Skillful De-embedding

Network analyzers and CAD are powerful tools which can provide accurate device models even in the presence of imperfect test fixtures. The author shows how to do this using device under test (D.U.T.) de-embedding.

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RF circuit design has changed significantly during the last two decades. The emergence of CAD has shortened product development times and designers are becoming more dependent on computerized procedures. Although CAD works very well when it is based on proper information, it can give a false sense of security when incorrect models are used. The expression, "Garbage in...garbage out" applies.

RF component measurement and characterization is a complex task[1] for many reasons:

1) Components generally cannot be connected directly to the appropriate calibrated test equipment. Rather, they must be measured using test fixtures. This produces data that includes the parameters of the fixture as well as the device under test (D.U.T.),

2) The measured data includes parasitics and losses of the test fixtures that are not easy to model, and

3) Complete circuit simulation requires statistical information that requires large samples and careful studies of parameter spreads.

This paper reviews the first of the above tasks, discussing instrumentation and calibration, measurements and data extraction, using the HP 8753 Network Analyzer. Comments are also made about similar measurements with the recently introduced HP 9114 Impedance Analyzer.

Network Analyzer Measurements and De-Embedding

Vector network analyzers measure the amplitude ratio and relative phase of two broadband swept signals. By using dual directional couplers, the instrument is able to separate the incident and reflected waves in a transmission line, thereby enabling designers to measure the impedance and the gain of RF and microwave circuits.

Network analyzer measurements are based on scattering parameter (s-parameter) principles that are the accepted standards in the high-frequency industry. Network analyzer s-parameter measurements have three types of errors which affect measurement accuracy: systematic, random, and drift errors.

Systematic errors are those which are stable and repeatable, and can be identified, characterized, and removed (mathematically) from the measurement system. This process describes the calibration of the network analyzer, resulting in the mathematical removal of the systematic errors. For a full two-port set of s-parameters, such errors include coupler directivity, source and load mismatch, transmission and reflection tracking, and finite port isolation.

To quantify and remove the systematic errors, a set of measurements is made using calibration standards or known entities. For a one-port case the systematic-error coefficients are reduced to three kinds: coupler directivity, load mismatch, and finite port isolation. The calibration process establishes reference plane(s) for the measurement of device s-parameters. The reduction of systematic errors through calibration is ultimately limited by the quality of the standards, and the magnitude of random and drift errors.

Random errors are those which are random in nature and cannot be characterized and removed, such as noise and connector repeatability. There are two different types of noise encountered in any measurement system: low level noise (system noise floor) and the phase noise of the source (or high level noise).

Drift errors fall into two classes: instrumentation and source drift. Instrumentation drift is largely due to temperature variations in the measurement environment. The temperature drift is composed of two parts: magnitude and frequency-dependent phase. Drift errors can be reduced by recalibrating the network analyzer.

One-port or two-port components are generally measured in test fixtures, which adds complexity to the measurement system. Fixturing moves the component to be measured from the calibrated network analyzer's error reference plane(s) to a different position. The fixture must be characterized to distinguish the component s-parameters from the fixture/component s-parameter measurements. The process of mathematically removing the fixture, leaving the net component s-parameters, is known as "de-embedding."

Network Analyzer Calibration/One Ports

Network analyzer measurements are based on the ratio of reflected and incident waves inside a Z_0 characteristic impedance system. Between the swept signal source and the port of measurements we find several components, such as transmission lines, switches, connectors, adapters, and directional couplers. Since all these system components represent discontinuities, an internal two-port sub-network exists with unknown finite transmission loss and input/output reflection coefficients (Figure 1) As a result, a calibration procedure is needed to remove the error produced by the component imperfections.

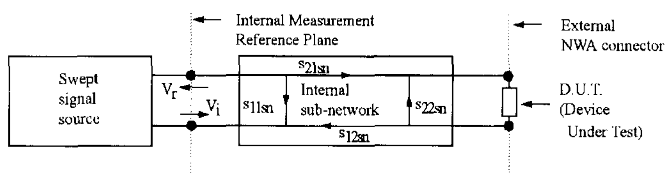

Figure 1. Simplified one-port network analyzer system block diagram. The imperfection of the internal sub-network introduces systematic errors to measurements.

The internal sub-network may be represented by three frequency-dependent two-port parameters: input reflection coefficient s_{11sn}, output reflection coefficient s_{22sn}, and a transmission coefficient $s_{Tsn}=s_{12sn}=s_{21sn}$, as shown in Figure 2.

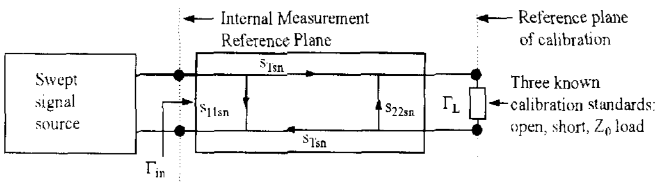

Figure 2. The one-port calibration process determines the errors represented by the various interconnecting system components. The error parameters are later used to correct mathematically any measured data.

The input reflection coefficient of this internal subnetwork can be found by flow-graph analysis (Figure 3).

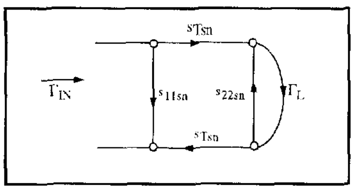

Figure 3. Flow-graph analysis used to determine the input reflection coefficient of the internal test fixture network.

(1)
$$\Gamma_{IN} = S_{11sn} + \frac{S_{Tsn} S_{Tsn} \Gamma_L}{1 - S_{22sn} \Gamma_L}$$

Using three different known terminations results in three frequency-dependent measured values for the input reflection coefficient. Writing and solving a system of linear equations with Equation 1, the three error parameters s_{11sn}, s_{22sn}, and s_{Tsn} are found. Then, rearranging Eq. 1, the error-corrected expression is established to determine the three reflection coefficient of an arbitrary termination Gamma(D.U.T.), as a function of the measured data and error parameters.

(2)
$$\Gamma_{DUT} = \Gamma_L = \frac{\Gamma_{IN} - S_{11sn}}{S_{Tsn}^2 - S_{11sn} S_{22sn} + \Gamma_{IN} S_{22sn}}$$

The three error parameters are determined by three independent measurements using three known terminations — generally an open, a short, and a matched (Z_0)load.

One-Port Text Fixture Calibration

Ideally, for high-level accuracy, the network analyzer should be calibrated at the plane of measurement by using open, short, and matched load (50 ohm) standards provided by the analyzer's manufacturer. However, not only are such test fixtures generally expensive, they may not be available for specific components. Therefore, for convenience and economy, components may be soldered to the "output" (panel) side of commonly available SMA (or other) connectors.

Since standards are not generally available for these low-cost "fixtures," the calibration is performed at the plane of the network analyzer's precision connector or adapter. Accordingly, the measured component data includes the parameters of the SMA (or other connector), and corrections (called de-embedding) must be performed to obtain the true data of the component under test.

Two procedures are shown below to obtain the s-parameters of an arbitrary test fixture. The first case assumes that calibration standards are available for the fixture. In the second method, we create an equivalent circuit for the test fixture and determine the circuit component values by computer optimization.

Calibrating the Network Analyzer Fixture using Appropriate Standards

The network analyzer is calibrated for one-port measurements using precision standards provided by the fixture manufacturer at reference plane 2, as shown in Figure 4. The appropriate standard parameters must be known and entered into the analyzer at the beginning of the calibration procedure.

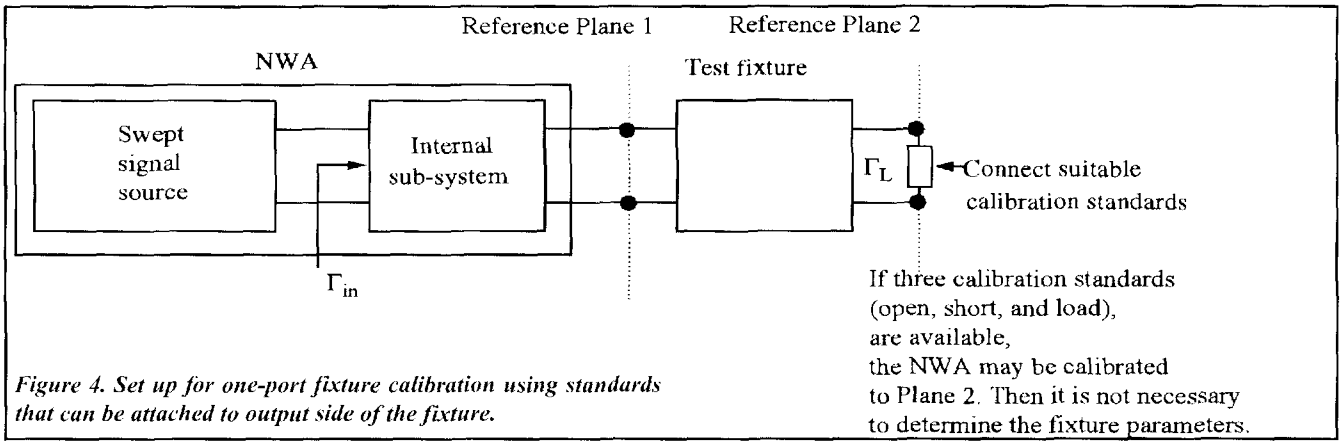

Figure 4. Set up for one-port fixture calibration using standards that can be attached to output side of the fixture.

SMA Connector Description

The connector consists of a threaded coaxial line, a flange which continues the transmission line, and a pin (which is an extension of the center conductor of the coaxial line). Most of the length of the transmission line, including that formed by the flange, is filled with the solid dielectric TFE Fluorocarbon.

The dielectric bushing is recessed from the input of the barrel, to a position that is flush with the outside of the flange. At the end of the short air-core section, the outer conductor diameter decreases slightly, creating a metal lip. This new diameter becomes the diameter of the dielectric; that is, it is the outer diameter of the dielectric-filled coaxial line. When a male connector is screwed into the sleeve of the female connector, and the dielectric sections of the two connectors meet, the effect is to eliminate that section of air-filled line. It is assumed herein that the surface at which the dielectrics meet is the plane of calibration.

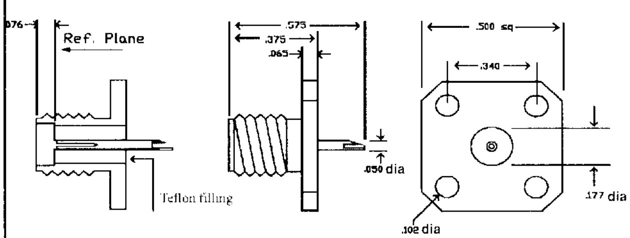

Figure A. Flange-mounted SMA connector (female) with Teflon dielectric (er = 2.14).

From the above discussion, it is clear that the transmission line section between the plane of calibration and the outer surface of the flange (where the connectors will be modified) is a dielectric-filled coaxial line of length L = 0.299in. = 7.6mm. Given the relative dielectric constant of 2.14, the electrical length E is given by:

(a) $$E = \frac{L}{\dfrac{c}{f\sqrt{\varepsilon_r}}} 360°$$

where,
c is the speed of light, in m/s
ε_r is the relative dielectric constant
f is the frequency in Hertz

Therefore, at 1GHz,

(b) $$E = \frac{0.76 \times 10^{-2}}{\dfrac{3 \times 10^{8}}{10^{9}\sqrt{2.14}}} 360° = 13.36 \text{ degrees}$$

In the following section, the connector is modeled by open-circuited network analyzer measurements. Using circuit optimization, equivalent circuit parameters were "fitted" to the measured data, resulting in a 13.63-degree electrical length (at 1GHz) and a small stray capacitance, which agrees with the value computed from the physical transmission line model. Male connectors are longer; their electrical lengths are 16.3 degrees at 1GHz.

Determining Fixture Models/Open-circuit

The network analyzer is calibrated for a one-port measurement at reference plane 1, using precision standards supplied by the manufacturer. The fixture is connected to the calibrated analyzer and broadband one-port measurements are taken. The measurements are examined and a model is assumed for the fixture (Figure 5). The values of the model were determined using computer optimization. For this case, the model was assumed to be a short transmission line segment with some parallel capacitance at its output. The optimized and measured results are in close agreement.

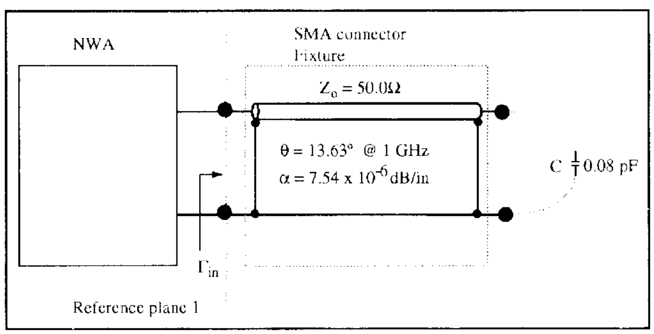

Figure 5. Fixture with optimized open SMA model values.

Terminating the fixture with impedances other than open, will modify the open-circuited fringing capacitance, and can be used to validate the accuracy of the model of the transmission line. Therefore, such a simple "test-fixture" is not accurate to measure small capacitances. Other components such as air-core inductors, will experience shielding effects caused by the metal case of the connector. For such components, a more complex fixture is needed — perhaps a combination of a connector and a microstrip transmission line segment. If the fixture does not contain too many components and transitions, the above technique may be extended for modeling purposes, based on one-port measurements, up to a few Gigahertz.

It is a good idea to build the fixture in a form similar to the application of the device to be tested. This way, difficult stray and grounding effects may be included in the model.

Occasionally the one-port fixture can be changed into a two-port form by attaching a connector to the "component" side, or to cascade two fixtures "back-to-back". In such cases a two-port characterization can be made after some modification to compensate for the presence of the added parts.

Network Analyzer Port Extension

If we assume that the fixture is an ideal loss less 50-ohm transmission line of known length, the "port extension" feature of the network analyzer can be used instead of the above procedure. This option adds a user-specified delay (positive or negative) to the calibration at plane 1. The delay is substituted for an ideal transmission line between planes 1 and 2, moving the reference plane to the measurement plane.

A reasonable approximation (to approximately 2GHz) is to assume that the connector is an ideal transmission line with known one-port group delay, *tau*, in nanoseconds:

$$\tau \cong \frac{2E}{360f} \tag{3}$$

Where E is the electrical length in degrees and f the frequency in GHz.

Note the factor of two used to account for the round trip of the reflected signal. Additional delay can be applied to account for the parasitic capacitive connector termination. The use of port extension delays assumes equal delay at all frequencies of interest. This means a constant relative dielectric constant versus frequency, and negligible parasitic contribution.

Two-Port Calibration and De-embedding

Most RF and microwave components and system blocks are *non-insertable* because their connectors do not mate directly with the network analyzer (we define a component to be *insertable* if it can be connected to the test system without using additional cables, connectors or adapters.) An insertable test device has two connectors of the same family (e.g. SMA) one being male the other female, or two "sexless" precision connectors (e.g. APC-7) which mate interchangeably with each other.

Non-insertable devices have either the same connector sex on both sides (reversible) or use different kinds of connectors (transitional or adapter.) The later category may use different types of connectors of the same family (e.g. Type-F to BNC) or different families, such as coax to waveguide. Figure 6 illustrates the various connector types under consideration. Note that the sexless (hermaphroditic) connectors may be considered either types.

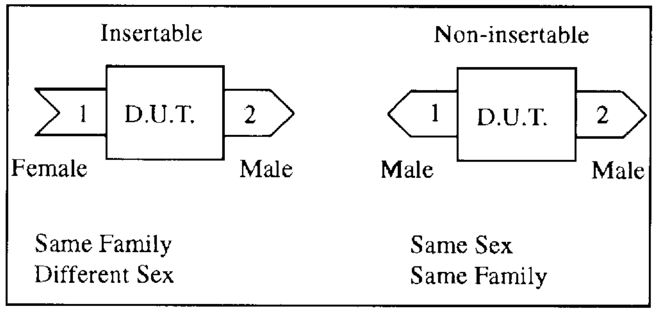

Figure 6. Classes of fixtures and devices under test (D.U.T.).

The main advantage of insertable devices is that the test system setup is not changed between the calibration and the measurement. The test setup is conveniently calibrated using cables, or port-extenders, with one male and one female connector (or two sexless connectors). The system is referenced to the plane at which the two connectors meet.

During test, the insertable device is placed directly between the two test system connectors. Since the transmission calibration does not require any "thru-line," measurement accuracy and convenience are usually very satisfactory.

In the case of non-insertable devices, since the fixture (D.U.T.) is not inserted into the exact configuration under which the system was calibrated, measurement uncertainties are introduced, affecting both magnitude and phase of the test results.

Accuracy Enhancement and Error Model

At RF and microwave frequencies, system-dependent effects such as leakage, test port mismatch, and frequency response produce uncertainties in the measurement data. However, in a stable measurement environment these effects are repeatable and can be taken into account by means of the calibration process of the network analyzer. During calibration a series of known devices (standards: open, short, and load) are connected to the test ports and then measured. The systematic effects are determined as the difference between the measured and known (or modeled) responses of the standards.

Fixture Parameter Measurements

Using one-port measurements with known standards in place of the D.U.T., the [F1] and [F2] s-parameter matrices can be determined. This method requires placing the standards into the component connection gap as shown in Figure 7. Commercial products are available for such measurements, for certain component types and sizes. When standards are not available the fixture may be modeled by the techniques outlined earlier. For example, the thru standard of Figure 8 is designed with a transmission line length that is shorter than the component fixture by an amount equal to the D.U.T. gap. To be insertable the fixture and thru standard must have sexless connectors or opposite sex connectors.

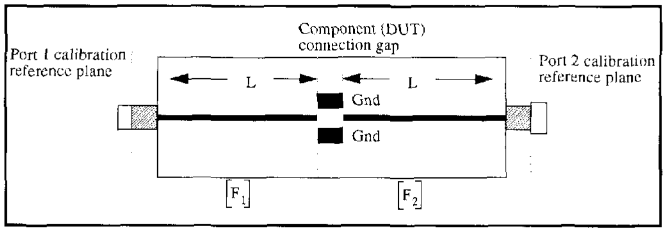

Figure 7. Two-port component measurement fixture.

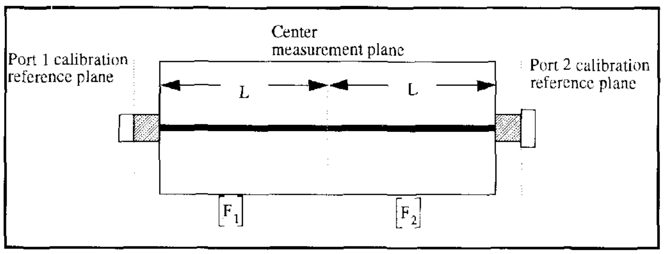

Figure 8. Two-port thru calibration fixture.

De-embedding with CAE

Most commercially available circuit optimization programs allow using negative component values, a convenience for negating unwanted circuit elements. For example, if a -5nH inductor is cascaded to a +5nH inductor, the result is a perfect "thru." Using this approach we can eliminate (negate) components of a test fixture to obtain de-embedded data of the device under test.

An even more convenient CAE feature allows negating complete sections of passive circuit components instead of individually eliminating the elements one by one. For example, if a device to be tested is embedded in a one-port test fixture and data can only be measured at the input of the fixture (Figure 9), the true de-embedded data of the device under test (D.U.T.) may be obtained by the procedure outlined below.

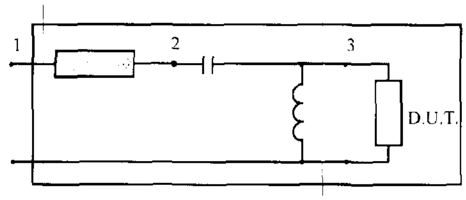

Figure 9. Three-element test fixture with D.U.T. connected between nodes 3 and 0. The input port of the fixture us between nodes 1 and 0.

Step a. Characterize or model all components (transmission lines, inductors, etc.) that exist inside the test fixture and combine them into a single two-port, illustrated as "A" in Figure 10.

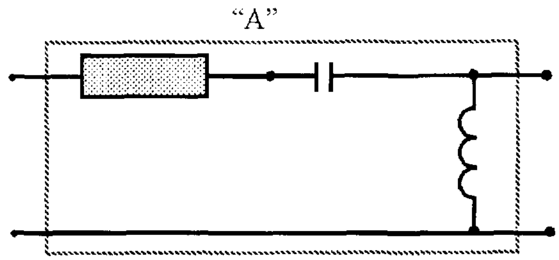

Figure 10. A section "A" which is negated in the calibration to compensate for the test fixture in which the D.U.T. is embedded.

Step b. Compute the two-port transmission matrix T_A of the test fixture circuit and create a new two-port that contains the reciprocal (negated) version of T_A.

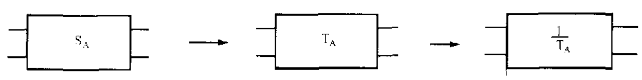

Figure 11. The two-port transmission matrix of T_A and a new two-port containing the reciprocal (negated) T_A.

Step c. The measured one-port data that includes the effects of the test fixture, is loaded into a one-port box "B" that is cascaded to the output port of a two-port containing the negated two-port form of the fixture (A^{-1}).

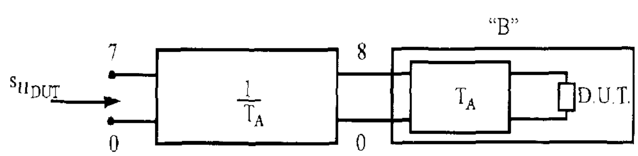

Figure 12. The measured one-port, including the test fixture parameters, is loaded into a one-port box "B" cascaded with the output port of a two-port containing the negated A (A^{-1}).

Step d. The resultant simulation of s_{11} of the cascade (at nodes 7 and 0) provides the net de-embedded data of the D.U.T.

The same procedure can be used for multiport de-embedding. For example, if the input and output portions of the two-port test fixture of Figure 7 have been characterized as F_1 and F_2, then the setup shown in Figure 13 will provide the net de-embedded two-port parameters of the D.U.T.

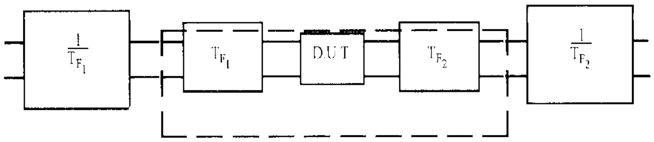

Figure 13. Application of the de-embedding technique to a multiport.

Matrix Conversions

For convenience the conversions between the transmission (T) and the scattering (s) matrices are given in Figure 14.

Conversion from S to T

$$[S] = \begin{bmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{bmatrix} \rightarrow \begin{bmatrix} T_{11} & T_{12} \\ T_{21} & T_{22} \end{bmatrix} \qquad \mathrm{DET}[S] = S_{11} \times S_{22} - S_{12} \times S_{21}$$

$$T_{11} = \frac{1}{S_{21}} \qquad T_{12} = \frac{-S_{22}}{S_{21}}$$

$$T_{21} = \frac{S_{11}}{S_{21}} \qquad T_{22} = \frac{-\mathrm{DET}[S]}{S_{21}}$$

Conversion from T to S

$$[T] \rightarrow [S] \qquad \mathrm{DET}[T] = T_{11} \times T_{22} - T_{12} \times T_{21}$$

$$S_{11} = \frac{T_{21}}{T_{11}} \qquad S_{12} = \frac{\mathrm{DET}[T]}{T_{11}}$$

$$S_{21} = \frac{1}{T_{11}} \qquad S_{22} = \frac{-T_{12}}{T_{11}}$$

Figure 14. Conversions between the transmission (T) and the scattering (s) matrices.

References:

1. L. Besser, Network analyzer measurements and de-embedding. RF Expo West 1994 Conference Proceedings, pp. 247-260.

Les Besser, a pace setter of the RF and microwave industry is President and founder of Besser Associates of Los Altos, California, a company offering short courses and videotaped continuing education to RF and microwave professionals. His firm has provided personal, live training to over 9,000 engineers and technicians worldwide.

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Concentrating on MICs, GaAs FET Amplifiers, and CATV systems at the Microwave and Optoelectronics Group of Fairchild, he wrote the SPEEDY CAD program containing a transistor database with high-frequency parameters.

Directing the microcircuit design and development effort at Farinon Electric Company, he authored COMPACT, the industry's first commercially successful microwave circuit optimization routine, the first industry CAD standard. He founded Compact Engineering, a pioneer CAD software company, serving the computer analysis and synthesis needs of the industry for ten years.

Dr. Besser, holding the BS, MS, and Ph.D. Degrees in Electrical Engineering, has published over 50 technical articles and contributed to several textbooks. Active in the IEEE, he received the IEEE MTT Microwave Applications Award (1983), the MTT career Award (1987) and a Fellow of the IEEE. From 1988 to 1990 he was Editorial Director of Microwave Systems News (MSN) *magazine.*

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(Required by 39 U.S.C. 3685)

1A. Title of Publication: APPLIED MICROWAVE & WIRELESS
1B. Publication No.: 0 1 1 - 5 9 6
2. Date of Filing: 9/30/94
3. Frequency of Issue: Quarterly
3A. No. of Issues Published Annually: 4
3B. Annual Subscription Price: $30 US, $50 Foreign
4. Complete Mailing Address of Known Office of Publication (Street, City, County, State and ZIP+4 Code) (Not printers): 8 Beach Road, Suite 2, PO Box 1504 E. Orleans, MA 02643 1504
5. Complete Mailing Address of the Headquarters of General Business Offices of the Publisher (Not printer): SAME
6. Full Names and Complete Mailing Address of Publisher, Editor, and Managing Editor (This item MUST NOT be blank)
Publisher (Name and Complete Mailing Address): J. F. White, 8 Beach Road, Suite 2, PO Box 1504 E. Orleans, MA 02643 1504
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2. Mail Subscription (Paid and/or requested)	9,408	13,598
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