Calibrated Linear and NonLinear pulsed RF measurements on an amplifier

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***Abstract* - The calibration of a nonlinear vectorial microwave network analyzer (NVNA) used for continuous wave measurements (moderate number of frequency components) is extended for pulsed RF measurements (very large number of frequency components). The new calibration is based on the combination of the regular RF calibration with a separate IF calibration. Experimental results in pulsed regime are compared with results from a pulsed RF vectorial network analyzer (VNA).**

I. Introduction

When measurements are performed with the nonlinear microwave network analyzer (NVNA) in continuous wave (CW), only a restricted number of frequency components are measured. To calibrate these frequency components, an absolute RF calibration is performed at each frequency component [2]. When measurements are performed in pulsed RF, a large number of frequency components is measured [3]. This implies that each frequency component has to be calibrated. To do this with the absolute RF calibration, it is very difficult and time consuming.

A solution to this problem is splitting the calibration in two parts. In the first part, the distortions introduced by the RF hardware is removed using an absolute RF calibration. This part of the calibration is called the RF Cal (it varies slowly over the frequency). In the second part, the distortions introduced by the downconvertor electronics are removed. This is done by using the frequency response function of the downconvertor. This part is called the IF Cal which varies over the IF bandwidth. This calibration method is well suited for pulsed RF measurements. The measured harmonics of the carrier are calibrated with the RF Cal, while the measured pulse modulation spectrum is calibrated with the IF Cal.

II. Applicability of the method

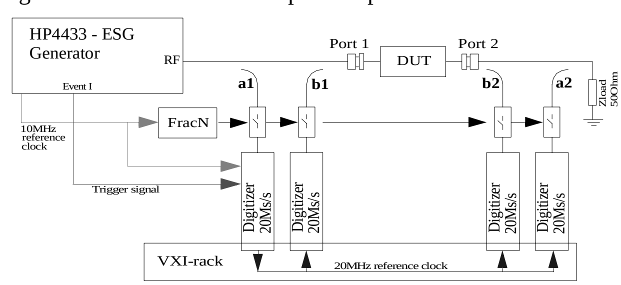
The method, which splits the calibration in a RF and IF part is possible when the following assumptions are made:

1. The frequency response function of the IF part (FRF) is independent of the RF carrier frequency, when the same grid (i.e. the downconversion frequency and clock frequency of the analog-to-digital (ADC) convertor is the same for several RF carrier frequencies) is used,
2. The FRF is independent of the downconversion frequency, when the same RF signal is used (i.e. FRF does not change if another downconversion frequency is used),
3. The characteristic of the couplers is flat and introduces only a linear phase distortion over the IF frequency band.

III. Measurement setup and principle

The block schematic of the NVNA [3] for pulsed RF measurements used here, is depicted in figure 1. The determination of the downconversion frequency is explained in [3].

Fig. 1. The measurement setup of the pulsed RF NVNA



IV. The RF calibration

To calibrate the harmonics of the carrier, an absolute calibration matrix (1) is used [2]:

$$\begin{bmatrix} a^i_{D1} \\ b^i_{D1} \\ a^i_{D2} \\ b^i_{D2} \end{bmatrix} = K^i \begin{bmatrix} 1 & \beta^i_1 & 0 & 0 \\ \gamma^i_1 & \delta^i_1 & 0 & 0 \\ 0 & 0 & \alpha^i_2 & \beta^i_2 \\ 0 & 0 & \gamma^i_2 & \delta^i_2 \end{bmatrix} \begin{bmatrix} a^i_{M1} \\ b^i_{M1} \\ a^i_{M2} \\ b^i_{M2} \end{bmatrix} \qquad (1)$$

with 'a' the incident wave, 'b' the reflected wave, 'D' the exact DUT waves, 'M' the measured waves, 'i' the frequency index and 'K^i' is a complex coefficient brought outside the calibration matrix.

The seven error correcting terms inside the calibration matrix are determined by use of a Load-Open-Short-Thru calibration procedure (SOLT). The amplitude of 'K^i' is determined by a power measurement, while the phase is determined by use of a reference generator.

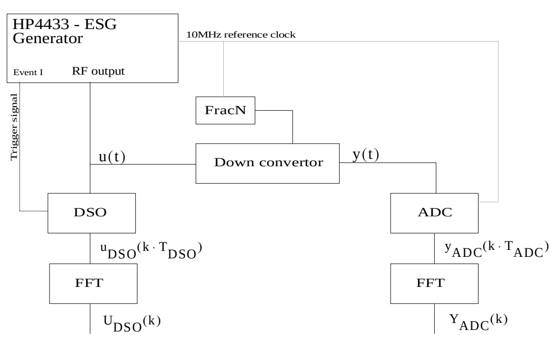
V. THE IF CALIBRATION

To calibrate the measured pulse modulation spectrum, the frequency response function of the IF part is used. Therefore, it is explained how the FRF is determined and how it is used to do the IF calibration. Note that this calibration step has to be achieved for each measurement.

A. Measurement setup and principle:

The setup to measure the FRF is shown in figure 2.

Fig. 2. Setup to measure FRF of the down convertor



A signal generator (type HP4433) produces a RF signal which is amplitude modulated (AM) by a multisine. This baseband multisine is defined as:

$$u_{mod}(nT_S) = \sum_{k=1}^{N} a_k \cdot \sin(k2\pi f_{mod} nT_s + \varphi_k) \qquad 0 < n < \infty \tag{2}$$

where 'f_{mod}' is the fundamental modulation frequency, 'N' the number of frequency modulation components with a maximum of $(IF_{bandwidth})/f_{mod}$, 'T_s' the sample period, 'n' the number of sample point, 'a_k' the amplitude and 'φ_k' the phase of the k'th sine. The phases of these N sinusoids are determined by use of the Schröder equation to reduce the crest factor [4]. The output signal $u(t)$ of the generator is the AM RF signal assuming that the generator produces no additional harmonic distortion. The signal $u(t)$ is measured with a calibrated digital sampling oscilloscope (DSO), which measures only the envelope of the signal using the envelope detection technique described in [5]. The signal $u(t)$ is also measured with the downconvertor and ADC of channel a1, which contains all the energy carrying frequency lines of the input signal. From this measured data, the frequency modulation components are selected and the envelope of the input signal, given in the FD by $Y_{ADC}(k)$, is calculated using the Hilbert Transform [6].

The FRF characteristic is then calculated by:

$$FRF(k) = \frac{Y_{ADC}(k)}{U_{DSO}(k)} \tag{3}$$

To calibrate the frequency modulation components of a measured wave (for example, incident wave a1), the following equation is used:

$$a^i_{EnvD1}(k) = \frac{a^i_{EnvM1}(k)}{FRF(k) \cdot S21_{coupler}\big|_{Frf}} \tag{4}$$

with 'EnvD' the exact DUT envelope waves, 'EnvM' the measured envelope waves and 'S21coupler' the S21 parameter of the coupler at the carrier frequency.

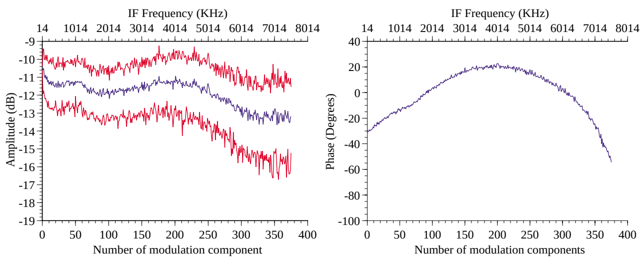
B. Experimental results:

For measuring the FRF, a baseband multisine with a fundamental modulation frequency of 20KHz and 375 frequency modulation components is used. The RF frequency is chosen at 1.008014GHz, because of two reasons. First, because the RF frequency may not be harmonically related to the fundamental modulation frequency when using the envelope detection technique [5]. Secondly, because the RF carrier has to fall on the IF grid in such a way that no spectral overlap between all the frequency components exist, when we know that the downconversion frequency is fixed at 16MHz [3]. The AM RF signal has a RF peak power of -10dBm. Channel 3 of the DSO is used and 16 successive measurements for 256 traces of 1024 sample points long were taken (note that 1 trace is equal to one modulation period). With the ADC a total of 1280000 sample points are taken, which contains also 16 successive measurements.

B.1. Hypothesis 1:

To check hypothesis 1, the RF carrier frequency is changed, so that all the frequency components fall at the same grid, while the downconversion frequency (Flo) is held constant. This means that carrier frequency lies at 14KHz after downconversion in all cases. The following values are used: 1.008014GHz (Frf1), 1.504014GHz (Frf2), 2.016014GHz (Frf3), 2.512014GHz (Frf4), 3.024014GHz (Frf5) and 3.504014GHz (Frf6). The resulting FRF at RF frequency 1.008014GHz for channel a1 is shown in figure 3, were the numerator and denominator of equation (3) contains here the sample mean over 16 successive measurements with his uncertainty region of 2 times the standard deviation. Note that the FRF for the other RF frequencies lies within that region. Remark that the upper x-axis shows the IF frequency, while the lower x-axis shows the number of modulation component.

Fig. 3. FRF down convertor for channel a1 in amplitude (left) and phase (right) for Frf1 and Flo=16MHz

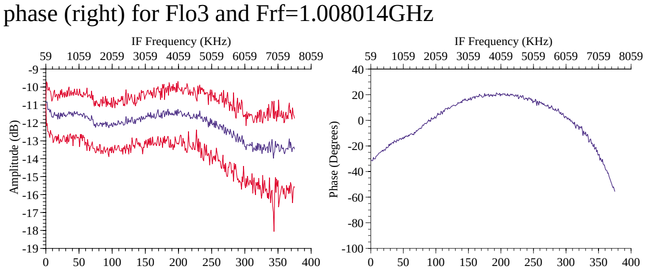


B.2. Hypothesis 2:

To check hypothesis 2, the RF carrier frequency is held constant at 1.008014GHz, while the downconversion frequency is changed. The following downconversion frequencies are used: 16MHz (Flo1), 15.75MHz (Flo2) and 15.507MHz (Flo3). The IF frequency (place of carrier in the IF band after downconversion) is respectively 14KHz, 14KHz and 59KHz. The resulting FRF at the Flo3 for channel a1 is shown in figure 4 in the same way as before.

When the amplitude characteristic of figure 3 and figure 4 are compared, the upper x-axis is important. As can be seen, a difference of 0.5dB at modulation component number 0 is established. This is normal because the carrier frequency lies in figure 3 at 14KHz and at 59KHz in figure 4.

Fig. 4. FRF down convertor for channel a1 in amplitude (left) and phase (right) for Flo3 and Frf=1.008014GHz



VI. Measurement results

A broadband amplifier (ERA-2 of Mini Circuits) is used as DUT. This device is measured with a pulsed RF VNA (Wiltron) and a pulsed RF NVNA (see section III.). The pulsed RF excitation signal used, is the same for both measurements and consist of a pulse waveform with a pulse period of 50us and a pulse width of 5us (duty cycle = 10%).

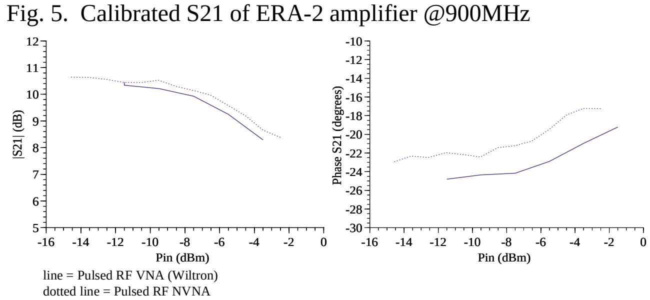
A. Pulsed RF VNA (Wiltron):

The DUT consist of the broadband amplifier plus a 20dB attenuator at the output. Before the measurements were taken, a linear calibration procedure (LOST) is done for an RF frequency sweep from 890MHz until 1200MHz with a frequency step of 1MHz (i.e. 311 frequency points). A dynamic range loss of -20.92dB results from the pulsed rf fixed profile measurement [7]. The RF peak power level at the input of the DUT is swept from -11.5dBm to -1.5dBm in steps of 2dB. Because the calibrated measured S21 contains both the S21 value of the amplifier and attenuator, the S21 of the attenuator is removed. Therefore, S21 of the 20dB attenuator was measured in CW. It gives at 900MHz a S21 value of -19.8dB for the amplitude and -27.5 degrees for the phase. The calibrated measured S21 of the amplifier as function of the input power is shown in figure 6 for a RF frequency of 900MHz. From this figure, it can be seen that the amplifier goes into compression when the input power level goes above -7.5dBm.

B. Pulsed RF NVNA (setup explained in section III.):

In this case, the RF frequency is swept from 900MHz to 1200MHz in two steps. The RF peak power level at the input of the DUT is swept from -14.6dBm to -2.5dBm in steps of 1dB. After performing a linear calibration (SOLT), the measured S-parameters are calibrated absolutely and the result for S21 as function of the input power is shown in figure 5 for a RF frequency of 900MHz. The difference in amplitude between the pulsed RF VNA and NVNA measurements is about 0.2dB for the overlapping input powers. The phase difference is about 2 degrees.

Fig. 5. Calibrated S21 of ERA-2 amplifier @900MHz



The time domain (TD) waveforms reconstructed from the calibrated data are shown for a RF carrier frequency of 900MHz and a RF peak power of -2.5dBm at the input of the DUT. During this measurement, the ADC has a fixed clock frequency of 20MHz and a block size of 35000 sample points. The calibration of the carrier harmonics is done for the first three harmonics using the absolute calibration matrix. The frequency modulation components are calibrated using the FRF of the downconvertor explained in section V. In figure 6, the reconstructed RF waveform of input wave a1, which is calculated using the Fourier Transform, is shown. In figure 7, the waveform a1 is zoomed in for the width of the pulse. The same is done for the output wave b2 in figure 8 and for the reflected wave b1 at the input of the DUT in figure 9.

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Fig. 6. Calibrated incident wave A1 (TD)

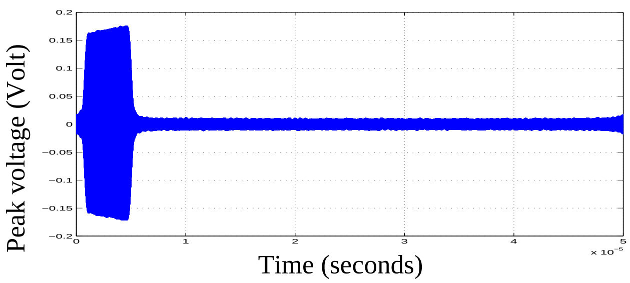


Fig. 7. Calibrated incident wave A1 (TD)

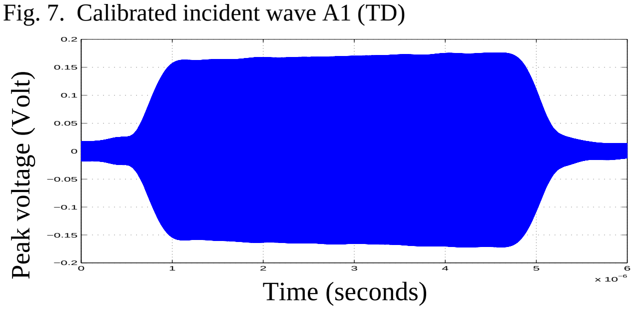


Fig. 8. Calibrated output wave B2 (TD)

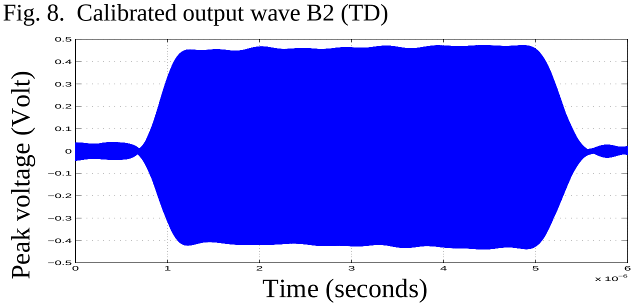
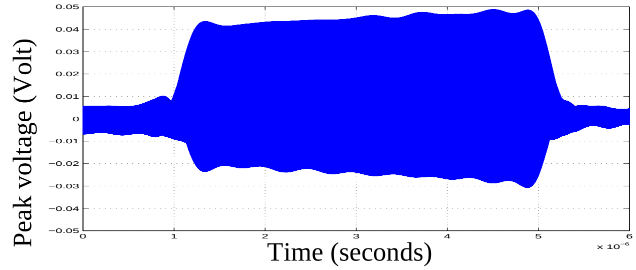


Fig. 9. Calibrated reflected wave B1 (TD)



VII. Conclusion

The measurement technique to determine the frequency response function of the downconvertor proposed in this paper, allows us to extend the calibration of a NVNA for pulsed RF measurements. The FRF can be used to calibrate the measured frequency modulation components (envelope) of the fundamental carrier frequency and his harmonics.

The measurement results allows us to visualize the transient response of the device to pulsed RF signals in both frequency and time domain. These results can give more insight in the nonlinear pulsed RF operation of a DUT.

References

[1] J. Verspecht, P. Debie, A. Barel, L. Martens, 'Accurate On-Wafer Measurement of Phase and Amplitude of the Spectral Components of Incident and Scattered Voltage Waves at the Signal Ports of a Nonlinear Microwave Device', *IEEE-MTT-S*, Orlando, U.S.A., May 1995, pp. 1029-1032.

[2] T. Van den Broeck, J. Verspecht, *'Calibrated Vectorial Nonlinear-Network Analyzers'*, IEEE-MTT-S, San Diego, U.S.A., 1994, pp 1069-1072.

[3] Philip Vael and Yves Rolain, 'Comparison of calibrated S-parameters measured under CW and Pulsed RF excitation with a Nonlinear Vectorial Network Analyzer', *55th ARFTG Conference*, Boston, USA, June 2000.

[4] M. R. Schroeder (1970), 'Synthesis of low peak factor signals and binary sequences with low auto correlation', *IEEE Trans. Inform. Theory*, Vol. IT-16, pp. 85-89.

[5] Alain Barel, Yves Rolain, 'A microwave multisine with known phase for the calibration of narrowband nonlinear vectorial network analyzer measurements', *IEEE-MTT-S*, Baltimore, U.S.A., 1998.

[6] J.S. Bendat, 'The Hilbert Transform and Application to Correlation Measurements', *Bruel & Kjaer*.

[7] Wiltron, 'Operating Manual of the pulsed RF VNA', Part number 360PS20A.