A DUAL FOUR-PORT FOR AUTOMATIC NETWORK ANALYSIS

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ABSTRACT

The concept, hardware, software, calibration and preliminary performance of a dual four-port automatic network analyzer is described.

Introduction

Automatic network analyzers (ANAs) in use today provide outstanding accuracy and ease of use, contribute significantly to better microwave component design, and lower business costs during both design and production stages. Yet one or the other of the two major ANA concepts have characteristics which still limit their usefulness, introduce errors after calibration, preclude manual (real time) operation and checkout, and/or in the millimeter wave bands, require more RF power than can be cost-effectively generated, or require flexible (and hence, variable mismatched) transmission lines within the unknown test circuit. This new approach, the dual four-port (DFP), yields significant improvements in these problem areas.

The objective of work is to develop two millimeter wave (MMW) ANAs, one at 35 GHz and one at 94 GHz. The work is being implemented in two steps. First, the development of a 2 to 18 GHz (microwave) ANA to check out the microwave frequency parts of the system (and provide new capability there) and second, to add the millimeter wave components and complete the work. It was earlier planned to report on both steps at this conference but delays in delivery of millimeter wave equipment has prevented reporting on the performance in those bands.

The RF block diagram (Figure 1) of the dual four-port appears very similar to the dual six-port proposed by Hoer[1] but with his two six-ports and their detectors replaced by magnitude and phase detectors. This change alone leads to cost-effective realizability in the millimeter wave bands and to the possibility of manual operation. The latter is desirable in practice to verify good connections to the device under test (DUT) and to verify proper functioning of the system. Such is not possible with six-ports because each measurement requires calculations to convert its power readings to vectors. Also at 94 GHz, a six-port based system requires approximately 700 MW of CW power to yield adequately noise-free signals to its detectors. Such sources do not exist over the planned 10 GHz bandwidth of the author's system nor is that power cheaply available even at a single frequency there.

Hardware

Figure 2 is a photograph and Figure 3 shows a block diagram of the 2 to 18 GHz version of the Dual Four-Port ANA. Comparison with the Hewlett-Packard catalog quickly reveals that the heart of the system is their HP-8409B phase-locked network analyzer. Differences include a substantially simplified test set, a second HP-8411 Harmonic Converter (also powered by the 8410 Network Analyzer mainframe), a SP3T IF switch to select one of the three test set signals being measured, two power splitters to transmit RF excitation of each test set and to distribute frequency stable L.O. power to the harmonic converters, and a programmable attenuator to vary the power in RF signal arm B during part of the measurement cycle. Variation of the RF signal in one arm is required in order to allow the system to mathematically separate reflected and transmitted signals associated with the DUT. Both of the "b" signals (refer to Figure 1) are mixtures of reflected and transmitted signals.

Three test signals from the two harmonic converters must be switched to the network analyzer and measured. That switch is a solid state type with 100 dB isolation chosen because of the need to switch it twenty-one times at each frequency to accomplish calibration and one measurement.

Extension to Millimeter Wave Bands

As previously mentioned, the major purpose for the development of the DFP ANA at Hughes is to extend automatic corrected measurements into the millimeter wavebands where no similar commercial test equipment exists. Additional equipment needed to accomplish this extension is shown in the MMW ANA block diagram, Figure 4. Added are four MMW mixers, two MMW local oscillators, a second synchronizer, a synthesized, crystal referenced source and waveguide couplers to make up the MMW test sets. Separate sets of the above MMW components are needed at each band to be covered.

To allow insertion of a DUT at the test ports, TP, (Figure 1) at least one of the four-port structures must be moveable. The authors chose to make both four-ports moveable for greatest utility thus requiring lengths of flexible transmission line between points labeled BB' and CC'. Realizing flexibility at 94 GHz, however, is not normally a simple problem. It can be readily solved in this application though by use of dielectric waveguide. There are no stringent requirements on the dielectric guide. That waveguide lies outside of the measuring circuit (i.e., outside of the B'-TP-C' region) and furthermore, each measurement is independent of all others (even at the same frequency). Hence, mismatch variations will have only secondary effects through effects on source matches.

The above feature contrasts significantly with alternative embodiments illustrated by the various Hewlett-Packard HP-87XX Network Analyzer test sets - the present day industry standards and examples of excellent equipment. All of these test sets include components within the test circuit which can vary slightly throughout the measurement (especially after calibration). These variations become first order errors in the measurement. Examples are: variations due to flexing the flexible coax cable used with the HP-8743 test set, and variations associated with a user-fabricated, length-compensating waveguide in the HP-8747 test set. Both lines are necessary when making two-port measurements and their mismatch cannot be distinguished from that of the DUT.

It must be mentioned that the DRP also has components which can vary during and after calibration and, hence, introduce errors. Recently discovered is a time-dependent relative phase shift in L.O. power in the two HP-8411 harmonic converters. This problem is discussed in more detail later.

The DFP has a further advantage of utility - especially for the waveguide-based systems. Use of the HP-8747 (and a similar TRG test set) requires substituting the DUT for a length of straight waveguide. This places two requirements on the DUT; its terminals must lie in a straight line, and a length-compensating waveguide must be fabricated. The compensating waveguide can be designed to accommodate DUTs without in-line terminals, but that is expensive and its inherent mismatch would degrade the measurement. Such added difficulty could discourage potential users. The dual approach with its substantial flexibility in orientation of its test plane connectors comes close to completely solving this problem.

Separate MMW local oscillators are used to minimize the number of flexible waveguide lines that must be routed to the moveable four-port reflectometers. Each L.O. is phase locked to common RF and crystal references to maintain phase integrity. A key element is the frequency stabilized source. To achieve convenient, programmable measuring capability, the source must be tunable over a substantial spectrum while furnishing adequate power to achieve noise free measurements. Present specifications are 10 percent bandwidth and 5 mW power. The manufacturer of this state-of-the-art component is experiencing difficulty in meeting both of these specifications simultaneously and delivery has been delayed.

Calibration Procedure

The objectives and techniques for calibrating the dual four-port (or dual six-port) is shown in Figure 5. The error two-ports are S-parameter matrices and fully describe the errors in the measurement system leaving, conceptually, two ideal four-ports with which measurements are made.[2,3,4] A computer program measures these error S-parameters by first making three calibration measurements at each frequency: measurement of a simple through (Thru) connection of the test ports, two identical short circuits, and a well matched delay line. The theory assumes the latter is reflectionless when connected, and its length cannot be a multiple of a half wavelength. With these assumptions, matrix manipulation yields the error two-port parameters which, in turn, are used with subsequent device measurements to yield the S-parameters of the DUT.

Software

The DFP software (designated GPMH, Hughes General Purpose Measurement program) is based on the Hewlett-Packard GPM2 general measurement program for two ports written for the HP-2100S computer. The major revisions to GPM2 are in the calibration, measurement and set-frequency routines. These were completely replaced. Other changes were to the instrument drivers. Although the instruments are primarily from the GPIB compatible HP-8409B ANA systems, no drivers existed to interface those equipments to the HP-2100 family. All of the drivers for the HP-8409B and substitute instruments were written from scratch.

The subroutines making up the calibration routine include special HP-8409B algorithms (HP made available by Hewlett-Packard), the dual six-port calibration algorithms[2] and modifications to the latter algorithms to make them compatible with the dual four-port (DFP) application. A block diagram of GPMH is shown in Figure 6. The "Calibrate" and "Measure Device" subroutines are entirely re-written. The "Initialize" and "Plot and Print" subroutines are largely taken from GPM2.

Measurement and calibration of a dual four-port bears little resemblance to the prior approach. The mathematics of the DFP is completely different and more complex. Extensive matrix manipulation is required. As a matter of interest, the characteristic values of the Line and Reflect standards need not be known. Their values are determined as a by-product of the calibration process. It is only necessary that the Line be reflectionless and the Reflect terminations be identical.

The measurement routine differs from prior techniques in that two measurements of the complex signal ratios are required - one at each of two different power levels in signal arm B. Figure 1 illustrates the parameters measured. After the first pass the power level in arm B is changed (from P_1 to P_2) and the parameters measured again. The uncorrected S-parameters are calculated from those measurements using the equations

$$S_{12} = \frac{\left(\frac{b_o}{a_o}\right)_{P_1} - \left(\frac{b_o}{a_o}\right)_{P_2}}{\left(\frac{a_3}{a_o}\right)_{P_1} - \left(\frac{a_3}{a_o}\right)_{P_2}}, \quad S_{11} = \left(\frac{b_o}{a_o}\right)_{P_1} - S_{12}\left(\frac{a_3}{a_o}\right)_{P_1}$$

$$S_{22} = \frac{\left(\frac{b_3}{a_o}\right)_{P_1} - \left(\frac{b_3}{a_o}\right)_{P_2}}{\left(\frac{a_3}{a_o}\right)_{P_1} - \left(\frac{a_3}{a_o}\right)_{P_2}}, \quad S_{21} = \left(\frac{b_3}{a_o}\right)_{P_1} - S_{22}\left(\frac{a_3}{a_o}\right)_{P_1}$$

Simulated Tests

To test the software and the calibration and measurement theory, simulated measurements were made. That is, fictitious values for the error box S-parameters representing the system errors were assumed; the values of calibration parameters the system should have measured were hand calculated, and entered into the calibration data arrays; and then the software was exercised to perform its normal inverse function and calculate the error box parameters originally assumed. Comparison of assumed and calculated results showed agreement within the accuracy of the computer word. Next the parameters of the same fictitious measurements of the three calibration standards were re-entered into the system, this time as simulated measured test data; the system was allowed to correct for its assumed errors and then plot the parameters of the standards. The results were near perfect being equal to the origianlly assumed data to within one part in 100,000. These results illustrate the accuracy of the theory, the software; and the adequacy of the choice of the number of significant bits in the calculations.

Performance

Actual calibration and measurements were not nearly as accurate as the simulated tests. Calibration and subsequent re-measurement of one of the calibration standards, e.g., the short circuit, which an HP-8542B ANA would have measured as 1 ±0.001 magnitude and 180° ±0.2°, was in error by ±0.01 magnitude ±1° phase. More significant, re-measurement of the through standard, a transmission measurement requiring comparison of signals from both 8411 harmonic converters, showed ±0.01 dB loss error and approximately 1 degree per gigahertz phase error. (See Figure 7.)

This much larger transmission measurement error suggested the existence of time dependent relative drift between the two converters. We now know that drift does exist between harmonic converters, and it has been shown to be drift in relative local oscillator phase. Part of the phase shift is associated with the small braided coaxial cables used to transmit the synthesized local oscillator power to the mixers. Flexing either 8411 cable caused as much as 10 degrees shift in the transmission coefficient phase displayed on the polar display. (Reflection, or one-converter, phase showed no discernable shift.) The major drift, however, is believed to be associated with varying temperature

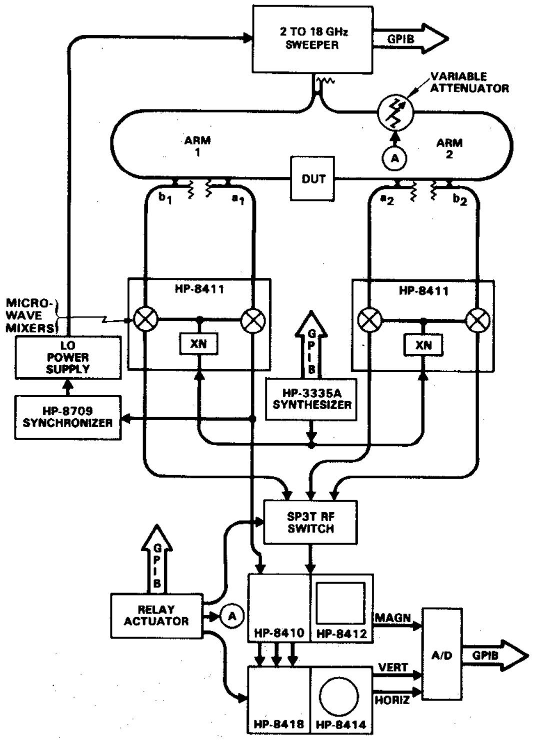

Figure 3. 2 to 18 GHz Dual Four-Port ANA

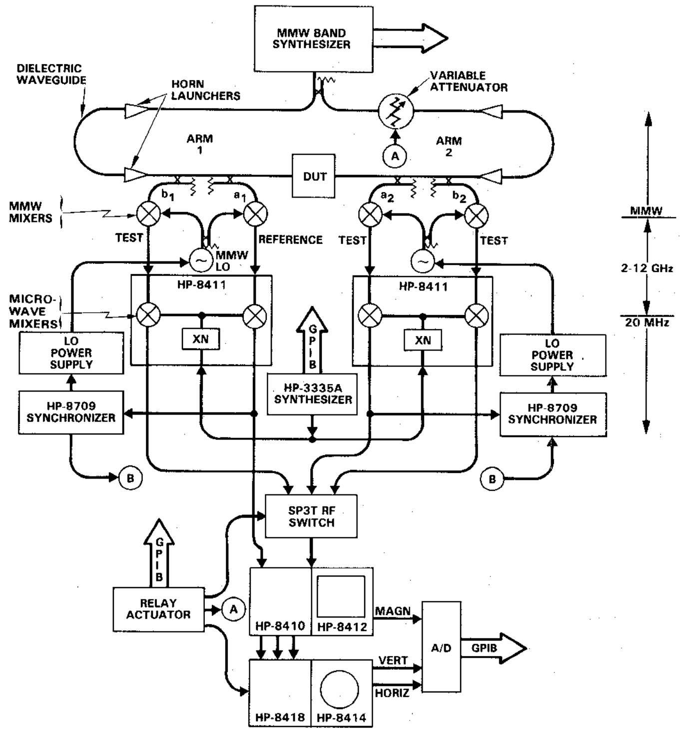

Figure 4. MMW Dual Four-Port ANA
The IF is phase locked to the synthesized L.O. by controlling the MMW L.O.s

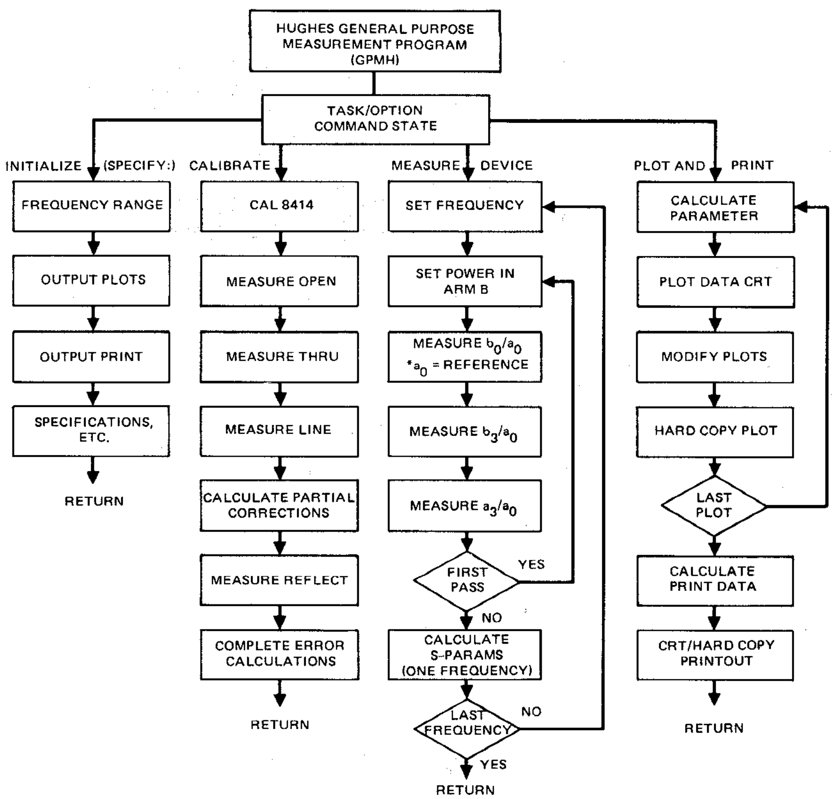

Figure 6. Sequencing of steps has been arranged to minimize measurement time and memory requirements.

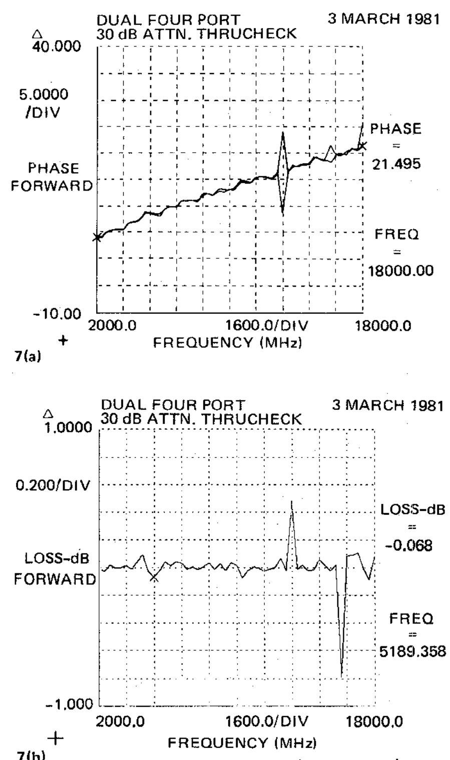

Figure 7. (a) Overlay of negative reverse phase on plot of forward phase
(b) Transmission loss.
Linear, sloped, near exact overlay, yet flat loss indicates pure L.O. phase drift error.

difference between the two 8411's. A fifteen hour computerized test periodically comparing all S-parameters, all voltages and the temperature difference between 8411's, support this belief. The correlation coefficient between the phase drift and the temperature difference was greater than .996. Correlation with voltages was essentially zero although it was zero only because the voltages are held constant by the well regulated 8410 power supplies. Other correlations are being measured and solutions to this phase drift are now under way.

It might be asked why the short circuit measurements (a one-converter measurement) were not more accurate. The answer is that the calibration process requires Thru and Delay measurements to generate the error matrices describing the system errors. Hence, the reflection error parameters also include drift related errors and therefore distort subsequent tests, even those involving only one test set and one 8411 converter.

Conclusions

The software to both calibrate and measure the dual four-port ANA has been tested and found to perform accurately confirming the Thru-Reflect-Line theory[2] for dual four-ports. The hardware has yielded moderately accurate measurements but has a time dependent drift in relative local oscillator phase which limits performance. Modifications are underway to reduce that drift.

On comparing detector ANAs (six-ports) and vector ANAs (dual four-port HP-8542B or HP-8409B) it appears that each has its limitations. The detector systems are power limited (especially in MMW bands), are affected by harmonics, and are not real time. The vector systems solve those needs but require accurate phase control. Which system will best satisfy user requirements may depend on future innovations and developments.

Acknowledgements

The well documented GPMH software was written by Gerald Klein. Appreciation is expressed to Irving B. Baker and Donald J. Beckendorf who constructed and assembled most of the hardware.

References

1. Hoer, C. A., "A Network Analyzer Incorporating Two Six-Port Reflectometers," MTT, V. 25, December 1977, pp 1070-1074.

2. Engen, G. F. and Hoer, C. A., "Thru-Reflect-Line": An Improved Technique for Calibrating the Dual Six-Port Automatic Network Analyzer," MTT, V. 27, December 1979, pp 987-993.

3. Franzen, N. R. and Speciale, R. A., "A New Procedure for System Calibration and Error Removal in Automated S-Parameter Measurements," Proc. 5th European Microwave Conf., Hamburg, W. G., 1-4 September 1975, pp 69-73.

4. Rytting, D., "Appendix to An Analysis of Vector Measurement Accuracy Enhancement Techniques," Hewlett-Packard Publication, Santa Rosa, California 95404.

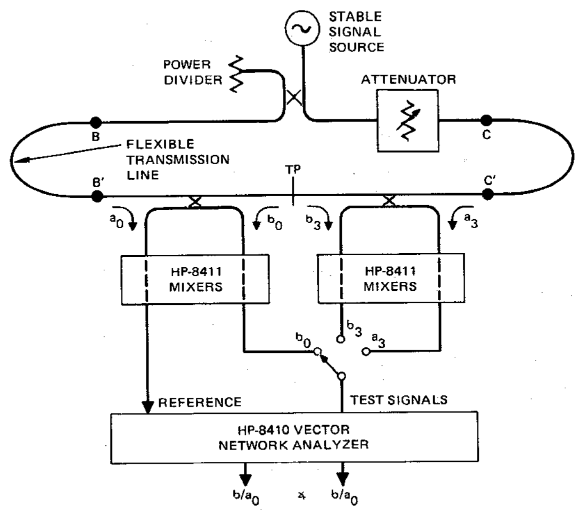

Figure 1. Hughes dual four-port concept

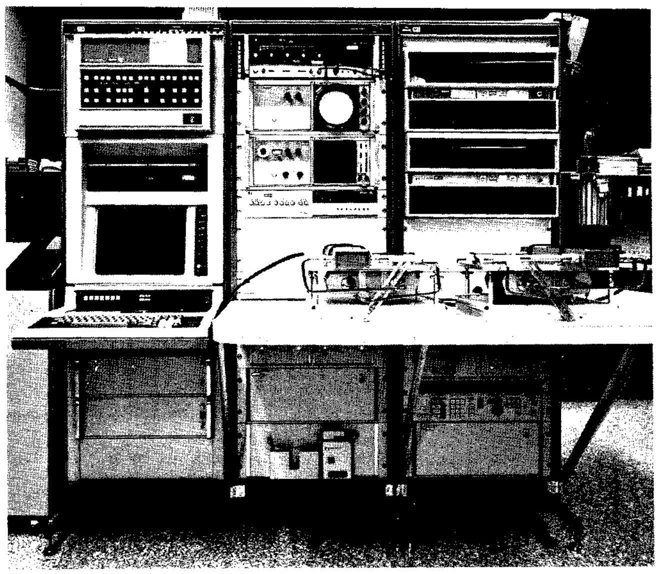

Figure 2. Test sets are mounted on air bearings for ease of aligning connectors

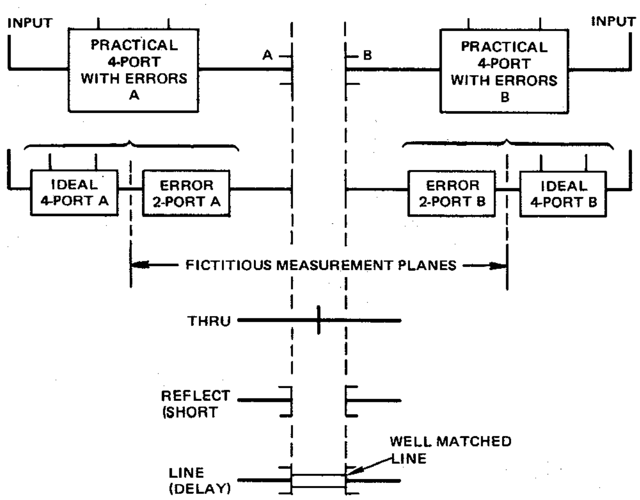

Figure 5. Calibration accomplishes replacement of real four-ports with ideal four-ports and error two-ports containing all errors.