A MICROWAVE MULTISINE WITH KNOWN PHASE FOR THE CALIBRATION OF NARROWBANDED NONLINEAR VECTORIAL NETWORK ANALYZER MEASUREMENTS.

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Abstract

A method is proposed to generate an RF multi-tone (up to 10GHz) calibration signal with a very narrow harmonic spacing (down to 100KHz) and a known phase relation between tones. This signal is requested for the phase calibration of a nonlinear vectorial network analyzer on a dense grid, as occurs when modulated signals are measured. The phase relation is traceable to a nose-to-nose calibrated microwave sampling oscilloscope.

Introduction

Calibration of nonlinear network analyzers [1,2,3,4] is requested for broadband and narrowband operation. One of the most challenging problems here is to obtain phase calibration over the frequency. Thereto, multitone signals with calibrated phase pattern [5] are requested.

The nonlinear network analyzers inherit all the classical calibrations methods, like f.i. SOLT, from their linear predecessors. However, they need two more calibrations: nl.

i) absolute amplitude response

ii) the relative phases at the frequencies where spectral energy is to be measured.

The absolute amplitude reference is performed using a power meter. The phase reference can only be performed through excitation of the nonlinear network analyzer by a phase calibrated signal.

When excited with a single tone, nonlinear components and nonlinear systems generate harmonics. Hence the calibrator signal must contain energy on an equally spaced broadband grid containing the fundamental frequency. When excited with multiple signals, nonlinear systems generate intermodulation between carrier and carrier, but also between modulating components. For the narrowbanded applications, i.e. applications where the carrier harmonics are eliminated by filters, the modulation/carrier or modulation/modulation intermodulation terms are the only measurable contributions. The frequency spacing of these tones is very low. To obtain calibrated measurements, the calibrator signal must also have tones at the same spacing positions.

This paper is entirely devoted to the design and the measurement of such a high frequency resolution multitone signal.

Principle of measurement

As explained in the paragraph about the measurement set-up, the calibrator signal is essentially a modulated signal. By choosing for this signal an amplitude modulated signal and by performing the measurements of the envelope with a microwave Digital Sampling Oscilloscope, we can extract from it the wanted phase relationship between the tones. The DSO is to our knowledge the only microwave bench instrument capable of measuring accurately the characteristics of a signal because it can be calibrated in amplitude and phase by a nose-to-nose calibration method [5,6].

The measurement of the envelope is not straightforward because a DSO cannot be triggered accurately on a modulated signal, so we can only trigger on the modulating signal and due to the phase incoherence between the carrier and the modulating signal, we will obtain time sequences of 1024 points randomly sampled on an amplitude modulated sinusoidal signal. By statistical processing of a large amount of such records we extract the envelope signal of the calibrator signal.

Indeed there are at least two methods to obtain the envelope:

i) we can use the 'Maximum-function' of the sampling scope to obtain the maximum value of the voltage at each sampled point.

ii) we can calculate the standard deviation of the voltage at each sampled point.

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The next question is how to estimate the phase of the different sideband frequency tones from the measured envelope.

The envelope detection is a deeply nonlinear operation for which the analytical expression is obtained after introducing the concepts of Hilbert transform and analytical signal [7,8] and it gives only the square of the envelope. So for a signal given by a grid of n sines:

$$s(t) = \sum_{p=1}^{n} a_p \cos(\theta_p) \qquad (1)$$

with $\theta_p = 2\pi f_p t + \varphi_p$, we obtain the square of the envelope function by:

$$a^2(t) = \sum_{p=1}^{n}\sum_{p=1}^{n} a_p a_q \cos(\theta_p - \theta_q) \qquad (2)$$

The signal s(t) will be declared to be a narrowband calibrating signal when we know the value of the phase φp for p=1 to n through measurements of the envelope signal a(t).

In our present case, for a carrier at f_c, that is double sideband modulated with a single modulation signal at frequency f_m, the square of the envelope function is given by:

$$\begin{aligned} a^2(t) &= a_2^2 + a_1^2 + a_3^2 + 2a_2a_1\cos(2\pi f_m t + \varphi_2 - \varphi_1) \\ &+2a_2a_3\cos(2\pi f_m t + \varphi_3 - \varphi_2) \qquad (3) \\ &+2a_1a_3\cos(4\pi f_m t + \varphi_3 - \varphi_1) \end{aligned}$$

where the amplitudes/phases of the carrier, the lower and the upper sidebands tones have respectively indexes 2, 1 and 3.

Both sidebands fold back, by pairs, on the same frequency f_m in the envelope.

The presence of a term at the double of the modulation frequency in this expression may not frighten us because it is a square of the time function. If we extract the square root of this expression, this term will disappear totally provide there is simultaneously: i) no over modulation, i.e. that the crest factor of the modulating multisine signal does not exceed the amplitude of the carrier and ii) no asymmetry or skewness of amplitude ($a_3 \neq a_1$) or phase ($\varphi_3 - \varphi_2 \neq \varphi_2 - \varphi_1$) appears between the lower and upper frequency sidebands due to imperfections of the amplitude modulation mechanism.

If both conditions are fulfilled, $a^2(t)$ behaves mathematically as a full square and the envelope function a(t) permits to measure the amplitude and the phase of the different frequency lines present in the calibrating multisine signal.

If the mixer behaves not symmetrically and produces skew sidebands, the method creates an undetermination because the measured phases of the envelope function are averages of the phases of the pairs of lower and upper sideband terms.

A simulation of the influence of the skewness of the amplitude modulator shows that the spectrum of the envelope signal undergoes a phenomenon of spectral regrowth, which means that besides the wanted modulation signals, a lot of intermodulation spectral lines do appear. Figure n° 1 illustrates the spectrum of the envelope of a carrier skewly modulated with a multisine of three components.

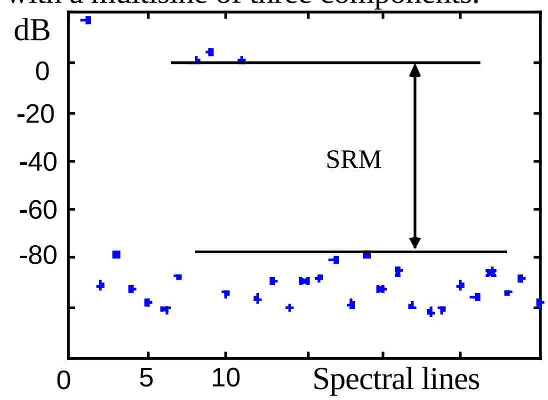

Figure n° 1: Spectral Regrowth Margin.

We see that we can define the ratio of the wanted to the spurious terms as f.i. a Spectral Regrowth Margin (SRM).

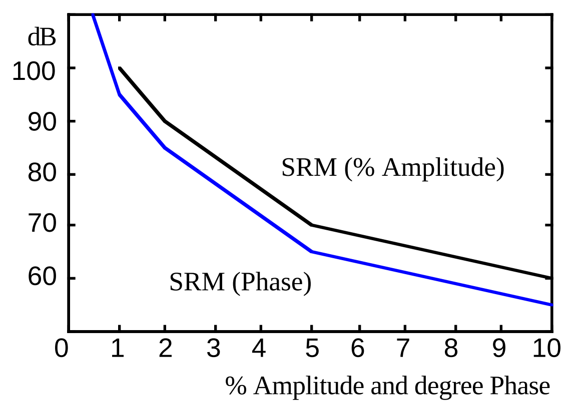

Figure n° 2: Spectral Regrowth Margin as function of skewness.

Figure n° 2 gives the influence of the skewness of the double sideband amplitude modulator on the Spectral Regrowth Margin due to amplitude unbalance (a_3/a_1) expressed in percent and the phase unbalance $[(\varphi_3-\varphi_2)-(\varphi_2-\varphi_1)]$ expressed in degrees.

Measurement set-up

The aim is to generate the narrowband calibrator signal through a single or a double sideband amplitude modulation of a microwave carrier by a baseband multisine. The baseband multisine contains three sinusiods, at about 100 kHz, 200 kHz and 300 kHz and relative phases of f.i. 0.0, + 90 and 0.0 degrees. It is produced by a VXI based arbitrary function generator of type HPE1340A.

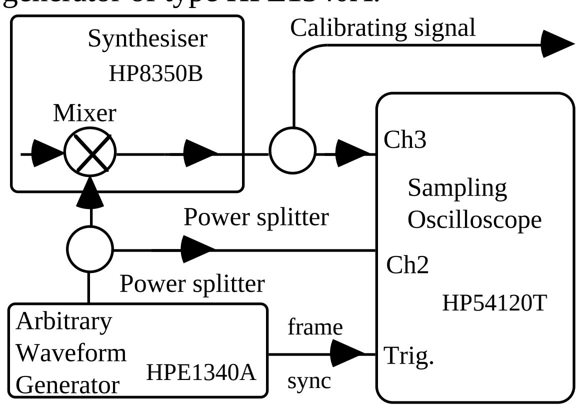

Figure nº 3: Measurement set-up

A HP 83650B microwave synthesizer produces a carrier at f.i. 10 GHz and by use of the internal modulation capability of the synthesizer it is mixed with the baseband multisine grid and produces as such a double sideband multisine, see figure nº 3 and 4.

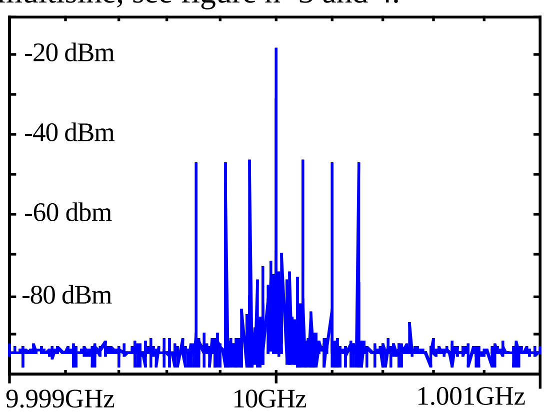

Figure nº 4: Spectrum of the calibrating multisine.

The measurement are all performed by a nose-to-nose calibrated microwave sampling oscilloscope type 54120T with a known amplitude and phase response up to 20 GHz. The scope is triggered from the basic clock available on the auxiliary output of the arbitrary function generator. The modulating multisine and the modulated calibrating signal are both connected to the sampling oscilloscope.

Experimental results

The measurement of the baseband multisine is an elementary operation and is shown in figure nº 5.

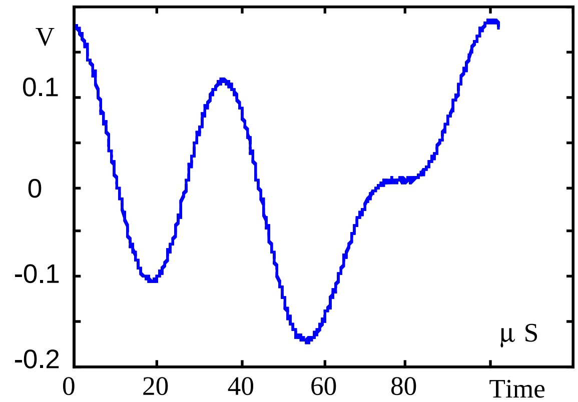

Figure nº 5: The modulating multisine signal.

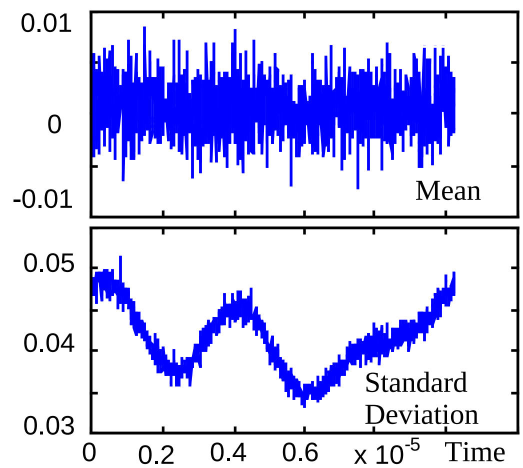

Figure nº 6: Envelope of the calibrating multisine measured by the standard deviation.

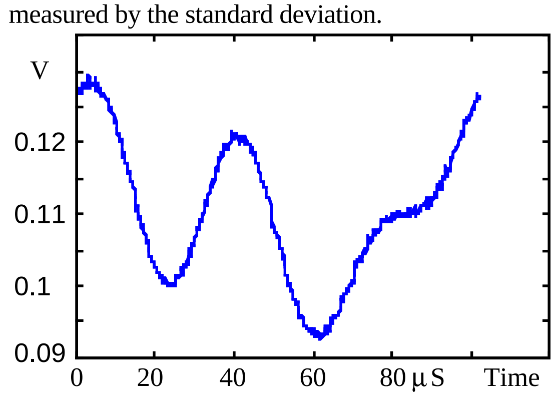

Figure nº 7: Envelope of the calibrator multisine measured by the 'Maximum-function' of the sampling oscilloscope.

The measured envelope obtained after processing 250 records is shown in figure nº 4 where the upper part shows the average and the lower the standard deviation while figure nº 5 shows the result of the 'Maximum-function' of the DSO. So both methods have been implemented and it is easy to conclude from this that the 'Maximum-function' behaves quite a lot less noisy.

The measurements performs very satisfactory as can be seen in figure nº 8 (where only the amplitude is shown) for a multisine with three terms at fm=97.65625 kHZ, 2fm and 3fm. These odd values of the frequency are chosen to avoid any frequency leakage of the Fourier transform performed on a sequence of 1024 time sampled points.

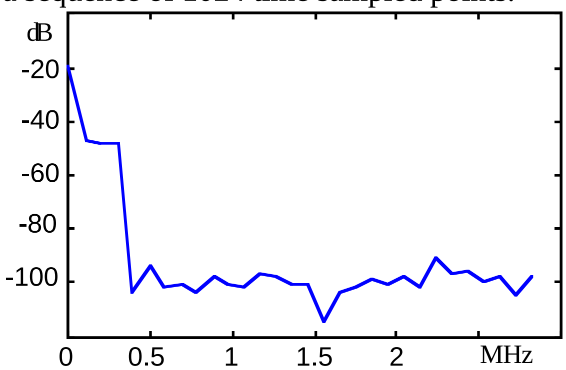

Figure nº 8: Amplitude of the envelope of the modulated signal.

The measurements of the phases of the three components fm, 2fm and 3fm of the envelope corresponding to the phases of the three components fc+fm, fc+2fm and fc+3fm of the calibrator signal are respectively -24.4, +43.6 and -67.2 degrees with a reproducibility of better than 1 degree. After reshuffling with formula (4), it gives the phases 0.0, +90.0 and +1.2 degrees.

The value of the Spectral Regrowth Margin of about 55 dB, see figure nº 8, compared with the results of the simulation of figure nº 2 should make us believe that the measured phases of the calibrator multisine signal are only known with an accuracy of ± 3.5 degrees. This is at least in contradiction with the above results and it make us think that there must happen a biasing of the envelope signal due to the measurement noise which needs to be further eliminated by an adequate estimator.

Conclusions.

A narrowband 10GHz calibrator multitone signal has been experimentally produced and the measurement of the envelope signal with a calibrated DSO permits to know the phases of the different sideband spectral tones.

Appendix about phases.

Note that the value of the phase of sinusoids at different frequencies has to be defined somewhat rigorously. It is obviously the argument of the complex value of the spectral line obtained after Fourier transformation of a time record, but the phase difference between two sinusoids at different frequencies increases linearly with the time, in fact with the moment on which the time record starts, so this figure has no absolute signification. On the contrary, if we consider three (or more) sinusoids of different frequencies, it is easy to prove that the phase differences calculated (modulo 2π) between three such spectral lines are proportional to the frequency differences.

$$\frac{(\varphi_3'' - \varphi_1'') - (\varphi_3' - \varphi_1')}{f_3 - f_1} = \frac{(\varphi_2'' - \varphi_1'') - (\varphi_2' - \varphi_1')}{f_2 - f_1} \quad (4)$$

where the phases $\varphi 1$,$\varphi 2$ an $\varphi 3$ belong to the spectral lines at the frequencies f1, f2 and f3, and the suffixes (') and (") correspond to two different measurement moments.

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