NON-INVASIVE WAVEFORM PROBING FOR NONLINEAR NETWORK ANALYSIS

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ABSTRACT

A novel and non-invasive technique has been developed for the measurement of fundamental and harmonic S-parameters as functions of input frequency and power. The advantage of this technique was demonstrated on a GaAs field-effect transistor by plotting its drain current versus voltage trajectory at 5 GHz which clearly showed the origin of its nonlinearity.

I. INTRODUCTION

In spite of the rapid advancement of on-wafer linear network analysis, nonlinear network analysis is still in its infancy. A recent development [1] involves the use of a HP 70820A Microwave Transition Analyzer for measuring both the magnitude and phase of harmonic signals. We have developed a new technique by using a 500 Ω Cascade XMP Module Probe in conjunction with the transition analyzer. The high-impedance probe causes insignificant perturbation to typical microwave circuits. By probing the voltage waveforms at four different locations on the input and output coplanar lines inside a test fixture, we were able to calculate the fundamental and harmonic S-parameters of the device under test. Here the harmonic S-parameter is defined as the ratio of the harmonic response wave to the fundamental incident wave. The main advantages of the present technique include: 1) complete information on both the voltage and current waveforms of the incident, reflected and transmitted waves, at fundamental and harmonic frequencies, 2) non-invasive nature for internal-node probing under various source- and load-pull conditions, and 3) in-situ measurement without precision fixtures or calibration standards. Thus, the present technique is a viable alternative to optical probing which tends to be tricky to implement and analyze [2].

II. MEASUREMENT TECHNIQUE

The measurement set up is similar to that used in traditional slotted-line VSWR measurements, but on a miniature scale. Figure 1 illustrates schematically the measurement set up. The device under test is mounted between two coplanar lines inside a coaxial test fixture. The high-impedance probe is used to sense the voltage waveforms at various locations along the coplanar line. The phase of the fundamental signal at each location is determined by referencing the load signal (Channel 1), while the phase of each harmonic signal is referenced to the fundamental signal.

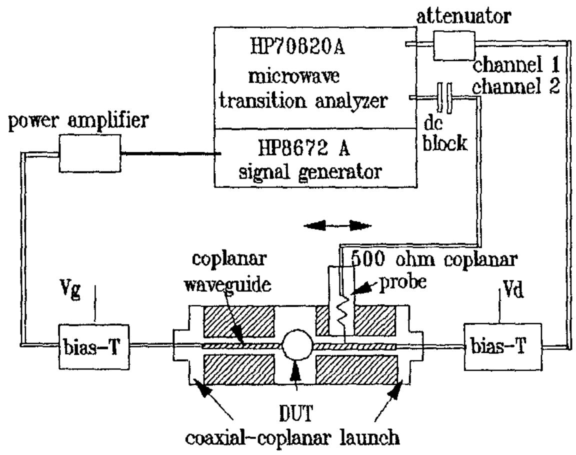


Fig. 1 Schematic illustration of the measurement set up.

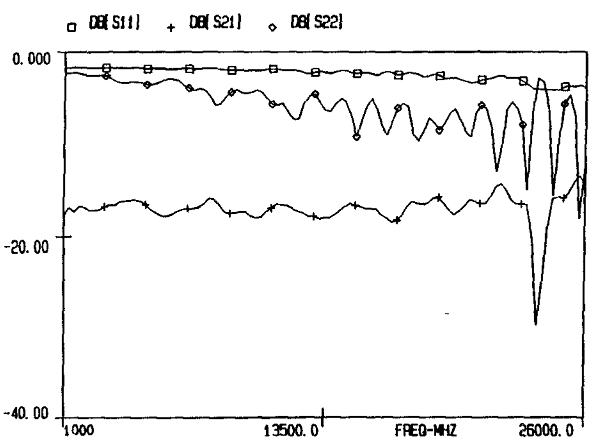
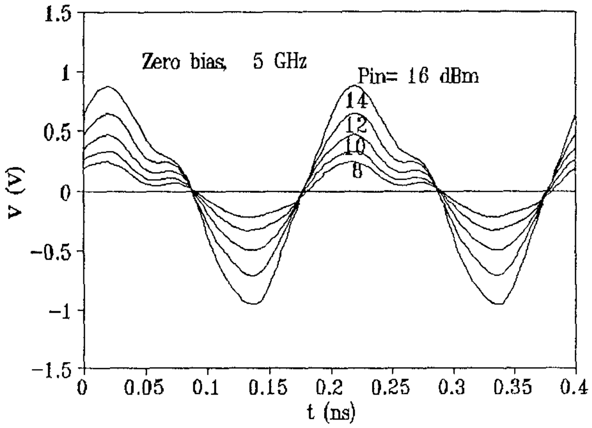


Fig. 2 S-parameters of the high-impedance probe.



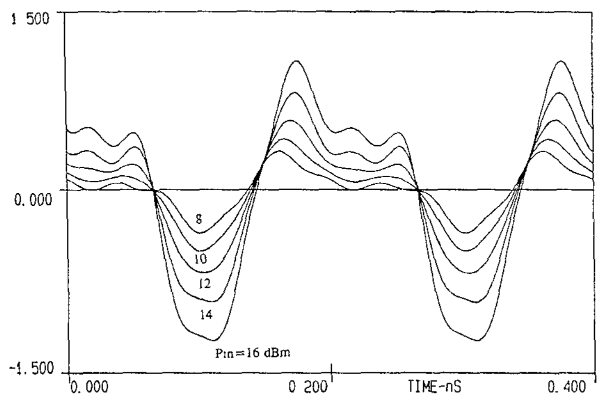


Fig. 3 (a) measured and (b) simulated voltage waveforms through a Schottky diode.

Given the voltages at two locations, V_{1n} and V_{2n}, the incident and reflected waves, A_n and B_n, are evaluated according to the following:

$$A_n = \frac{V_{1n}\exp(-in\omega\tau) - V_{2n}}{-2\sin(n\omega\tau)}$$

$$B_n = \frac{V_{1n}\exp(in\omega\tau) - V_{2n}}{2\sin(n\omega\tau)}$$

where n denotes the nth harmonic and τ is the wave transit time between the two locations. The current, I_n, is calculated by

$$I_n = \frac{B_n - A_n}{Z_o}$$

where Z_o is the characteristic impedance of the coplanar line. Usually locations one tenth of wavelength apart are sufficient to yield accurate current values. We used 1.5 cm long coplanar lines which are more than adequate for 2 to 26.5 GHz measurements. This results in at least five harmonics for fundamental frequencies from 2 to 5 GHz.

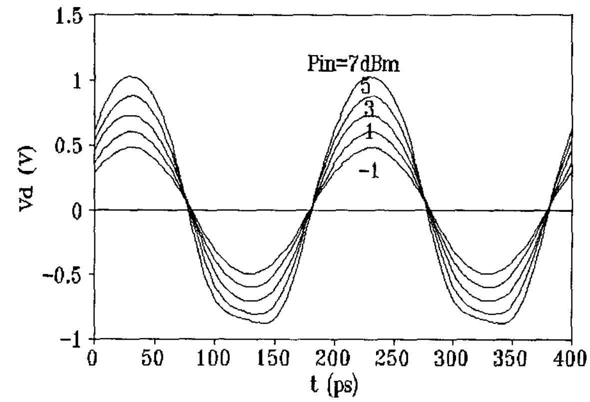


Fig. 4 Drain voltage waveforms of the transistor.

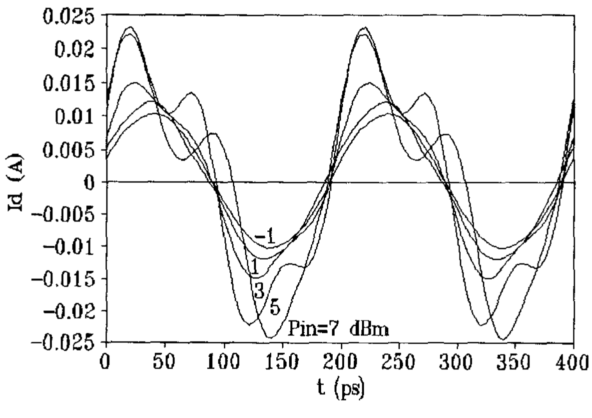


Fig. 5 Drain current waveforms of the transistor.

The high-impedance probe has a nominal bandwidth of 12.5 GHz but was found to have sufficient dynamic range ($\geq$40 dB) up to 26.5 GHz. The probe can be calibrated with or without ground contact at the probe tip. For accurate broad-band measurement, ground contacts are provided through the 50 Ω coplanar lines inside the test fixture. The calibration procedure involves de-embedding the high-impedance probe from a series combination of a high-impedance probe, a 50 Ω through line, and a conventional 50 Ω probe. Figure 2 shows the de-embedded S-parameters of the high-impedance probe. It can be seen that S_{21} is rather flat across the band except for a resonance near 24 GHz. Using these S-parameters, the voltage waveforms measured through the probe are transformed to the probe tip.

The calibration procedure has been verified on a Schottky diode at 5 GHz. The voltage waveforms are measured and compared to those simulated with EEsof's harmonic balance program, LIBRA. Up to five harmonics are included in the simulation. Figure 3 shows that the measured and simulated waveforms are in reasonable agreement over various input power levels. The minor discrepancy can be attributed to parasitics associate with the diode carrier.

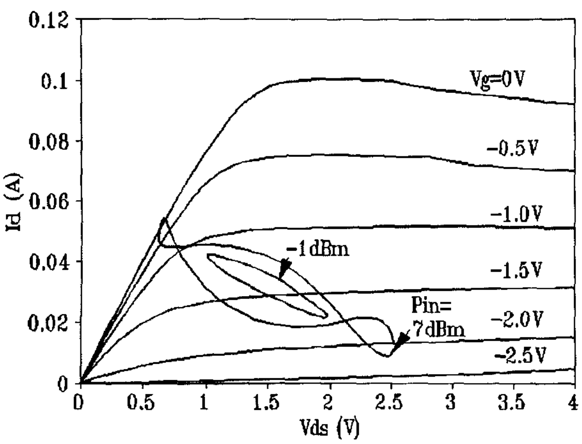


Fig. 6 RF trajectory superimposed on dc characteristics.

III. RESULTS

As an example, we report the measured results from a GaAs power field-effect transistor of 1 μm gate length and 400 μm gate width. To avoid heating effects, the device was conservatively biased at a gate voltage of -1.7 V and a drain voltage of 1.5 V, with a quiescent drain current of 32 mA. Figures 4 and 5 show the time-domain an input drive of 5 GHz and -1 to 7 dBm. It can be seen that, with increasing input power, the voltage wave becomes clamped in the negative direction. The results can be better visualized by superimposing the RF trajectory on the dc drain characteristics, as shown in Fig. 6. Under an input of -1 dBm, the RF trajectory is essentially elliptical around the 50 Ω load line. Whereas under an input of 7 dBm, the trajectory is considerably distorted as the device swings near the linear and pinch-off regions.

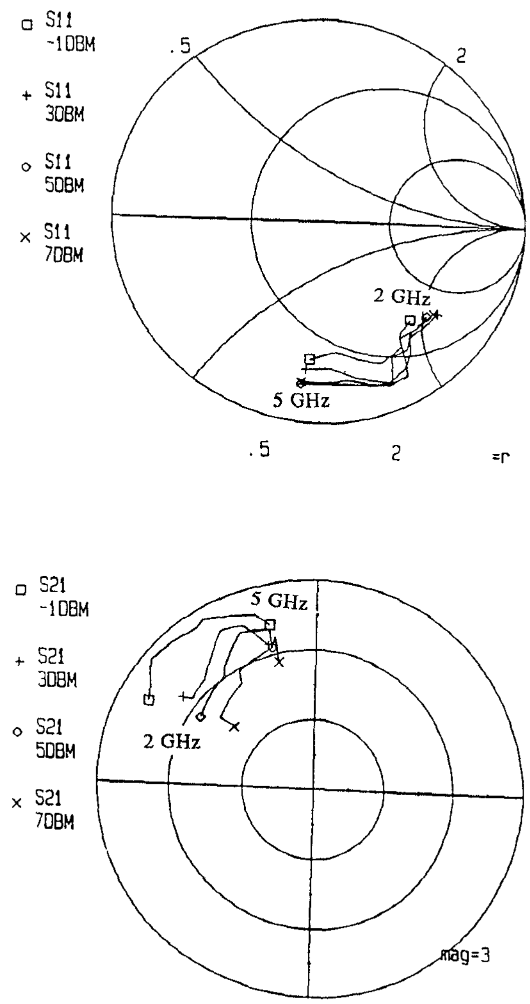


Fig. 7 Fundamental (a) S_{11} and (b) S_{21} of the transistor.

IV. CONCLUSION

For the first time, the voltage and current waveforms of a nonlinear microwave device were measured

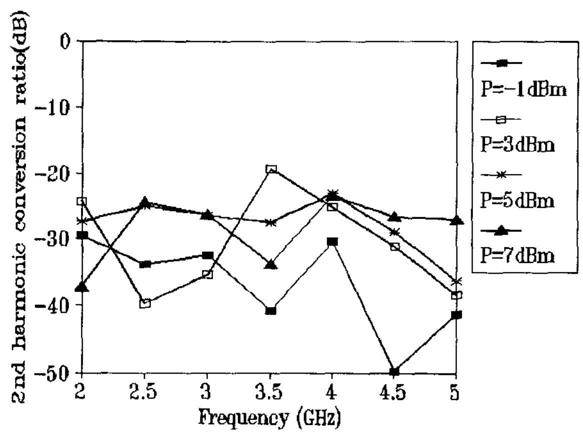


Fig. 8 Second harmonic S_{21} of the transistor.

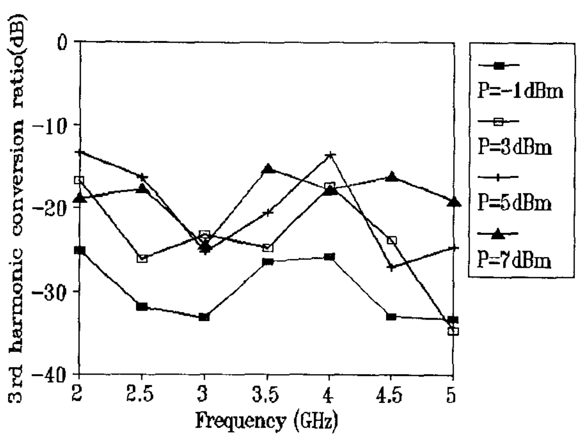


Fig. 9 Third harmonic S_{21} of the transistor.

microwave transition analyzer. From the measured waveforms, fundamental as well as harmonic S-parameters up to 26.5 GHz were determined as functions of input frequency and power. By superimposing the RF trajectory on the dc characteristics, the origin of the device nonlinearity was clearly shown. The results enable one to characterize the nonlinear behavior and to verify the large-signal model of the device in both the time and frequency domains. The present technique can be readily extended to internal-node probing and load-pull measurement without the interference of fixture effects. This technique presents a viable alternative to optical probing which tends to be tricky to implement and analyze.

ACKNOWLEDGEMENT

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