An Automatic Network Analyzer Using a Slotted Line Reflectometer

E. MARTÍN, MEMBER, IEEE, JOSÉ MARGINEDA, MEMBER, IEEE, AND J. M. ZAMARRO

Abstract—**An automatic network analyzer (ANA) based on a 5-port reflectometer is presented. The measuring circuit consists of a slotted waveguide with sliding probe. A group of three fixed probes may be used instead. A microwave source, frequency counter, and power meter are used all controlled by a desktop computer. The theory is simple and the algorithm for obtaining the complex reflection coefficient from experimental data is fast. Some results are given for measurements carried out at X-band frequencies. Successful measurement accuracy is achieved with relatively noncomplex hardware. Multioctave bandwidth operation is expected for the proposed technique.**

I. Introduction

With the advent of computer controlled microwave instruments new possibilities have arisen for the automatization of measurements [1]. In particular for network analyzers it has been possible to eliminate the need for costly and complex heterodyne systems by using less complicated configurations. In this way, only simple amplitude detectors are needed to find the complex reflection coefficient. One example is the 6-port automatic network analyzer [2]. Another advantage of these new systems is that their principle of operation can be adapted to measure at higher frequencies, where traditional systems are either ineffective or they become less reliable [3], [4].

The slotted line technique is the simplest and most widely used for measuring reflection coefficients at a fixed frequency; with this technique the complex reflection coefficient can also be obtained from amplitude measurements.

Following this idea, this paper presents a measurement technique based on the use of a slotted line with sliding probe and power sensor for obtaining the data. The paper describes an algorithm which allows the complex reflection coefficient to be calculated from the readings obtained at three different positions of the probe. The use of a desktop computer to control signal source and power meter allows measurements to be taken under swept frequency conditions.

In this way, the authors have developed an ANA based on a 5-port junction, with no limitation on high VSWR conditions found in other 5-port ANA's [5].

Other measurement schemes based on multiple probes have been described. One of the most outstanding was an automatic system presented by Hu [6]. Hu also carried out a critical revision of these systems, principally directed towards the determination and real time presentation of the reflection coefficient. The system described in this paper is also called automatic but in the sense that Engen [2] described it. This means that a desktop computer is used not only to process the results but also to control the experiment.

Manuscript received August 10, 1981; revised November 11, 1981.
The authors are with the Departamento de Física, Facultad de Ciencias, Universidad de Murcia, Murcia, Spain.

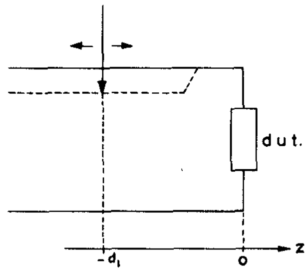


Fig. 1. Measuring circuit.

II. The Measurement Principle

The diagram in Fig. 1 shows the measuring circuit which constitutes the basis for obtaining data. It consists of one sliding probe which can be located in three known positions sampling the field given by

$$E_i = E_0\left(e^{-j\beta z_i} + R_0 e^{+j\beta z_i}\right), \qquad i=1,2,3$$

where $R_0 = \rho e^{j\psi}$ is the reflection coefficient of the device under test (DUT)), referred to the $z=0$ plane, and β the propagation constant in the slotted line which is assumed to be lossless.

A square-law detector or a power sensor coupled to the probe, will detect a signal given by

$$L_i = C'_i|E_i|^2 = C_i\left(1+\rho^2+2\rho\cos(2\beta z_i+\psi)\right).$$

Parameter C_i depends only on the probe frequency response assuming a good power stability and that the incident power to the measurement device is load independent. When the DUT is in position, the ratio between the power meter reading at each frequency and the value of C_i will satisfy the following equation:

$$l_i = L_i/C_i = 1+\rho^2+2\rho\cos(2\beta z_i+\psi).$$

The values of ρ and ψ are found by combining the values of l_i in the following way:

$$l_1 - l_2 = A_{12}x + B_{12}y$$
$$l_1 - l_3 = A_{12}x + B_{13}y$$

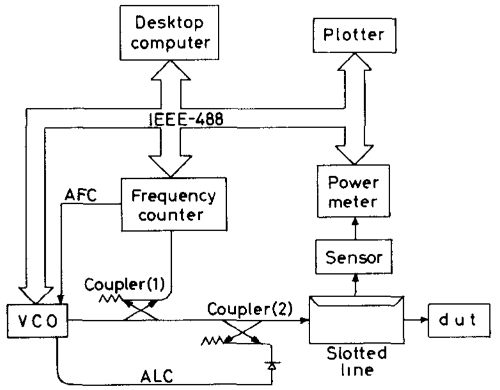


Fig. 2. Block diagram of the measurement setup. Coupler (2) is a 10-dB directional coupler with reflection coefficient less than 0.02.

where $x=\rho\cos\psi$ and $y=\rho\sin\psi$, and

$$A_{ij}=2(\cos 2\beta z_i-\cos 2\beta z_j)$$

$$B_{ij}=-2(\sin 2\beta z_i-\sin 2\beta z_j)=2(\sin\beta d_i-\sin 2\beta d_j)$$

where $d_i=-z_i$ is the absolute distance from the probe to the reference plane. In this way, a simple and fast algorithm is obtained.

III. Experimental System and Measurement Procedure

Experimental verification was carried out at X-band frequencies. A rectangular slotted waveguide was used as the measuring circuit, coupled to a sliding probe and power meter. Fig. 2 shows a diagram of the whole setup.

The frequency counter has the possibility of locking a microwave source with frequency modulation capabilities, so that an automatic frequency control (AFC) loop can be obtained. The same stability for the microwave source as that of the counter time base can thus be achieved. An automatic level control (ALC) is established before the measuring circuit. The sweep oscillator, the counter, and the power meter are all controlled by a desktop computer via an IEEE 488 interface bus. A computer program was developed which controls the digital frequency sweep, stores the power readings, and processes all the data in order to obtain the complex reflection coefficient at each frequency. The complex reflection coefficient can then be displayed in a suitable manner.

The measurement procedure is as follows.

1) Once the frequency range and the frequency step between consecutive points have been fixed, a series of data is taken using a matched load with the probe in an intermediate position between those positions to be used later on.

2) The next stage is to substitute the DUT for the matched load and three new series of measurements are taken with the probe at the three known positions.

3) All the data are then normalized to the readings which correspond to the matched load for each frequency. The system of equations is solved to find the corresponding values of magnitude ρ and phase ψ.

A possible modification of this system would be for the slotted line and sliding probe to be substituted by a group of three fixed probes without any alteration of the system characteristics. In this case, only two frequency sweeps would be needed, one with a matched load and the other with the DUT, the data being taken by the three probes at each frequency simultaneously.

IV. Analysis of the Errors

The errors associated with this particular experimental system are due mainly to the following sources: the measuring circuit; the oscillator; the power meter; source matching problems; and "matched load" mismatch. Numerical calculation was used to carry out the analysis of errors in this section. The calculated errors agreed with those obtained experimentally, as shown in Section V.

The calibration of the slotted guide was made by fitting the theoretical expression corresponding to the field in a short-circuited waveguide to the experimental standing wave data, obtained by sweeping the frequency and with the probe in a fixed position [7]. In this way, it was possible to obtain an effective width of 2.275 ± 0.005 cm for the slotted guide used (nominal width, 2.286 cm), which took into account the effect of the slot. Likewise the absolute distance from the probe to the reference plane (right flange face) may be measured to an accuracy of 0.1 mm. This error basically affects the determination of the phase, causing an inaccuracy of less than 1°.

We also studied how the separation between the probe locations affects the accuracy of the technique. This separation can be measured to an accuracy of 0.01 mm using a dial indicator fitted to the slotted guide. According to Engen's proposal [8], it was found that the optimum separation is $\lambda/6$, although it is not critical. Its incidence will be evaluated later on.

With respect to the signal source, two problems must be overcome, one due to the power stability and the other to frequency stability. The ALC placed close to the slotted guide assured that any errors due to the variations in power would be negligible, assuming that the matched load calibration and the measurements with the DUT are carried out in a short time. Frequency stability was approximately 5×10^{-9} and the frequency could be varied in 0.1-MHz steps throughout the band. Frequency errors are then also negligible.

Power can be measured from 0.3 nW to 10 μW up to three significant figures. This wide dynamic range is suitable for the type of measurements normally found. Besides, the high sensitivity of the sensor allows the probe to be sufficiently taken out to avoid probe loading problems. With other types of detectors, square law response deviations should be studied.

The speed at which the data are taken depends mainly on the power meter. The calculator program controls the stabilization of the power meter reading and the oscillator frequency locking. An average of 2 s is needed for each reading.

The main source of error observed in the present system is the source matching. Any reflection, of the signal reflected by the load, in any part of the system before the measuring device will induce errors in the readings due to the fact that they were not previously present in the calibration process with the matched load. These errors that are dependent of the product of the load and discontinuity reflection coefficients will be more important for a highly reflecting load. They were considerably reduced by means of the ALC located just before the slotted guide. As the 10-dB directional coupler used in it has a maximum reflection coefficient of 0.02, it was possible to reduce the errors from this effect to less than 0.3 dB in return loss, and 2° in ψ under short-circuit conditions.

Another type of error comes from the nonideal matched load used in the calibration process. This limits the present system to measure loads with reflection coefficients greater than the coefficient of the matched load ($\rho < 0.0075$).

It must be pointed out, as was confirmed experimentally, that the accuracy of the results was not improved by the use, in the calibration stage, of the readings taken from the three positions of the probe. So the readings in an intermediate position were used only in order to reduce the time needed in taking data.

Taking into account the previous results, the effect of the probe separations have been analyzed in order to evaluate the potential bandwidth and dynamic range capabilities of the proposed technique. The following conclusions may be drawn up.

The probe needs to be situated as near as possible to the load if the effect of the losses of the slotted guide (not taken into account in the system analysis) are to be avoided. On the other hand, if the maximum separation between the probe locations is less than $\lambda/2$, ambiguity problems do not exist.

It was also seen that the separation between neighboring probe locations could be reduced to $\lambda/12$ while an accuracy of 0.3 dB in ρ and 1° in ψ is achieved for values of $\rho > 0.05$. These errors increase to 1 dB and 4° when ρ is as low as 0.01. If the last mentioned errors are accepted as being admissible, a 40-dB dynamic range may be established for the proposed technique with a bandwidth of up to 3 octaves. This bandwidth together with the upper frequency limit could be increased if the restriction of the $\lambda/2$ margin in the positioning of the probes is eliminated. In this case, a deeper analysis of the effect of the losses and their possible compensation is needed. This is presently under study.

In our present system, the bandwidth, limited by the available instrumentation, is 8.2 to 12.4 GHz. This restricted bandwidth may be extended by using commercially available slotted lines or custom-made three-probe reflectometers. Mention must also be made of the potential contribution of using this system in millimeter waves.

V. Experimental Results

Table I presents the results of measurements between 8.5 and 11.5 GHz for a fixed short circuit for step frequency of 0.1 GHz. Obviously lower accuracy is expected for this particular configuration. The errors observed with respect

TABLE I
Reflection Coefficient of a Fixed Short Circuit

Frequency (GHz)	Reflection Coef. Magnitude	Argument (deg.)
8.500	.985	179.0
8.800	.970	179.5
9.100	.971	180.1
9.400	.988	180.0
9.700	.989	179.4
10.000	.965	179.7
10.300	.992	180.2
10.600	.982	180.0
10.900	.971	180.0
11.200	.979	180.6
11.500	.990	179.1

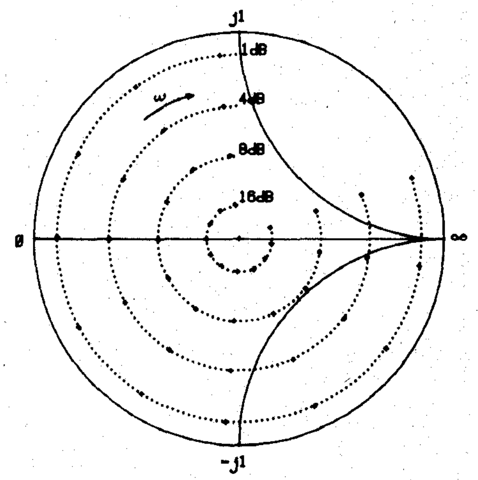


Fig. 3. Reflection coefficient of a rotary vane attenuator terminated with a short circuit (+ + + experimental points). Nominal return losses are indicated (dotted lines), corresponding to the following attenuator settings: 0.5, 2, 4, and 8 dB. Frequency range: 9.0–9.2 GHz.

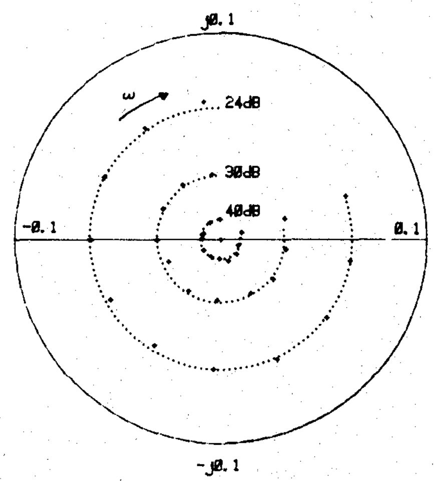


Fig. 4. Same as in Fig. 3 but with nominal attenuator settings: 12, 15, and 20 dB. (Expanded Smith diagram.)

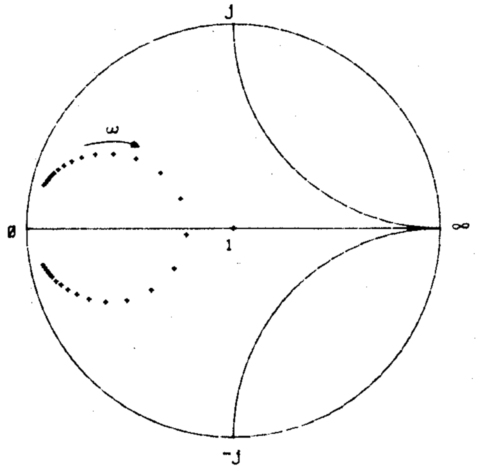


Fig. 5. Reflection curve of a resonant cavity. Frequency range: 9.000–9.014 GHz.

to the theoretical value of $R_0 = -1$ are 0.3 dB in the amplitude and 1° in the argument. These errors are within the previously mentioned theoretical limits.

Figs. 3 and 4 presents the differential attenuation measurements carried out on a precision rotary vane attenuator terminating in a fixed short circuit. These measurements were corrected on the basis of the data taken when a matched load was substituted for the short. As shown in Fig. 3, there is a good agreement between the values obtained for the magnitude of the reflection coefficient and those corresponding to the nominal attenuator settings (dotted line). With respect to the phase of the reflection coefficient, the results obtained for different attenuator settings at a frequency are on radial lines. This is in agreement with the characteristics of the rotary vane attenuator in which the phase change for different attenuator settings must be negligible.

Fig. 4 shows that the present system can measure return loss up to 40 dB with no appreciable accuracy degradation.

Fig. 5 shows the complex reflection coefficient of a resonant cavity. These results point out the possibilities that the frequency stabilization has to offer when measuring highly selective loads.

VI. Conclusions

This paper shows the theory behind an ANA offering enough accuracy for most types of measurements frequently found in practice. The feasibility of the system is shown by its practical application in the measurement of characteristics of different components at X-band frequencies. Some of these results are presented.

Some possible modifications or generalizations of the system can be developed. For instance, the slotted line and sliding probe can be substituted by a group of three probes as outlined in the paper. Also, four or more probes can be used in order to increase the accuracy [6]. On the other hand, different probe arrangements could be used for measuring the transfer function or the scattering matrix of 2-port devices [9].

References

[1] T. Mukaihata and R. D. Johnstone, "Implementation and use of small automated-test systems," *Proc. IEEE* vol. 66, pp. 403–413, 1978.

[2] G. F. Engen, "Advances in microwave measurement sciences," *Proc. IEEE*, vol. 66, pp. 374–384, Apr. 1978.

[3] M. P. Weidman, "A semiautomated six port for measuring millimeter-wave power and complex reflection coefficient," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-25, pp. 1083–1085, Dec. 1977.

[4] H. P. Groll and W. Kohl, "Six port consisting of two directional couplers and two voltage probes for impedance measurement in the millimeter-wave range," *IEEE Trans. Instrum. Meas.*, vol. IM-29, pp. 386–390, Dec. 1980.

[5] G. P. Riblet, "A compact waveguide 'Resolver' for the accurate measurement of complex reflection and transmission coefficients using the 6-port measurement concept," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-29, pp. 155–161, Feb. 1981.

[6] C. J. Hu, "A novel approach to the design of multiple-probe high-power microwave automatic impedance measuring schemes," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-28, pp. 1422–1428, Dec. 1980.

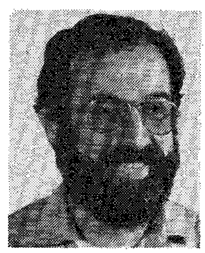
[7] E. Martín *et al.*, "Automatización toma de datos en guía ranurada," in *Proc. I Simposium Nacional U.R.S.I.*, (Madrid, Spain), pp. 55–57, 1980.

[8] G. F. Engen, "The six-port reflectometer: An alternative network analyzer," *IEEE Trans. Microwave Theory Tech.* vol. MTT-25, pp. 1075–1080, Dec. 1977.

[9] C. A. Hoer, "A network analyzer incorporating two six-port reflectometers," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-25, pp. 1070–1074, Dec. 1977.

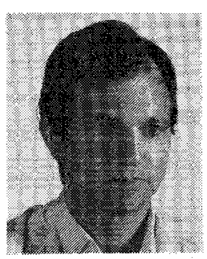
E. Martín (M'78) was born in Tenerife, Spain, on April 7, 1946. He received the "Licenciado" degree in physics in 1968, and the "Doctor en Ciencias" degree in 1972 from the University of Madrid (Complutense), Spain.

He served as a Teaching Assistant in the Department of Electricity and Electronics, University of Madrid. From 1973 to 1977 he served as "Profesor Agregado" of electricity and magnetism at the University of Valladolid, Spain, and since 1977 he has been "Catedrático de Electricidad y Magnetismo" at the University of Murcia, Spain. His scientific activity has been devoted mainly to classical electromagnetism and microwaves.



José Margineda (M'79) was born in Balaguer (Lleida), Spain, on August 10, 1948. He received the "Licenciado" degree in physics from University of Madrid in 1972 and the Doctor in Science degree from University of Valladolid in 1977.

He served as a Teaching Assistant in the Department of Electricity and Electronics of University of Valladolid from 1973 to 1977. From 1977 to 1979 he had been "Profesor Agregado" of Electricity and Magnetism in that department. Since 1979 he has been "Profesor Adjunto" in the Department of Physics, University of Murcia, Spain. His scientific activity has been devoted mainly to classical electromagnetism and microwaves.



J. M. Zamarro was born in Zaragoza, Spain, on May 29, 1946. He received the "Licenciado" degree in physics from the Universidad Complutense, Madrid, Spain, in 1971 and the "Doctor en Ciencias" degree from the Universidad de Murcia, Spain, in 1979.

He is a "Profesor Adjunto" in the Department of Physics, Universidad de Murcia, Spain. His fields of interest are microwaves and ferrites.