.

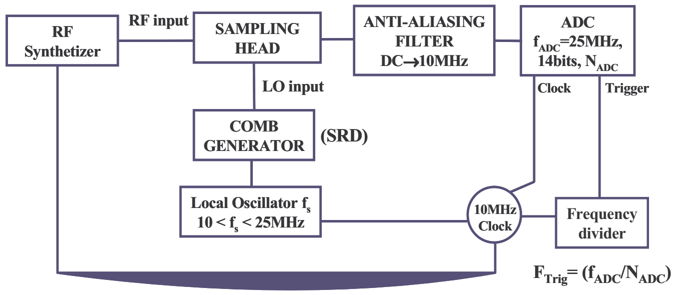

Fig. 1. Block diagram of the LSNA.

Let's take for example a RF input spectrum which is composed of harmonics of a CW microwave frequency as depicted in Figure 2.

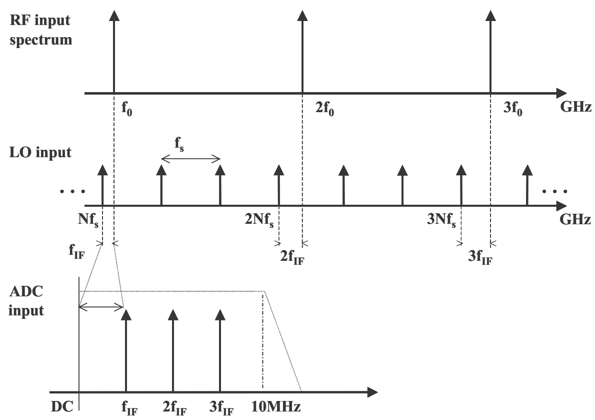

Fig. 2. Principle of harmonic sampling in CW mode.

If the frequency f_s of the oscillator is tuned so that $f_0\text{-}N\,f_s = f_{IF}$ then $(2f_0\text{-}2Nf_s) = 2f_{IF}$ and $(3f_0\text{-}3Nf_s) = 3f_{IF}$, N is an integer.

Nf_s, $2Nf_s$, $3Nf_s$ are harmonics of the oscillator frequency that are generated by the comb generator.

f_{IF}, $2f_{IF}$, $3f_{IF}$ are mixing products that fall within the bandwidth of the low pass filter following the sampling head. By using this harmonic sampling principle these low frequency components (f_{IF}, $2f_{IF}$, $3f_{IF}$) result from a frequency translation and compression of the input microwave spectral components at f_0, $2f_0$ and $3f_0$

The low frequency signal with f_{IF}, $2f_{IF}$, $3f_{IF}$ spectral components is then digitized by a 25MHz, 14bits ADC and a time domain waveform of the RF input signal is extracted.

Let us now consider the spectrum of an input RF modulated signal as depicted in Figure 3

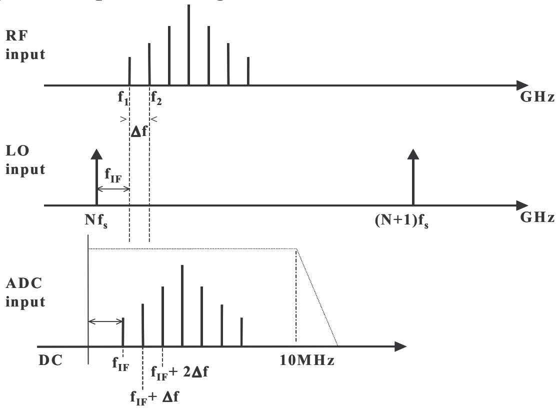

Fig. 3. Principle of harmonic sampling with modulated signal.

Nf_s is still tuned so that $(f_1-Nf_s) = f_{IF}$; f_1 being the first spectral component of the RF input spectrum.

Then $(f_2-Nf_s) = (f_2-f_1)+f_{IF} = f_{IF}+\Delta f$

It can be seen from this simple relationship that the modulated input RF spectrum is not compressed but only translated within the DC-10MHz bandwidth.

As a consequence, by using this principle for modulated or multitone RF signals, the measurement bandwidth is limited to 10MHz. Otherwise mixing products between the RF input spectrum and harmonic $(N+1)f_s$ of the oscillator fall within the DC$\rightarrow$10MHz bandwidth and therefore aliasing effects occur.

In the following we propose a method that enables wider bandwidth measurements.

III. THE PROPOSED METHOD

We want to measure a multitone signal on a frequency band larger than 10MHZ by using the LSNA measurement principle described above.

A. Definition of a multitone signal

Generally, a multitone signal is mathematically described by a set of discrete frequencies and the associated value of the spectral components. A periodic multitone signal is composed of N tones uniformly distributed with a tone spacing noted Δf. Each tone is defined by its amplitude A_k and its phase φ_k, the spectrum is centered around f_c, which is called the carrier frequency.

Figure 4 describes the spectrum of this signal:

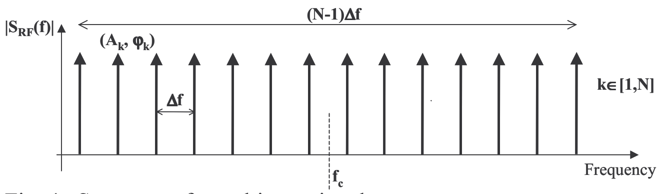

Fig. 4. Spectrum of a multitone signal.

This RF signal will be described as the product between the complex envelope (low frequency signal) and the carrier (high frequency signal):

$$S_{RF}(t)=\mathrm{Re}[env(t).s_c(t)] \quad (1)$$

Where ***env*(*t*)** indicates the complex envelope given by:

$$env(t)=\sum_{k=1}^{k=N} A_k e^{j\varphi_k}.e^{jk\left[-\frac{N-1}{2}\Delta\omega+(k-1)\Delta\omega\right]\cdot t} \quad (2)$$

The term $s_c(t)$ corresponds to the carrier signal, and is described by the following equation:

$$S_c(t)=A_c e^{j\varphi_c}\cdot e^{j\omega_c t} \quad (3)$$

The spectral components are represented by a complex number, having a phase and an amplitude. In what follows we will refer to a complex number as a phasor. It can be written as:

$$phasor(k)=X_k=A_k e^{j\varphi_k} \quad (4)$$

The transposition of these tones in the microwave domain requires the use of IQ modulators which modify the values of the phases applied to the tones generated at baseband. This work explains how harmonic sampling principle can be used to acquire the relative phase between the tones of a broadband multitone signal.

B. Repetitive Sampling

The sampling operation realizes a multiplication in time domain between the RF input signal and a comb signal generated by a SRD (Step Recovery Diode). The Figure 5 presents this principle:

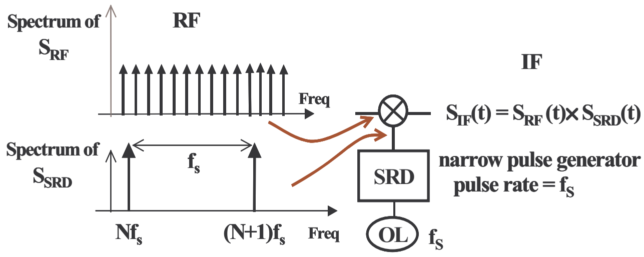

Fig. 5. Schematic of the harmonic sampling principle for a multitone input signal.

We consider a multitone signal which is composed by 14 tones. The bandwidth of this signal is wider than IF bandwidth.

Equations 5 and 6 describe the two RF input signals:

$$S_{RF}(t)=\sum_{k=1}^{k=N} A_k\cdot Cos\left[2\pi\left(f_0+(k-1)\Delta f-((N-1)\Delta f/2)\right)\cdot t+\varphi_k\right] \quad (5)$$

$$S_{SRD}(t)=\sum_n A_{LOn} Cos\left[2\pi\cdot n f_s\cdot t+\varphi_{LOn}\right] \quad (6)$$

The output IF signal is represented by equation 7 :

$$S_{IF}(t-\tau)=S_{RF}(t-\tau)\times S_{SRD}(t-\tau) \quad (7)$$

The delay τ represents the random start time of the ADC acquisition. By using a triggering technique, we assume that we have repetitive measurements.

Figure 6 represents the mixing process:

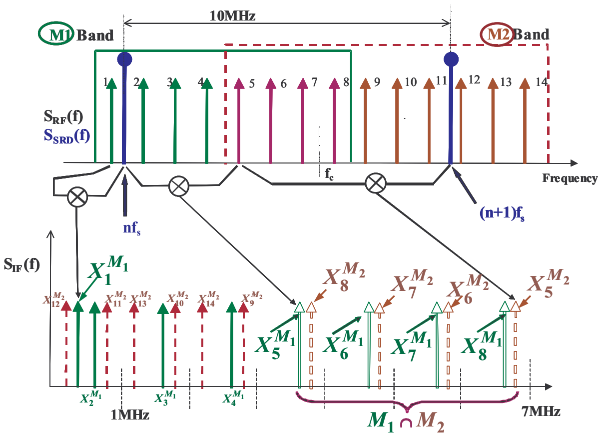

Fig. 6. Schematic of Principle for Spectral Stitching.

The 14 tones are mixed with two successive harmonics ((nf_s and $(n+1)f_s$) of the LO comb signal. So, the spectral components of the multitone input signal are scrambled in the 7MHz bandwidth of the IF low pass filter. The IF signal is digitised by the ADCs. A FFT algorithm enables us to compute the complex phasor X_k. The phase of tone number k=1 mixed with nf_s is:

$$\angle X_1^{M1}=-(n\cdot\omega_s-\omega_1)\cdot\tau-(\varphi_1-\varphi_{LOn}) \quad \textbf{Lower sideband (of nf}_s\textbf{)} \quad (8)$$

For k=2 to 11 mixed with nf_s :

$$\angle X_k^{M1}=(n\cdot\omega_s-\omega_k)\cdot\tau+(\varphi_k-\varphi_{LOn}) \quad \textbf{Upper sideband (of nf}_s\textbf{)} \quad (9)$$

For k=2 to 11 mixed with $(n+1)f_s$:

$$\angle X_k^{M2}=-((n+1)\cdot\omega_s-\omega_k)\cdot\tau-(\varphi_k-\varphi_{LOn+1}) \quad \textbf{Lower sideband (of (n+1)f}_s\textbf{)} \quad (10)$$

For k=12 to 14 mixed with $(n+1)f_s$:

$$\angle X_k^{M2}=((n+1)\cdot\omega_s-\omega_k)\cdot\tau+(\varphi_k-\varphi_{LOn+1}) \quad \textbf{Upper sideband (of (n+1)f}_s\textbf{)} \quad (11)$$

This technique enables us to realize a translation and a compression of a RF broadband multitone signal in a narrowband IF bandwidth. A 'descrambling' operation must be applied to recover the initial spectrum. A specific technique is used to eliminate the phase offset contribution (φ_{Lon} and φ_{Lon+1}) of the harmonics nf_s and $(n+1)f_s$. Van Moer and Yves Rolain [2], proposed a technique to improve the IF measurement bandwidth of LSNA.

C. Spectral Stitching

The idea is to measure the total spectrum using LSNA system to deduce different spectral parts around each harmonic of the Local Oscillator (LO) and to "stitch" all of the parts together in post-processing. Comparisons between the values of the phasors (Figure 6) measured in two different bands (M1, M2) can be used to eliminate the unknown phase contribution between consecutive spectra.

In the following, X_{kc} is defined as the common phasor measured in overlap between the M1 and M2 Band. According to Fig. 6, k_c can be equal to 5_c,6_c,7_c and 8_c.

For example, the correlated measured IF signal must lead to the following equality:

$$\angle X_{5_c}^{M1}=-\angle X_{5_c}^{M2} \quad (12)$$

Due to the differences of phase θ of the nf_s and the $(n+1)f_s$ frequency components of the comb generator, the previous equation (12) must be written :

$$\angle X_{5_c}^{M1}=-\angle X_{5_c}^{M2}+\theta \quad (13)$$

The objective of the spectral stitching technique is to determine the value of θ. This determination is realized by using a least-squares-error estimator based on the cost function C(θ) defined as:

$$C(\theta)=\sum_{k_c}\left|conj(X_{k_c}^{M2})-X_{k_c}^{M1}.e^{j\theta}\right|^2 \quad (14)$$

Despite the apparent obviousness of this technique only one reference was found mentioning the term "stitching" in relationship with frequency domain measurements [3].

The optimal value of θ, which minimize the cost function, can be determined by using equations 9 and 10 with $k_c=5_c,6_c,7_c$,or 8_c:

$$\theta_{min}=(\varphi_{LOn}-\varphi_{LOn+1})+\omega_s\cdot\tau \quad (15)$$

Then the value θ_{opt} can be used to eliminate the unknown phase contribution in M1. In practice the measurement of the phasor permits us to compute the cost function; the minimum of the cost function correspond to θ_{opt}.

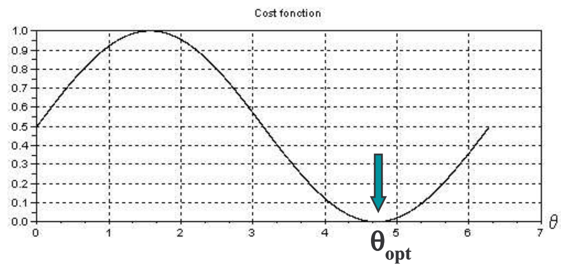

Fig. 7. The cost function

The same method can be applied to stitch together adjacent parts of the spectrum.

IV. The Results

The characteristics of the modulated signal generated with a Rohde & Schwarz signal generator are as follows:
The center frequency is f_c = 1.3GHz. The signal is composed of 32 tones. The tone spacing Δf is 2MHz. The total bandwidth is 62MHz. The amplitude of the tones are identical and their phases are equal to zero degree.

The parameters of the LSNA are as follows:

First, f_s= 10.47MHz has been tuned so that no aliasing occurs. Secondly, the ADC is triggered on a low frequency signal whose frequency is (f_{ADC} /N_{ADC}), This ensures the periodicity of the IF Measured signal. f_{ADC} = 25MHz and N_{ADC} the number of data acquisition is equal to 250000.

The hardware introduces systematic errors due to both amplitude and phase distortion. In order to remove these systematic errors, a proper calibration methods must be applied. In the first time we applied a proprietary IFCal procedure to compensate the effects of the filtering IF part. In the second time we applied the cost function to measure the spectrum of the multitone signal using seven adjacent measurement bands; finally the SOLT calibration (Short-Open-Load-Thru), allows to relate the raw measured quantities to the quantities at the calibration planes[4]. The method is applied to measure the group delay of a band pass filter at L Band by using a multitone signal. The schematic of this operation is illustrated in figure 8.

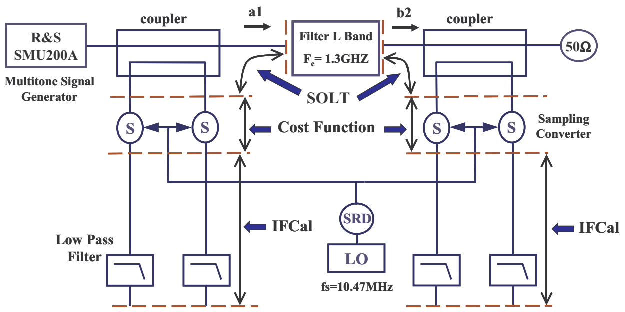

Fig. 8. The Schematic of the measurement using LSNA to measure the group delay of a band pass filter at L Band.

By derivating the phase difference (phase[b_2]-phase[a_1]) versus frequency, we extract the group delay of the filter under test.

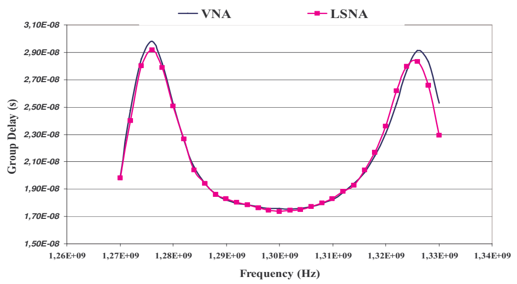

Fig. 10. Comparison of Measure of group delay of the filter by using LSNA and VNA.

Figure 10 presents a comparison of the group delay extracted from multitone measurements with LSNA and the group delay measured with a conventional vectorial network analyzer. The two curves are practically identical, except a little difference on the edge of the filter. Then this comparison confirms the validity of this method.

These results show the usefulness of this method to characterize the non-linearities of power amplifiers.

V. Conclusion

This study consists in implementing a method to accurately measure the modulated high frequency signal. These modulated signals will consist of several tones spaced by a fixed distance of frequency Δf which can vary from hundreds of Hertz to some Megahertz. The method based on " Spectral stitching " by using LSNA shows that it is possible to know the relative phase between tones of the broadband multitone resulting from the transposition of low frequencies towards high frequencies. Characterization of linearity of power transistors in term of NPR, is also possible. The measurement tool and the proposed technique is also expected to be very useful for the behavioral modeling of non-linear devices with memory. An other application of this technique, is the time domain waveform measurement of broadband multicarrier signal to evaluate the multipactor effect in satellite system. This work is in collaboration with French National Space Agency (CNES).

Acknowledgement

The authors wish to acknowledge the assistance and financial support of the CNES, the technical support of Marc Vanden Bossche (NMDG Engineering bvba, Bornem, Belgium), and the TARGET organization for the financial support in the context of the Workpackage 2.2.B.1-NOE classic-B Front-End Sampler Group (n° contract:507893).

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