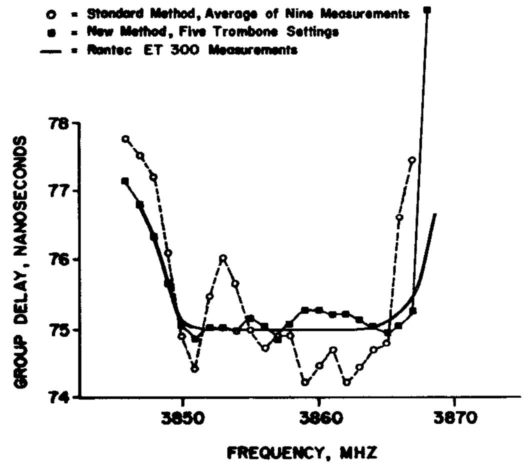

Fig. 1. Comparison of group-delay measurements of filter by two methods on H-P 8542A automatic network analyzer with Rantec ET-300 measurements.

ponent, which can be left connected throughout the measurements. All differences between measured results must be attributed to the system, not the component.

This concept is put into effect by first calculating the group delays for each set of measurements from the phase differences, using the true frequency differences. Then the differences between the successive group delays are calculated, again for each set of measurements. Next, the group-delay differences corresponding to a given frequency are compared and one is selected that is relatively small in absolute magnitude.

Specifically, if five replications are involved, the group-delay difference with the smallest absolute value is selected. If six to eight replications are available, the next-to-smallest-magnitude group-delay difference is selected. A single list of group-delay differences as a function of frequency is thus composed. Group delay as a function of frequency is calculated by summing along this list and adding a constant.

The constant may be chosen so that the average group delay over the passband is equal to that measured in the usual way over a large frequency interval corresponding to most of the passband. A still more accurate average value of group delay could be obtained by selecting the frequency interval so that the phase change is close to 360° or a multiple thereof. This refinement was not included since the main interest is in group-delay variations rather than absolute value of delay.

Well-matched pads for source and load make it unnecessary to correct for mismatches.

A measurement of a prototype linear-phase filter is shown in Fig. 1, along with the results obtained from a standard measurement on the same system and the presumably more accurate results from a Rantec ET-300 group-delay test set.

While the procedure that has been described is bound to give a smoothing effect, it preserves data that would be suppressed by a simple smoothing with respect to frequency of a single set of measurements. If a component truly has a defect, evidence of it will probably be present in all of the replicate measurements and the defect is not likely to be concealed (extremely unlikely if the next-to-smallest group-delay difference is used). On the other hand, when a component is designed to give a smooth response and the smoothness is confirmed by one or two measurements, one would be foolish to penalize the component for other measurements made on equipment known to be prone to frequent relatively large errors. Nor is an average of good and bad results a fair representation of the component's performance—hence, the term "noncentral statistics."

No claim is made that the method can compete in accuracy with special group-delay measuring equipment employing modulated signals. The objective has simply been to extend the usefulness of the point-by-point CW automatic network analyzer.

ACKNOWLEDGMENT

The author wishes to thank Dr. R. Levy of Microwave Development Laboratories for the long-term loan of the specimen filter and for the Rantec ET-300 measurements.

MICTPT—A Minicomputer General-Purpose Microwave Two-Port Analysis Program

D. H. OLSON AND F. J. ROSENBAUM

General-purpose microwave network-analysis programs [1], [2] are typically organized on a time-shared basis using large-scale computers. As minicomputers become widely available, it is desirable to have a compatible general-purpose analysis program to assist the microwave engineer in his design efforts. The purpose of this letter is to describe the implementation of one such program for machines with 4K words of memory. Although MICTPT was designed for a Digital Equipment Corporation PDP-5 computer with 4K (4096) of 12-bit word core storage, the approaches used are applicable to any similar small computer.

The program is capable of the frequency analysis of networks which include interconnections of lumped elements, transmission lines, and waveguides, and any two-port which is described by the elements of a scattering matrix. The present implementation will not handle four-port elements or completely arbitrary network interconnections, such as bridged tees, etc. Other implementations are, of course, possible [3].

In order to meet the size objective, MICTPT is organized in three parts: the "source" describing the network is first created and edited using the operating system EDITOR which allows manipulation of the description statements. It is then stored on magnetic tape and a second program MICVER is run to compile the "source" description into an "object" description, which is also stored on tape. Finally, the analysis MICTPT is run with the "object" description as the input.

This technique, although requiring some effort to change the

Manuscript received September 14, 1973; revised November 12, 1973. This work was supported in part by the National Science Foundation under Grant GY-1814 and in part by the National Aeronautics and Space Administration under Grant NGR-26-008-054.
The authors are with the Department of Electrical Engineering, Washington University, St. Louis, Mo. 63130.

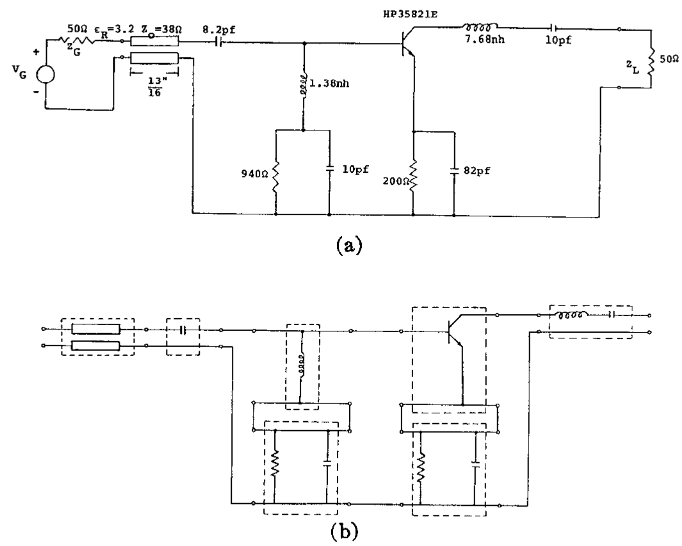

Fig. 1. (a) High-frequency broadband transistor amplifier. (b) Two-port equivalent schematic.

network description, presents two important advantages. Firstly, the network can be described mnemonically rather than by numerical codes, making it easy for the microwave engineer to quickly learn and remember how to use the system. Secondly, networks of arbitrary size can be accommodated since MICTPT reads the network description into a buffer, one tape block at a time, as needed. The entire program is written in assembly language (Pal) in order to minimize its length.

Analysis of a network is begun by describing it in terms of a standard set of descriptors (available in the operating manual) using the EDITOR routine. Once the network description is stored on tape, the program MICVER is run. It requests the starting tape block where the mnemonic "source" is stored and where the compiled "object" description should be stored. It then verifies the syntax and converts the mnemonic description to a coded format for the analysis routine. The original description is printed out as the conversion is done. Finally, the last tape block on which the "object" has been stored is given.

Now MICTPT is run. When started, it requests the location of the tape block where the "object" has been stored and the starting, ending, and incremental frequency (in GHz) for which the network is to be analyzed. Next, the complex terminating voltage and current (equivalent to a termination impedance) is requested. Finally, the complex generator impedance is requested. The input impedance is normalized to this value for the calculation of reflection coefficient, etc.

The program then begins analysis. For each frequency in the range the entire network is collapsed into a single equivalent A matrix and the input impedance, etc., is calculated. Changes in the network parameters require return to the source program. All the steps are then repeated for the new network. An example program for a transistor amplifier is shown in the Appendix. The transistor is described in terms of its scattering matrix. Approximately 5 s of run time are required to obtain the input return loss and gain at each frequency, excluding printing time.

Through the use of chain programming techniques, networks consisting of an arbitrary number of linear two-port elements can be analyzed on a minicomputer with 4K words of memory and a magnetic tape drive. The program described here was configured for the needs of this laboratory. Although it is not as powerful or as convenient to use as commercial time-sharing packages, MICTPT does permit the economical use of the minicomputer for many of the tasks encountered by the microwave engineer.

Appendix

The high-frequency amplifier of Fig. 1(a) is analyzed in MICTPT as an example of its use. The amplifier is drawn in terms of two-ports as shown in Fig. 1(b). The description for input to the MICVER compiler is as follows.

CSC				Beginning of a cascaded section;
TEM	3.2	0.8125	38	microstrip $\epsilon_R = 3.2$, $D = 0.8125$ in, $Z_0 = 38\ \Omega$;
ZSS	0	0	8.2	further cascade (coupling capacitor);
***				end of cascaded section.
SER				Start of series connection;
ZSP	0	1.38E-3	0	could contain any number of cascaded sections;
***				end of first two-port to be series connected;
SER				start of second two-port in series connection.
ZPP	940	0	10	
***				End of entire series connection;
CSC				start of dummy section cascaded
TRF	1			between two succeeding series
***				connections.
SER				Start of second series connection;
MXT				S parameter table representing the transistor.
***				
SER				
ZPP	200	0	82	
***				
CSC				
ZSS	0	7.68E-3	10	
***				
FIN				End of network.

From the above, note several things. First, once a connection topology has been named, cascades within that connection are specified merely by listing them in order from input to output. For the parallel and series connections, each two-port may consist of several cascades and must be described separately surrounded by the connection name on one side and asterisks on the other. Multiple parallel two-ports may be described in any order. Multiple series two-ports must be described consecutively but may be described from top to bottom or bottom to top. Cascades of series or parallel connections must be separated by a dummy section (1:1 ideal transformer).

Acknowledgment

The authors wish to thank L. K. Berger and C. R. Stone, formerly of Washington University, for their help in establishing some of the basic approaches used to implement MICTPT.

REFERENCES

[1] W. N. Parker, "DIPNET, a general distributed parameter network analysis program," *IEEE Trans. Microwave Theory Tech.* (*Special Issue on Computer-Oriented Microwave Practices*), vol. MIT-17, pp. 495–505, Aug. 1969.

[2] P. E. Green, "General purpose programs for the frequency domain analysis of microwave circuits," *IEEE Trans. Microwave Theory Tech.* (*Special Issue on Computer-Oriented Microwave Practices*), vol. MTT-17, pp. 506–514, Aug. 1969.

[3] S. E. Ramey, *9820A Microwave PAC*, vol. 1. Loveland, Colo.: Hewlett-Packard, Part Number 09820-71200, 1972, pp. 57–67.

Computer Program Descriptions

Computation of Dielectric Properties from Short-Circuited Waveguide Measurements on High- or Low-Loss Materials

PURPOSE: Computation of the relative complex permittivity components ϵ_r' and ϵ_r'', loss tangent, and conductivity from measurements data on materials in coaxial, rectangular, or cylindrical waveguides.

LANGUAGE: Fortran IV; 393 cards, including comments.

AUTHORS: S. O. Nelson, C. W. Schlaphoff, and L. E. Stetson, U.S. Department of Agriculture, ARS, and University of Nebraska, Lincoln, Nebr.

AVAILABILITY: ASIS/NAPS Document No. 02272. Listing, typical I/O data and description in U.S. Department of Agriculture Publication No. ARS-NC-4, November 1972.

DESCRIPTION: The program was developed for calculation of dielectric properties from data obtained using the short-circuited waveguide technique originally reported by Roberts and von Hippel [1] and employing relationships for wall-loss corrections described by Westphal [2]. In preliminary calculation stages, the program employs simplified relationships developed by Dakin and Works [3] that are valid for low-loss materials. Final calculations, however, are based on the general equations that are valid for high-loss materials as well.

Required information for determining the dielectric properties of a sample include the voltage or current standing-wave node locations with respect to the short-circuit termination, both with and without the sample in the waveguide, and the respective standing-wave ratios for these two situations. Also required are the frequency, the length of the sample, and the dimensions of the waveguide unless it is a coaxial line.

The program accommodates input data from measurements on coaxial lines, or cylindrical or rectangular waveguides. It properly performs all necessary calculations for either low-loss or high-loss dielectric samples and provides values for ϵ_r', ϵ_r'', the loss tangent ($\tan \delta$), and the conductivity (σ).

Input data include sample description and other sample identifying information, waveguide dimensions, width of the slot in the slotted waveguide section, a reference dimension corresponding to the approximate distance (within $\pm\lambda_g/4$) between the short-circuit termination and the slotted-section probe when the probe is positioned at zero on its scale, frequency (either directly or in terms of adjacent standing-wave node data), slotted-section scale readings taken at 3-dB points (or any other decibel level) on both sides of the air node (empty line or waveguide) and sample node (sample in place at short-circuited end of line or waveguide), the decibel level employed for each node-width measurement, the length of the sample, and an estimate of the value of the dielectric constant (ϵ_r'). The program accepts any air node or any sample node without regard to relative positional relationships.

The program corrects all slotted-waveguide-section data for the influence of the slot. An iterative method is employed to solve the necessary cubic equations for the true guide wavelength in rectangular and cylindrical waveguides. Standing-wave ratios are calculated from node-width measurements using an exact relationship. The fact that measurements are taken in air rather than vacuum is taken into account.

Detailed explanations of the computations and subroutines employed have been described [4]. The input estimate for ϵ_r' provides, through simplified relationships of Dakin and Works [3], an estimate for $\beta_2 d$, the product of the phase constant in the sample (β_2), and the sample length (d). A special subroutine is then employed to find the three values of $\beta_2 d$ closest to the initial estimate of $\beta_2 d$, that satisfy the equation of Dakin and Works, $(\tan \beta_2 d)/\beta_2 d = C$, where C is a real number obtained from measurements data. Estimates for $\alpha_2 d$ are then obtained using another equation of Dakin and Works [3], and the three corresponding values of $\gamma_2 d = \alpha_2 d + j\beta_2 d$ are provided by another subroutine that alternately adjusts values of $\alpha_2 d$ and $\beta_2 d$ until the complex transcendental equation $(\tanh \gamma_2 d)/\gamma_2 d = Ce^{j\zeta}$ is satisfied to within the desired limit. $Ce^{j\zeta}$ is a complex number obtained from measurements data.

The values of $\gamma_2 d$, the product of sample length, and the complex propagation constant in the sample material, thus provide three sets of values for ϵ_r' and ϵ_r'' that have ϵ_r' values closest to the estimated dielectric constant of the sample. Three sets of values for ϵ_r', ϵ_r'', $\tan \delta$, and σ are printed out along with the input data and a few diagnostics. When calculations are performed by the program for a number of different sample measurements (up to 50), a summary table is provided in the printout which includes only that set of dielectric properties for each sample that matches most closely the input estimate for the dielectric constant. The detailed printout of input data and three sets of values for the dielectric properties of each sample measurement can be suppressed if desired.

Calculations were programmed for computation on an IBM 360 model 65 computer. When compiled under IBM OS/MVT, the program executes in 40K of core. Typical central-processing-unit time required for processing 50 sample measurements is less than 20 s. There are no files other than the input (reader) and the output (printer) files.

On rare occasions when the sample length is an odd-multiple quarter-wavelength, values for some of the functions become infinite. The program includes tests to circumvent this problem and prints out a statement identifying the problem, approximate values for the dielectric constant, and zeros for the other properties.

This computer program has been used successfully for several different systems for dielectric-properties measurement, including a rectangular waveguide X-band system, a cylindrical waveguide system operating at 8.5 GHz, and three coaxial systems operating in the range from 1 to 6.3 GHz. It incorporates a number of convenience features for an already convenient measurement method whose principal disadvantage is in the tedium of calculation. The computer program eliminates this disadvantage and improves the precision of calculation, making the method more attractive, especially for the determination of dielectric properties of high-loss materials.

Manuscript received March 19, 1973; revised August 7, 1973. Published as Paper 3581, Journal Series, Nebraska Agricultural Experiment Station.

See NAPS Document No. 02272 for 30 pages of supplementary material. Order from ASIS/NAPS, c/o Microfiche Publications, 305 E. 46th St., New York, N. Y. 10017. Remit in advance for each NAPS accession number $1.50 for microfiche or $5.00 for photocopies. Make checks payable to Microfiche Publications.