A METHOD FOR MEASURING MAGNITUDE AND PHASE OF HARMONICS GENERATED IN NONLINEAR MICROWAVE TWO-PORTS

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ABSTRACT

A new method for simultaneously measuring magnitude and phase of the harmonics generated by a microwave two-port is described. The measurement system has a dynamic range superior to time-domain measurements due to its reduced noise bandwidth. Sample measurements on a GaAs MESFET under large-signal operation are presented.

INTRODUCTION

Nonlinear circuit simulation is becoming more and more important for microwave designers, in particular using the harmonic balance method [1..3]. This increases the need for measurement systems to characterize nonlinear devices and circuits.

The paper presents a new method for simultaneously measuring amplitude and phase of harmonics. A nonlinear two-port device under test is driven with a sinusoidal microwave signal. The output harmonics are analyzed in the frequency domain.

The first part of the paper presents the measurement system. The phase calibration using a high-speed diode is discussed.
In the second part, results obtained from measuring a commercial MESFET are presented. They are compared with

a) measurements of harmonics by a scalar network analyzer with suitable filters (magnitude only)

b) time-domain waveforms (as measured with a sampling oscilloscope)

The data up to the 4th harmonic show reasonable agreement with both of these well-known methods.

The main advantage of the new procedure compared with time-domain measurements is increased dynamic range. The elimination of the fundamental from the measurement process and the reduced noise bandwidth help in observing harmonics with small amplitudes.

I. THE MEASUREMENT SYSTEM

The principal components of the measurement system (figure 1 on the next page) are a signal generator with an internal multiplier (HP8350 with HP 83595A RF plug-in) and a vector network analyzer (eg. HP8410). The measurement setup has an electrical length of many wavelengths so the generator has to be phase-locked to a stable reference.

The fundamental signal of the generator (3.5 ... 6.5 GHz with the 83595A plug-in) is amplified to a level of 23dBm. A low-pass filter removes the harmonics. The variable attenuator allows to adjust the input power to the device under test (DUT).

The multiplied output of the generator is fed to the network analyzer (NA). The NA is configured for a forward transmission measurement from port 1 to port 2. The broadband coupler C_1 combines the signal of the NA port 1 with the output of the DUT. A high-pass filter reduces the amplitude of the fundamental component to avoid an overload of the NA input (port 2). Because of the inherent selectivity of the NA harmonic converter, there is no need to suppress the fundamental frequency completely.

Fixed attenuators are used to define the 50 ohm source and load impedances at the DUT as well as throughout the system for setting appropriate signal levels. (They are omitted from figure 1 to reduce the complexity of the drawing.)

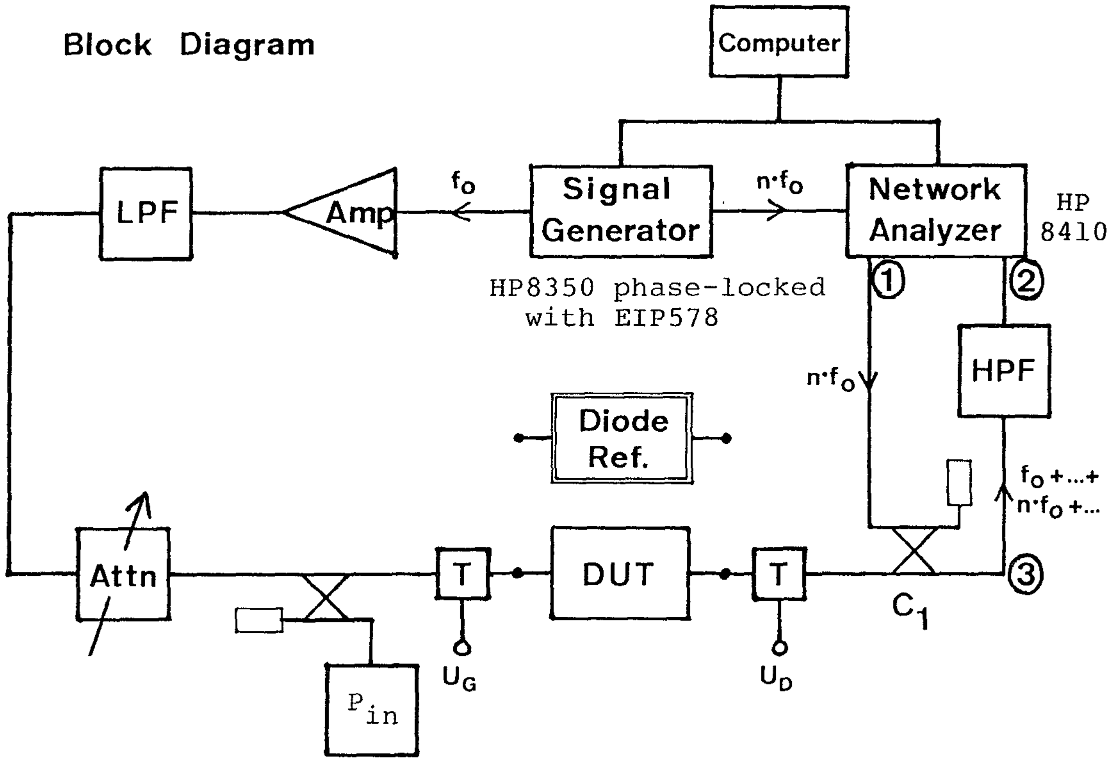

Figure 1: Block diagram of the measurement system

First the network analyzer is calibrated for a forward transmission (S_{21}) measurement at the frequency of the harmonic to be measured (DUT removed). The calibration normalizes the signal from NA port 1 to $1.0\angle 0°$. This is the phasor CAL in figure 2.

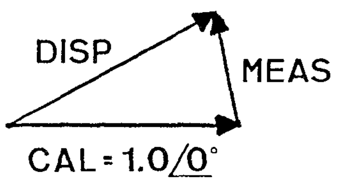

Figure 2: The signals at point 3 of the measurement system for one particular harmonic $n \cdot f_o$

The phasor DISP in figure 2 is what we see on the network analyzer display with the DUT in place. It is the sum of the signal CAL from NA port 1 and the signal MEAS from the DUT. Therefore we can determine the unknown component MEAS by

$$\text{MEAS} = \text{DISP} - \text{CAL} \qquad (1)$$

For the calculation of the absolute magnitude and phase of the harmonic MEAS we need a reference power and a phase reference. The reference power P_{ref} is obtained from a power measurement at point 3 in figure 1 (DUT disconnected). This value is equal to the 1.0 magnitude of the CAL phasor in figure 2. The phase of the harmonic is still unknown because the phase difference between the two outputs of the signal generator (f_o and $n \cdot f_o$) as well as the length differences in the system are arbitrary.

<u>Phase calibration at the n-th harmonic</u>

In the following, we describe the fundamental and harmonic components by their complex amplitudes

$$a_n = |a_n| \cdot e^{j\varphi_n}, \quad n = 1,2,3,\ldots \qquad (2)$$

Without loss of generality we may set $\varphi_1 = 0°$.

The phase relation between the fundamental and the n-th harmonic is a priori unknown. In the system of figure 1, a very high-speed (ie. mm-wave) diode is used to establish this phase relation.

It is mounted in parallel from a microstrip transmission line to ground (figure 3).

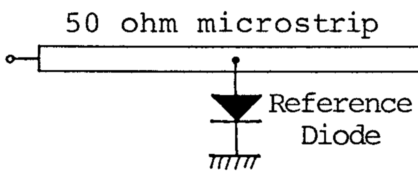

Figure 3: The diode reference circuit

Simulations of this "Diode Reference" circuit with SPICE 2G6 have shown that the GaAs Schottky diode used (C_j=15fF, C_p=15fF, R_s=8Ω) is a well-defined source of harmonics. The phase of the 4th harmonic at 20 GHz (calculated with SPICE) differs less than 10° from the ideal limiter diode phase. (This equals a phase error of less than 2.5° referred to the fundamental at 5 GHz.)

Prior to measuring the DUT, the diode reference circuit is connected. The resulting vector $MEAS_{ref}$ is calculated according to (1). Its angle is the phase reference for the n-th harmonic, $\varphi_{ref,n}$.

Next, the DUT is inserted. The vector MEAS is calculated and decomposed to $c_{MEAS,n} \cdot e^{j\varphi_{MEAS,n}}$. The true phase of the n-th harmonic, with reference to φ_1 = 0°, is given by (3).

$$\varphi_n = \varphi_{MEAS,n} - \varphi_{ref,n} - 180° \quad (3)$$

(For an ideally limiting diode mounted with its cathode to ground, the correction term of -180° is valid for all harmonics n≥2.)
The power of the n-th harmonic is calculated from (4).

$$P_n = (c_{MEAS,n})^2 \cdot P_{ref} \quad (4)$$

Of course, the attenuation from the DUT output to point 3 and a possible length difference between the diode reference circuit and the DUT must be included in the calculations.

Magnitude and phase of S_{21} at the fundamental can be determined with the same setup, the diode reference circuit replaced by a through line.

II. MEASUREMENT RESULTS

The harmonics generated in the small-signal MESFET NEC NE 710-83 have been measured. At the input and output of the device, attenuators were used to set the termination impedance to 50 ohms. Data of the first four harmonics of f_1 = 5 GHz for three different bias conditions are summarized in table I.

a) Bias conditions: U_D = 3 V, U_G = -1 V

P_{in}	f_0		$2 f_0$		$3 f_0$		$4 f_0$	
	mag.	phase	mag.	phase	mag.	phase	mag.	phase
[dBm]	[mV]	[deg.]	[mV]	[deg.]	[mV]	[deg.]	[mV]	[deg.]
2	316	84.7	151	22.5	26.8	-59.7	12.2	64.4
4	476	83.8	215	19.2	30.5	-71.8	23.8	57.4
6	714	85.9	307	19.9	31.6	-80.3	37.6	52.8
8	1010	84.5	414	15.8	33.5	-108.0	56.9	44.9
10	1414	85.1	566	15.6	39.4	-129.7	81.1	43.3

b) Bias conditions: U_D = 3 V, I_{DO} = 5 mA

P_{in}	f_0		$2 f_0$		$3 f_0$		$4 f_0$	
	mag.	phase	mag.	phase	mag.	phase	mag.	phase
[dBm]	[mV]	[deg.]	[mV]	[deg.]	[mV]	[deg.]	[mV]	[deg.]
2	775	83.0	170	5.0	33.2	-244.9	6.5	-27.5
4	975	82.3	235	3.9	42.9	-245.1	13.8	-1.5
6	1229	82.8	316	6.8	54.4	-229.6	24.0	8.5
8	1546	81.8	412	4.5	70.6	-236.6	39.5	7.9
10	1916	82.5	529	6.5	104.5	-239.6	74.7	9.7

c) Bias conditions: U_D = 3 V, U_G = 0 V (I_D = I_{Dss})

P_{in}	f_0		$2 f_0$		$3 f_0$		$4 f_0$	
	mag.	phase	mag.	phase	mag.	phase	mag.	phase
[dBm]	[mV]	[deg.]	[mV]	[deg.]	[mV]	[deg.]	[mV]	[deg.]
2	1261	74.7	20.5	-32.2	2.8	-239.2	0.8	-54.4
4	1584	75.1	30.5	-32.6	7.7	-272.6	1.7	-22.6
6	1957	76.5	38.0	-24.8	32.1	-273.9	8.2	-42.4
8	2207	78.2	93.5	-9.9	114.5	-270.5	19.1	-80.0
10	2293	82.3	249.0	5.9	217.0	-254.9	58.4	-55.3

TABLE I: Harmonic components at the drain of a NE 710-83 for three different bias conditions at f_1=5GHz (I_{DO}: bias current without RF excitation)

To check the accuracy of the results, the magnitude values can be compared with direct power measurements [4]. These measurements have been made with a scalar network analyzer (HP8756A) and a generator in power sweep mode. As an example, figure 4 shows a comparison of the third harmonic (15 GHz).

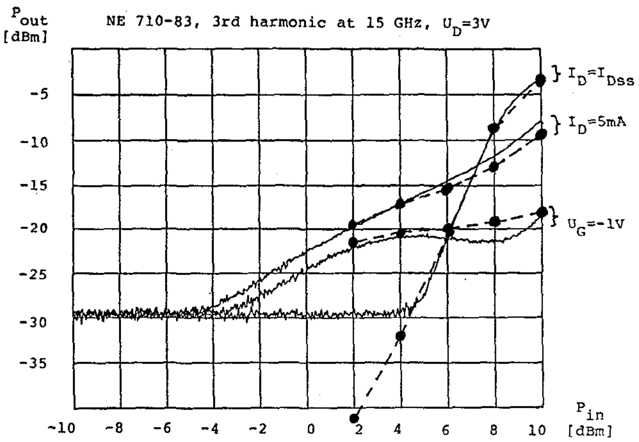

Figure 4: Comparison of the 3rd harmonic power level for three different bias conditions
——— power measurement (HP8756)
----- magnitude result obtained from the described method

With U_G set to zero volt ($I_D = I_{Dss}$) the agreement is good. The increased dynamic range of the frequency domain measurement is clearly seen below the noise floor of the power measurement (-30 dBm because of the DUT output attenuator). At the two other bias conditions, there is a 2 dB maximum difference. (Part of this difference is due to difficulties in exactly reproducing the gate bias point.)
For the same FET, time domain waveforms at the drain have been computed. In figure 5 three such waveforms (calculated from measured data given in table I) are shown. The agreement with the curves obtained in [5] from a sampling scope system is good.

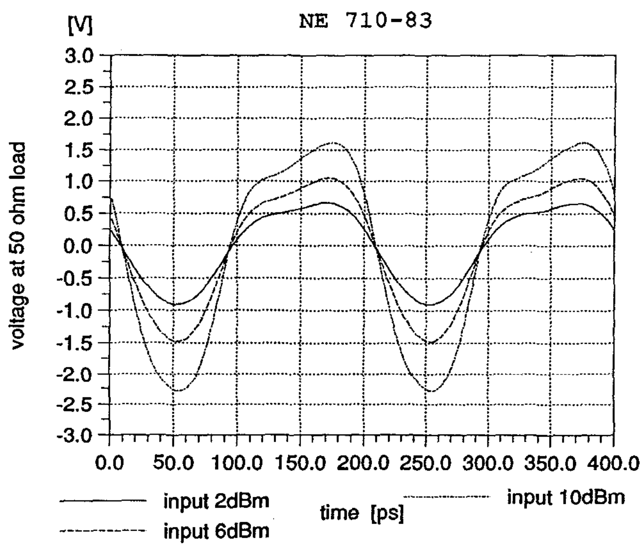

Figure 5: Time-domain waveform of drain voltage (first 4 harmonics of f_1=5GHz measured at 3V/5mA)

CONCLUSIONS

The described system allows the measurement of harmonics with a phase accuracy of about 10° at 20 GHz. All kinds of microwave two-ports can be characterized without knowledge of their internal structure. The system can be built for any frequency (<40 GHz) where a vector network analyzer and a suitable signal generator with multiplier are available. With a modified measurement setup the load-pull technique [6] could be used to measure harmonics generated at non-50-ohm loads. A combination with harmonic load-pull [7] is also possible.

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References

[1] V. Rizzoli, A. Lipparini, E. Marazzi, "A general-purpose program for nonlinear microwave circuit design", IEEE Trans. MTT, vol. MTT-31, Sep. 1983, pp. 762 - 770

[2] K.S. Kundert, A. Sangiovanni-Vincentelli, "Simulation of nonlinear circuits in the frequency domain", IEEE Trans. on CAD, vol. CAD-5, no. 4, Oct. 1986, pp. 521 - 535

[3] C. Holmes, O. Pitzalis, Y.-C. Yuan, "Harmonic balance software simulates nonlinear circuits", Microwaves & RF, vol. 26, no. 10, Oct. 1987, pp. 141 - 149

[4] H.A. Willing, C. Rauscher, P. de Santis, "A technique for predicting large-signal performance of a GaAs MESFET", IEEE Trans. MTT, vol. MTT-26. no. 12, Dec. 1978, pp. 1017 - 1023

[5] F. Sechi, H. Huang, B. Perlman, "Waveforms and saturation in GaAs power MESFETs", Proc. 8th European Microwave Conference, Microwave Exh. & Publishers, 1978, pp. 473 - 477

[6] Y. Takayama, "A new load-pull characterization method for microwave power transistors", 1976 IEEE MTT-S Int'l Microwave Symposium Digest, pp. 218 - 220

[7] R.B. Stancliff, D.D. Poulin, "Harmonic load-pull", 1979 IEEE MTT-S Int'l Microwave Symposium Digest, pp. 185 - 187