“Calibrated Vectorial ‘Nonlinear Network’ Analyzers”

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Calibrated Vectorial Nonlinear-Network Analyzers

(Expanded version)

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Abstract — **The vectorial nonlinear-network analyzer concept is introduced and realized in practice. A vectorial nonlinear-network analyzer excites a nonlinear microwave device-under-test with a combination of sinewaves of different frequencies and accurately detects the phase and amplitude of all frequency components of the incident and the scattered waves. A new, statistic efficient, absolute calibration procedure is developed based on a low crest factor multisine reference generator characterized by a broadband sampling oscilloscope. This makes the calibration traceable to the accuracy of a so-called nose-to-nose measurement.**

I. INTRODUCTION

Many hardware and software tools are available for an efficient design of microwave circuits. Vectorial network analyzers and calibration techniques are hardware tools that allow an accurate characterization of linear circuits by the measurement of the associated s-parameters. Together with linear circuit simulators a very efficient design is possible. The network analyzer measurements can be used for the development of better simulator models as well as for a verification of the correspondence between the actual device behaviour and the simulated behaviour. For nonlinear circuits the situation is different. Several powerful simulators for nonlinear microwave circuits are available. These simulators allow a coherent calculation of all spectral components of the output waves as a function of the spectral components of the input waves. No commercial instrument is however available to accurately measure the value of all these input and output components. The lack of such an instrument makes it hard to build and verify models for nonlinear microwave devices.

Since such an instrument is considered as an extension of the measurement capabilities of vectorial network analyzers [1], it will be called a vectorial nonlinear-network analyzer (VNNA) in what follows. In the past, several prototypes of such instruments have already been built ([2], [3] and [4]). The most fundamental problem with the instrument prototypes mentioned is the accuracy and traceability of the calibration procedures.

In this article will be shown how several new VNNA prototypes were built and some comments will be given concerning the specific problems with the calibration procedures used in [2], [3] and [4]. A new calibration procedure is proposed and tested in practice. The calibration procedure is based on the use of a stable multitone microwave generator. It is shown in this article that the use of a special developed so-called “microwave multisine source” [5] results in much better statistic efficiency than the use of classical comb-generators. The accuracy of the proposed calibration procedure is primarily determined by the accuracy of the signal analyzer that is used to characterize the multitone generator. In this article, a broadband sampling oscilloscope (HP-54121T) is used as a signal analyzer, such that the accuracy of the calibration is traceable to the so-called “nose-to-nose” calibration procedure [6].

II. HARDWARE IMPLEMENTATION OF A VNNA

The VNNA hardware has three major parts. A first part is the signal generation. Depending on the application, the signal generators must be capable of generating multitone signals. A second part of the VNNA is the test set. This test set directs the generator signals to the signal ports of the device-under-test (DUT) and detects the incident and scattered waves. A third part is the data acquisition. This part must be capable to coherently “digitize” the high frequency waves, so that the phase and amplitude information of all spectral components of the input and output waves can be interpreted by a computer. In what follows a two-port VNNA will be considered, since all prototypes built are of this type. It is however possible to extend everything what follows to calibrated N-port VNNA’s. All VNNA prototypes built are “rack-and-stack” setups, where all instruments are connected with a controller thru IEEE-488. As signal generators, two microwave synthesizers (HP-83640A) are being used, together with power combiners, splitters and computer controllable attenuators. Two kinds of test sets are being used. A first type of test set is based on couplers to detect incident and reflected waves at both ports. This test set allows the detection of waves with frequencies ranging from about 45 MHz to 40 GHz. A second type of test set is based on resistive bridges, allowing to detect waves with a frequency range from DC to 8 GHz. The connection between the test set and the DUT is done with standard HP-8510 test port cables. For the data acquisition part two types of instruments are being used. The first type of instrument used is an equivalent-time broadband sampling oscilloscope (an HP-54121T). This four-channel oscilloscope can be synchronized with the multitone signals by 2 possible methods. If there is a fundamental frequency component available the scope is triggered on this signal. If no fundamental frequency component is available to trigger the scope, it is synchronized with the 10 MHz reference clock of the synthesizers. A consequence of this is that all frequencies used are to be a multiple of 10 MHz. A second type of data acquisition instrument are two modified and synchronized HP-75100A’s [7] (MTA in what follows). An MTA is essentially a two-channel broadband downconvertor. The use of MTA’s has several advantages compared to the use of a sampling oscilloscope. The main advantage is that an MTA allows a much faster data acquisition than what is possible with any sampling oscilloscope. The physical sampling rate of an MTA is typically 20 MHz, for a broadband sampling oscilloscope this is typically about 2 kHz. A second advantage of the MTA is the elimination of all timebase related effects which are present in a scope, such as trigger drift, timebase jitter and timebase distortion. The dynamic range of both setups is about 60dB.

III. ABSOLUTE CALIBRATION: THEORY

Undoubtedly there are significant systematic errors when one builds a VNNA. In [8] three approaches are cited to calibrate a VNNA. The first method is based on a characterization of the test set with a vectorial network analyzer and on a model of the data acquisition, a second method is based on the availability of a “golden diode” and the third method is based on the availability of a multitone reference generator. The first method is used in [3], [4] and the second in [2]. In this article the third method is used, and it will be explained in what follows why this choice was made. The approach of the first method is conceptually fine but there are several practical problems involved. The main problem is the necessity to disconnect the test set from the data acquisition part and to connect it to a vector network analyzer. This raises the problem of repeatability since this operation needs many connections, disconnections and cable manipulations. The second calibration method mentioned is based on the availability of a “golden diode”. This is a nonlinear device from which one assumes to have a perfect nonlinear model. Because one has a perfect nonlinear model of this device, one can predict the amplitude and phase of all harmonics. By comparing the amplitude and phase of the harmonics as measured by the VNNA with the values as generated by the perfect model, it is possible to calibrate the VNNA. The first problem with this method is the availability of a “golden diode”. The most accurate model available at this moment is probably the Root-model [9]. The main problem with this approach however is the signal-to-noise ratio. In order to be able to do an efficient calibration harmonics are needed with amplitudes comparable to the amplitude of the fundamental. Problem is the generation of the high amplitude harmonics and the validity of the “perfect” model at these amplitudes. In order to avoid the problems encountered with the first and second method, the third method is being used in this article. This method is based on the availability of a multitone reference generator. This reference generator is characterized by an accurate broadband signal analyzer. As signal analyzer a broadband sampling oscilloscope (HP-54121T) is being used, which means that the calibration is traceable to a “nose-to-nose” procedure [6].

The calibration procedure that was developed will be explained in what follows. The calibration is based on the assumption that the 4 digitized wave quantities are linearly related with the 4 physical waves at the device ports (for each port, an “input wave” and an “output wave” is measured). The relationship between the 4 physical waves and the 4 digitized quantities will be characterized by complex square matrices with 16 elements (one matrix for each frequency component that is present in the signal).

The calibration procedure will identify the 16 elements for all matrices. First a calibration is performed identical to the calibration procedure for a “linear network” analyzer [10]. When this “relative calibration” is finished, every matrix is completely determined except for one element per matrix. If one is interested in both amplitude and phase of these elements, one connects a multitone reference generator to one of the VNNA ports. A reference generator is a multitone generator with an accurately known output impedance, where the absolute amplitudes and relative phases of all frequency components are stable and accurately specified. By comparing the frequency components as measured by the relatively calibrated VNNA with the reference generator specification, all unknown matrix elements can be determined. This part of the calibration is called the absolute calibration of the VNNA.

For the relative calibration a standard 3.5mm calibration set is used. Two types of reference generators are used for the absolute calibration. The first type are step recovery diode based comb-generators, with significant energy available until frequencies well above 20 GHz and with a fundamental frequency ranging from about 50 MHz to 1 GHz. This kind of signal generator can be used for calibration purposes, but can only generate a very small amount of energy for each frequency component, since the amplitude of the pulse has to be lower than 100 mV to assure a linear behaviour of the data acquisition. To solve the problem of the signal-to-noise ratio with pulse like comb generators, a new type of calibration generator has been developed, a so-called “microwave multisine source” [5]. The characterization of the “calibration generator” is done with a calibrated sampling oscilloscope. A prototype of such a generator was built with a fundamental frequency of 100 MHz and with a bandwidth of 2 GHz.

IV. ABSOLUTE CALIBRATION: MEASUREMENTS

To prove that the concept of the absolute calibration can be realized in practice the following experiment is done. A broadband (50 GHz bandwidth) 6 dB gain travelling wave amplifier is chosen as the device-under-test (DUT). A harmonic distortion experiment is performed on this DUT with two significantly different measurement setups. Both setups are absolutely calibrated and the results of both measurements (amplitude and phase of fundamental and harmonics) are compared with each other. By showing that these results are almost equal it is proven that the reference generator can be used as an absolute calibration transfer standard.

Both setups used are based on the 2 MTA's and on the use of couplers. As reference generator a 1 GHz step-recovery-diode comb generator is being used. This reference generator is characterized by a sampling oscilloscope.The significant difference between the two setups are the couplers used. For the first setup 14 dB couplers are used and for the second setup 20 dB couplers. Note that the characteristics of both coupler types are quite different, not only concerning the amplitude but also concerning the phase characteristic.

The DUT is excited by an input signal with a fundamental frequency of 4 GHz. The amplitude of this signal is swept from -2.5 dBm to 15 dBm. For each input amplitude the amplitudes and phases of the fundamental component and 3 harmonics are measured, both for the incident and scattered waves at port 1 and port 2 of the DUT (the frequency components measured are 4 GHz, 8 GHz, 12 GHz and 16 GHz).

An example of the results of such an experiment can be seen in figure 1 to figure 4. On the x-axis the incident fundamental power is indicated in dBm. On the y-axis one sees 4 independent measurement curves (two measurements performed with setup 1 and two measurements performed with setup 2). In figure 1 one finds on the y-axis the power (dBm) of the fundamental component (frequency 4 GHz) at the DUT output, in figure 2 one finds the phase (degrees) of the same component. In figure 3 and figure 4 the same information is given for the third harmonic (frequency 12 GHz) at the output. Note that the phase of a component is defined as the phase that the component has when a delay is applied such that the phase of the fundamental excitation signal is equal to zero. This definition for the phase of an harmonic has the advantage to be invariant towards time delays.

In figure 1 and figure 2 can be seen that there is a very close correspondence for the fundamental output component between the 4 measurements. This result can however be achieved by only using a power meter, without using a reference generator.

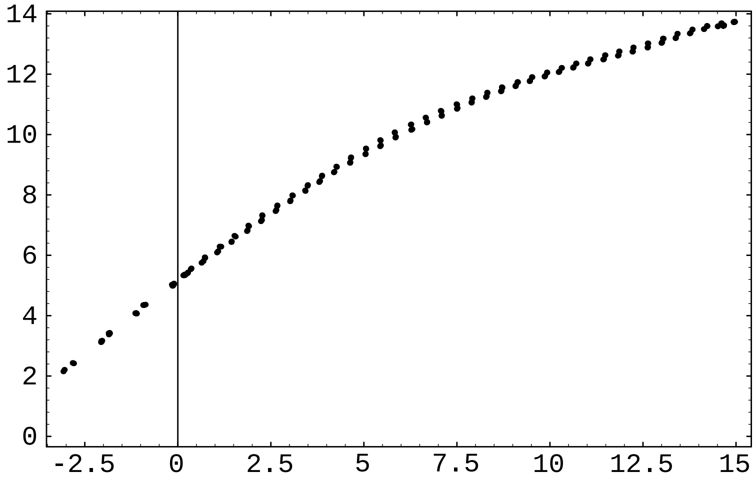

Fig. 1. Power (dBm) of the fundamental at the output vs. incident fundamental power (dBm) for 4 measurements

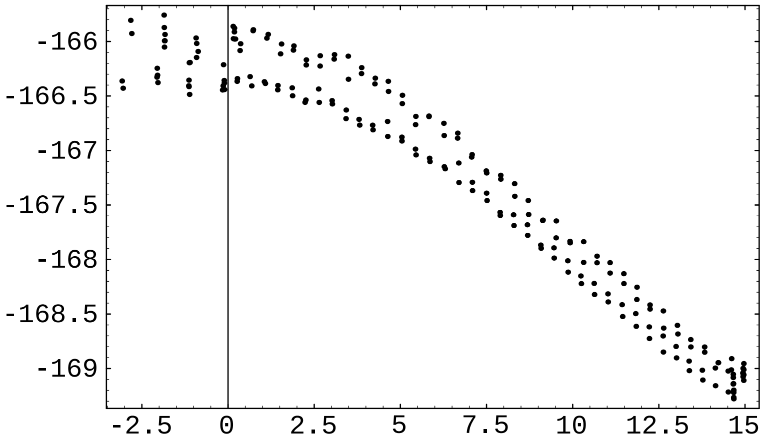

Fig. 2. Phase (degrees) of the fundamental at the output vs. incident fundamental power (dBm) for 4 measurements

In figure 3 and figure 4 can be seen that the third harmonic component (frequency 12 GHz) agrees for all 4 measurements within 300 mdB for the amplitude and within 3 degrees for the phase. Without applying an absolute calibration by means of a reference generator the phase difference between the two setups would be about 16 degrees.

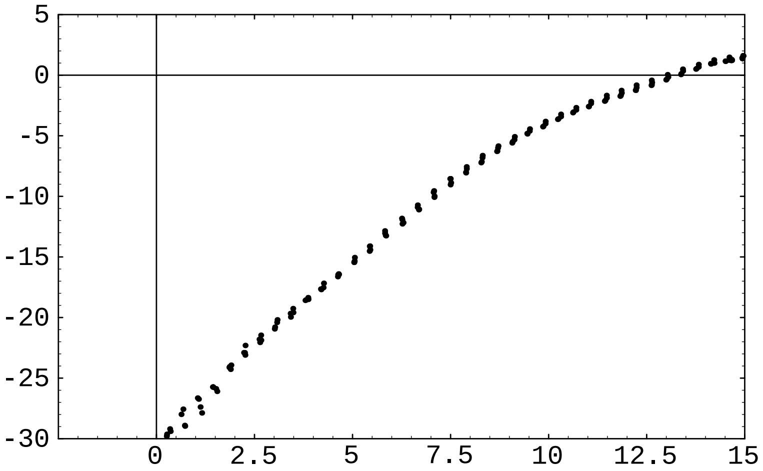

Fig. 3. Power (dBm) of the 3rd harmonic at the output vs. incident fundamental power (dBm) for 4 measurements

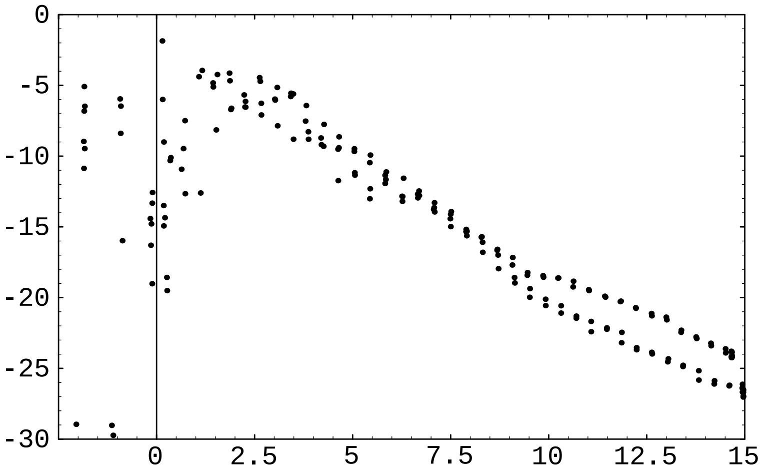

Fig. 4. Phase (degrees) of the 3rd harmonic at the output vs. incident fundamental power (dBm) for 4 measurements

Although a phase correspondence of 3 degrees between the measured third harmonic with setup 1 and with setup 2 (see figure 4) is considered as a good result, measurements show that the repeatability for one setup is significantly higher than this 3 degrees (repeatability typically better than 0.5 degrees). This means that the repeatability error (due to connections as well as additive noise) can not explain the difference of 3 degrees between the two different setups. More measurements indicate that this difference is not due to a repeatability error of the absolute calibration procedure, but is due to small nonlinear effects generated inside the MTA's data acquisition. If these nonlinear effects would not be present, the authors believe that the correspondence between the two different setups would only be limited by the repeatability (a correspondence better than 0.5 degrees).

V. MICROWAVE MULTISINE SOURCE: THEORY

As stated before, absolute calibration suffers from the low signal-to-noise ratio available with pulse like calibration generators. To solve this problem, a new type of generator has been developed: the microwave multisine source (MMS).

In contrast to low frequency applications, where arbitrary waveform generators based on digital techniques exist, microwave frequencies require analog filtering for wave shaping. Therefore, we will first present an appropriate filter synthesis procedure for this purpose, based on an estimation algorithm for linear systems in the Richards variable S.

A. Estimation of Linear Systems in the Richards Variable S (ELiSRich)

Microwave commensurate filters, i.e. filters built with transmission lines of equal electrical length, can be represented as a rational function in the Richards variable S:

$$H(S) = \frac{F(S)}{G(S)} \qquad \text{with} \quad S = \tanh s\tau \quad \text{and} \quad \tau = \frac{1}{4f_r} \qquad (1)$$

with f_r the repetition frequency. F(S) and G(S) are polynomials in S.

Using this formulation, a maximum likelihood estimator ELiSRich was developed in analogy to ELiS [11] for classical continuous time systems (Laplace variable s) and discrete time systems (variable z). This technique can also be applied to allpass filters, in which case all poles and zeros of H(S) are organized in quadrature. Using this extra information in ELiSRich, a rational allpass function in S can be estimated. Although this technique is intended for the estimation of the parameters of existing systems, it can also be used for synthesis purposes. The rational function found can then be realized using a cascade of coupled transmission line sections. The last section will represent a shorted coupled transmission line. The physical realization can be made in stripline technology [5].

B. Application: Microwave Multisine Source (MMS)

In practical measurement applications the excitation amplitude should always be limited to ensure linear operation of the instrumentation. On the other hand, signal power should be as high as possible to enable measurements with high signal-to-noise ratio. Therefore, high crest factor signals (high ratio of peak value to effective value; pulses have typically high crest factors) result in low signal-to-noise ratio measurements. This can be illustrated as follows. Since the crest factor of a signal is defined as $Cr = L_\infty / u_{eff}$, where L_∞ and u_{eff} are respectively the maximum absolute value and the effective value of the signal, the signal-to-noise ratio can be written as [5]:

$$\frac{S}{N} = \gamma - 20 \log Cr \qquad (2)$$

with γ a constant depending on the noise level of the system. A typical crest factor gain from 8 (pulse) to 2 (low crest factor multisine) results in a 12 dB signal-to-noise ratio improvement.

In order to obtain a low crest factor microwave multisine source (MMS) several phase behaviors can be proposed (e.g. a Schroeder phase [5]). The idea is to start with a given broadband signal with sufficient harmonics in the band of interest (typically a pulse from a step recovery diode). The goal phase can then be realized using the techniques described in the previous paragraph.

C. Use of the MMS in VNNA Calibration

The absolute calibration of a VNNA can be done by first characterizing a reference generator (pulse or MMS) in amplitude and phase using calibration techniques described in [6]. Subsequent calibrations can then be done by using this fully characterized reference generator as a standard. It will be shown that the MMS has a superior signal-to-noise ratio compared to pulse reference generators due to the low crest factor.

VI. MICROWAVE MULTISINE SOURCE: MEASUREMENTS

A. Measurement Setup

The setup is described in figure 5. The system is based on an HP-54121T sampling oscilloscope for data acquisition. As source an HP-83040 synthesizer is used. As test set, resistive bridges (6 dB attenuators) are used (in analogy to [12]). For measuring active devices, bias tees are inserted between the resistive bridges and the test ports.

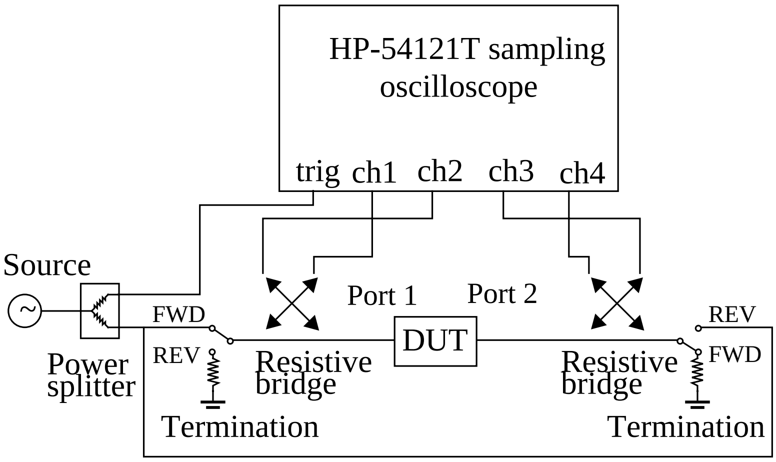

Fig. 5. Setup

For the reference generator required during the absolute calibration, two alternatives were used with about the same amplitude spectrum (within a scaling factor) up to 2 GHz. First, we took a pulse originating from a step recovery diode (HP-33002A) driven by a 27 dBm, 100 MHz signal (with 46 dB attenuation at the output). In a second approach we used an MMS based on the same step recovery diode but now with supplementary amplitude and phase filters [5] (plus extra attenuators for a total of 26 dB).

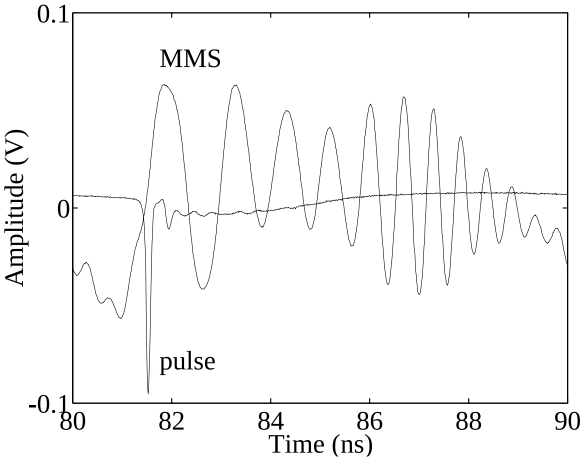

Fig. 6. MMS and pulse reference generators in time domain

B. Relative Calibration

Due to the construction of test set and data acquisition hardware there is no interference between port 1 and port 2. Consequently, the relation between measured and calibrated waves for every frequency index i can be written as:

$$\begin{bmatrix} a_{d1i} \\ b_{d1i} \\ a_{d2i} \\ b_{d2i} \end{bmatrix} = \alpha_i \begin{bmatrix} 1 & e_{12i} & 0 & 0 \\ e_{21i} & e_{22i} & 0 & 0 \\ 0 & 0 & d_{11i} & d_{12i} \\ 0 & 0 & d_{21i} & d_{22i} \end{bmatrix} \begin{bmatrix} a_{m1i} \\ b_{m1i} \\ a_{m2i} \\ b_{m2i} \end{bmatrix} \qquad (3)$$

The unknown elements in the calibration matrix are determined by a relative calibration (open - short - load - thru), except for α.

The relative calibration was performed using a stepped sine (HP83640A synthesizer) signal source. To test the validity of the relative calibration and to illustrate the use of the MMS we used the calibrated linear network analyzer with three different test signals: a stepped sine, the MMS generator and a pulse generator. The stepped sine is superior in signal-to-noise ratio but slow (especially with a samplescope since for every frequency a time record has to be measured). The MMS and the pulse are very fast (only one time record for the full frequency range has to be measured, applying an FFT to get the frequency domain data). The signal-to-noise ratio of the pulse measurement is very poor, the MMS however is significantly better. This is illustrated in table I where the standard deviations are given on S_{21} amplitude measurements of a low pass filter (3dB cut off frequency 750 MHz) at 1 GHz (20 experiments for each source).

TABLE I: Standard deviations on $|S_{21}|$ measurements for different sources

	mean($\lvert S_{21}\rvert$)	std($\lvert S_{21}\rvert$)
Stepped sine	0.384	0.002
MMS	0.404	0.020
Pulse	0.368	0.067

In figure 7 the measured $|S_{21}|$ of the DUT is given together with the 95% confidence intervals and an HP-8510B reference measurement.

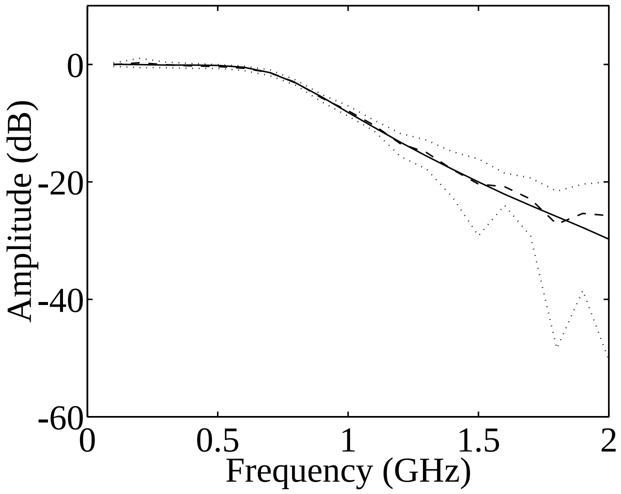

Fig. 7. Amplitude of S_{21} (dashed line) and 95% confidence interval (dotted lines) for MMS setup and reference (solid line)

From this figure it can be seen that the results from the MMS are unbiased and from figure 8 it follows that the MMS setup gives a smaller uncertainty than the pulse based measurements. This also verifies that our relative calibration is correct.

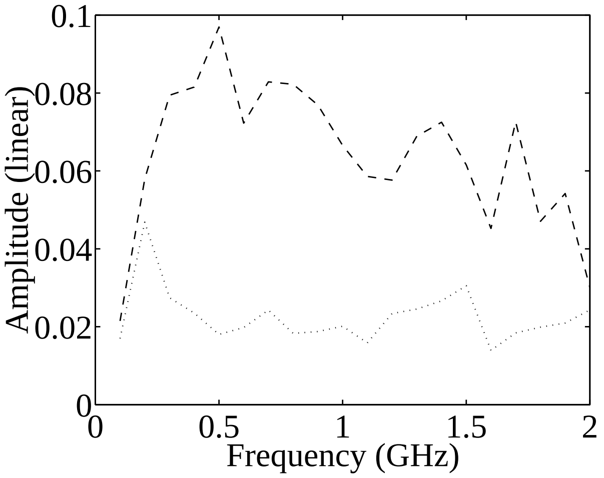

Fig. 8. Standard deviations on $|S_{21}|$ for MMS (dotted line) and pulse setup (dashed line)

C. Absolute Calibration

In nonlinear measurements, it is necessary to know the phase and amplitude of each harmonic relative to the fundamental frequency. Therefore, α has to be determined. We apply the reference generator (pulse or MMS), with known output wave and reflection coefficient, to test port 1. To insure linearity of the sampling oscilloscope, we limited the amplitudes of the reference generators to 105 mV peak-to-peak for the one-sided pulse and 117 mV peak-to-peak for the MMS (voltages measured into 50 Ω). The corresponding crest factors are 9.0 and 2.1 respectively. In figure 9 the resulting absolute calibration factor α is plotted in both cases (at 1.0 GHz) for 20 experiments.

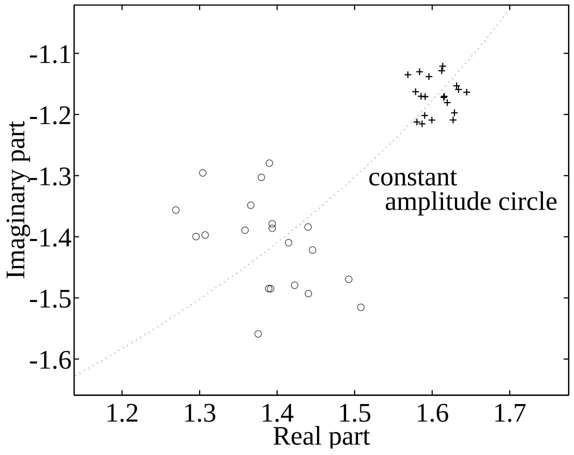

Fig. 9. Scatter plot of α (o: pulse; +: MMS)

It is clear that the standard deviation on the MMS measurement is significantly lower than on the pulse measurement. Another observation is that the average amplitude of α in both cases is the same (around 2 - see circle segment in figure 9), where the phase is different. This is normal since α is only determined within a linear phase, i.e. the phase of the fundamental frequency of the reference generator has to be chosen at random.

In figure 10 and figure 11 it is illustrated that the MMS allows measurements of α with a better statistical efficiency for the same setup and measurement conditions (full scale settings, averaging factor). The mean standard deviation on α improves from 0.080 to 0.022, i.e. a factor 3.6. This is the type of improvement we expected theoretically (12.6 dB or 4.3 linear).

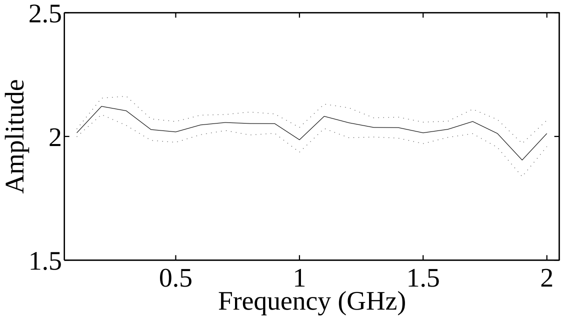

Fig. 10. Amplitude of α (solid line) for MMS and 95% confidence interval (dotted lines)

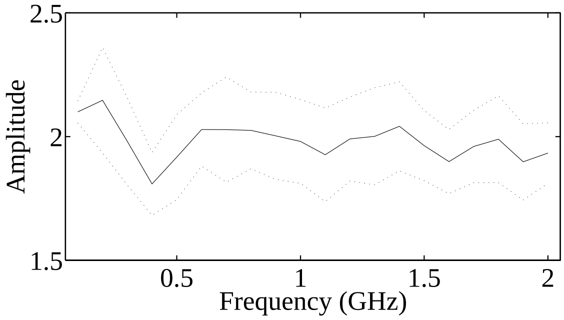

Fig. 11. Amplitude of α (solid line) for pulse and 95% confidence interval (dotted lines)

D. Measurement of a Nonlinear Device

To illustrate the use of the calibrated vectorial nonlinear-network analyzer, we measured a nonlinear device (parallel connected diode HP-5082-0830, biased by a current of 5.2 µA). We excited the device by a 500 MHz, 5 dBm signal and measured the transmitted and reflected waves up to 2 GHz.

In these experiments we used two different measurement setups. Setup 1 is as described in figure 5, while setup 2 is the same but with a phase distortion introduced in the path to channel 2. Relative and absolute calibration were performed on both setups, using the MMS as the reference generator. The phase of the fundamental in the incoming wave was set to zero in all measurements to avoid problems with the undetermined linear phase in the calibration factor α.

TABLE II: Phase (deg) of reflected wave harmonics at port 1

	0.5 GHz	1.0 GHz	1.5 GHz	2.0 GHz
Setup 1 (relative calibration)	137	-36	94	-142
Setup 2 (relative calibration)	138	-67	-24	0
Setup 1 (absolute calibration)	137	-38	92	-145
Setup 2 (absolute calibration)	138	-37	89	-146

As can be seen in table II, the measured phases of the harmonics in the reflected wave differ substantially for both setups if only a relative calibration is performed. If a supplemental absolute calibration is performed however, phases agree within 3 degrees.

The same is true for the harmonics of the transmitted wave, as illustrated in table III.

TABLE III: Phase (deg) of transmitted wave harmonics at port 2

	0.5 GHz	1.0 GHz	1.5 GHz	2.0 GHz
Setup 1 (relative calibration)	-124	-50	80	-166
Setup 2 (relative calibration)	-124	-82	-38	-25
Setup 1 (absolute calibration)	-124	-53	77	-169
Setup 2 (absolute calibration)	-124	-53	75	-170

VII. CONCLUSION

Several VNNA prototypes were described. In order to accurately measure amplitude and phase of different harmonics an absolute calibration is indispensable. This is illustrated by the measurements. Our calibration method relies on an accurately known reference generator, which is characterized by a sampling oscilloscope with well known characteristics. We have also shown that a reference generator with a low crest factor (a MMS) enables an absolute calibration with a better statistic efficiency.

VIII. ACKNOWLEDGEMENT

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