© CREATAS

VNA Calibration

Andrej Rumiantsev and Nick Ridler

It was during the late 1950s that the need for reliable measurement, and therefore reliable measurement standards, at RF and microwave frequencies began to emerge. This led to the introduction of precision coaxial air lines as primary reference standards of impedance [1], [2]; see Figure 1. These lines use conductors made from very-high-conductivity metals and air as the dielectric, due to the simple and predictable electromagnetic properties (i.e., permeability and permittivity) of air at RF and microwave frequencies [3]. This ensured that the properties of these lines were very close to those of ideal lines [4].

Also during the late 1950s and throughout the 1960s, much work was undertaken to develop precision coaxial connectors to ensure that very repeatable and reproducible measurements could be made at microwave frequencies [5], [6]. To help focus this effort, committees were established (including an IEEE subcommittee on precision coaxial connectors [7]) tasked with producing standards for these precision connectors. Finally, by the late 1960s, the first fully automated vector network analyzers (VNAs) providing high-precision measurement capabilities were introduced (e.g., [8], [9]). The stage was now set for work to begin on introducing reliable measurement assurance techniques for measurements made using VNAs (Figure 2).

However, there were several other key developments that took place during the 1970s, 1980s, and 1990s that greatly improved the state of the art of measurements made using VNAs. These included the introduction of:

- smaller precision coaxial connectors (beginning with the 3.5-mm connector [10] and ending with the 1-mm connector [11]), enabling measurements to be made over wider bandwidths
- VNA calibration and verification kits containing high-precision devices suitable for calibrating and/or verifying the performance of the VNAs
- reliable VNA calibration techniques [including thru-reflect-line (TRL) [12], line-reflect-line (LRL) [13], etc.)

Andrej Rumiantsev is with SUSS MicroTec Test Systems GmbH, Germany. Nick Ridler is with the National Physical Laboratory, United Kingdom.

Digital Object Identifier 10.1109/MMM.2008.919925

 1527-3342/08/$25.00©2008 IEEE

- six-port VNAs [14] used by national measurement standards laboratories [such as the National Institute of Standards and Technology (NIST) in the United States and the National Physical Laboratory (NPL) in the United Kingdom, etc.] to provide an independent measurement method to verify the performance of the commercially available VNAs.

Finally, also by the late 1980s and early 1990s, national measurement standards laboratories (i.e., NIST, NPL, etc.) began turning their attention to demonstrating the reliability of VNA measurements made on planar circuits (such as on-wafer measurements) to support the rapidly developing microelectronics industry. Both NIST and NPL produced standard wafers [15], [16] that contained the planar circuit equivalent to the coaxial air line—i.e., precision sections of coplanar waveguide and/or microstrip transmission line. These lines provided the reference standards for calibrating VNAs for on-wafer measurements.

All of the above activities greatly improved the state of the art for practitioners and users of VNA measurements. Also, in addition to all these activities, much was done by measurement experts working in industrial, academic, and government laboratories to establish traceability and other quality assurance mechanisms for these VNA measurements. These topics are discussed in "What is Traceability?" and "Measurement Assurance."

Systematic Measurement Errors

What Is Calibration and Error Correction?

Calibration is defined as the "set of operations that establish, under specified conditions, the relationship between values of quantities indicated by a measuring instrument or measuring system, or values represented by a material measure or a reference material, and the corresponding values realized by standards" [17]. As such, calibration traditionally involves having an instrument or component sent away periodically to a standards and/or calibration laboratory, who then undertake the calibration process. This often results in a certificate of calibration being issued that demonstrates the current condition of the instrument or component.

However, in the context of a VNA, the term calibration can have at least two different meanings. First, the traditional concept of calibration can still be applied, with the VNA being sent away for calibration, typically every year or so. (Alternatively, some companies offer periodic on-site calibration, performed by a visiting calibration specialist.) However, of more relevance to this article is another form of calibration that is performed locally, usually each time the instrument is set up and configured for a given series of measurements. This second form of calibration is intended to remove systematic errors from the instrument hardware (and to take into account the presence of any accessories that may have been added to enable specific measurements to be performed) at the required frequencies for the measurements. For example, measurements may be required to be made in an on-wafer environment. In which case, first cables need to be connected to the VNA front-panel connectors, followed by coaxial adaptors, and finally on-wafer probes (Figure 3). This second form of calibration will correct for the effects of these added components as well as correct the systematic errors in the VNA. This is why this type of calibration is often referred to as *error correction*, and it is this type of calibration that will be discussed in this article.

The demand for increased measurement accuracy from the VNA can be achieved by improving the hardware, the models used for characterizing measurement errors, the calibration methods used for calculating these errors, and the definitions of calibration standards. For *S*-parameters, the systematic errors are often represented using so-called error models of the measurement system (i.e., VNA). The number of error coefficients included in the error model, as well as the type of error model, depends on

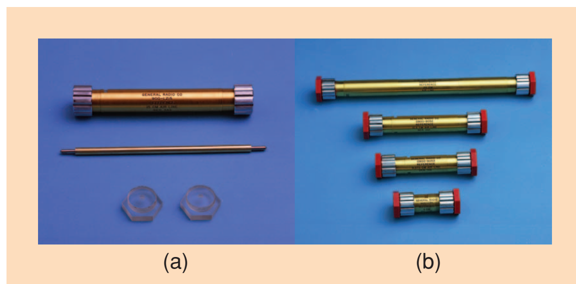


Figure 1. *An example of precision reference coaxial air lines of different length.*

Figure 2. *A coaxial mm-wave measurement bench based on the Agilent 8510 VNA. This analyzer was the industry reference for microwave measurements for many years.*

What Is Traceability?

Traceability, in the context of a measurement, is defined as the "property of the result of a measurement or the value of a standard whereby it can be related to stated references, usually national or international standards, through an unbroken chain of comparisons all having stated uncertainties" [17]. Applying this concept to a VNA measurement, the stated references could be precision air lines (or their equivalent), the VNA is the transfer device used as part of the unbroken chain of comparisons, and the precision connectors enabling these comparisons to be made within acceptable limits to the uncertainty of measurement.

The benefit of having a measurement that is traceable stems from the fact that it can be used to demonstrate the equivalence of measurements made independently of one another. This is of paramount importance in a customer/supplier relationship where a common understanding is needed of the parameters that define (or specify) the performance of the device being bought or sold. Therefore, if two measurements of a quantity are made independently, and these measurements are both traceable, then their values will agree to within the stated uncertainties of the measurements. This is, therefore, an extremely valuable process that can provide the necessary underpinning assurance that is needed when operating within a truly global marketplace where the customer and supplier may be located in different parts of the world.

The vital role that traceability can play was recognized long ago and led to the introduction of national measurement accreditation schemes so that customers and suppliers could fully demonstrate the quality of their measurements to an independent third party (i.e., the accreditation body). These days, such accreditation processes are controlled by international standards (e.g., [72]), thus ensuring that the accreditation process is itself applied uniformly across all types of measurements and at all locations around the world. Most countries maintain a national accreditation body for this purpose, and these bodies are themselves linked through international accreditation organizations such as the International Laboratory Accreditation Cooperation (ILAC, www.ilac.org).

When traceability is harmonized within an agreed system of units (e.g., the international system of units, SI), then not only is it possible to demonstrate equivalence between measurements of the same quantity, but it also becomes possible to demonstrate the equivalence of measurements of different quantities. This is achieved through the relationship of these quantities to the so-called base quantities within the system of units. (In SI, the seven base quantities are length, mass, time, electric current, thermodynamic temperature, amount of substance, and luminous intensity.)

By following the traceability path of a measurement back to its fundamental base quantities, it is possible to demonstrate the harmonization of the measurement within the system of units. For example, a reflection measurement made along a transmission line can usually be traced back to dimensional measurements, since it is the dimensions of the transmission line that determine the impedance and therefore the amount of signal that is reflected by the line. The base quantity for dimensional measurements is length. Similarly, for power and noise measurements, these can usually be related back to heating effects. Therefore, the base quantity is thermodynamic temperature. In just about all microwave measurements, the frequency of the measurement needs to be known. Since frequency is the reciprocal of periodic time, the base quantity is time.

A key role of a national measurement standards laboratory (such as NIST, NPL, etc.) is to maintain primary reference standards of measurement. For example, at microwave frequencies, these are usually standards of power, impedance, attenuation, noise, etc. In addition, the national measurement standards laboratory is tasked with realizing the seven SI base quantities. By linking these two roles, the national measurement standards laboratory is able to deliver a wide range of traceable measurements to industry that are also harmonized within the SI.

The subsequent 'linking' of the capabilities of one national measurement standards laboratory to others is achieved through participation in international measurement comparison programs conducted under the auspices of organizations such as the International Bureau of Weights and Measures (BIPM, www.bipm.org) and their consultative committees. The results from these comparison exercises are analyzed and placed on a database maintained by the BIPM that demonstrates the capability of each national laboratory.

Finally, it is worth mentioning that these days, with the global accessibility of the Internet, measurement services that make extensive use of the Internet are beginning to be developed. These services are starting to play a role in providing traceable measurements in a highly efficient manner. For example, a system has recently been put in place by NPL that uses the Internet to provide traceability for high-precision measurements using VNAs at any location around the world [73].

- the hardware topology of the VNA,
- the number of VNA ports and measurement receivers
- the required measurement accuracy.

The following section presents commonly used models of *S*-parameter systematic measurement errors.

Flow-Graph S-Parameter Representation

The first error models used for automated S-parameter error correction were introduced at the end of the 1960s. They addressed the bidirectional two-port system and defined the influence of system imperfection on reflection (S_{11}, S_{22}) and transmission (S_{21}, S_{21}) measurements. These models were developed to represent systematic measurement errors using imaginary two-port error networks. They were described by S-parameters and were included in the measurement signal paths [8]. The model for a reflection (one-port) measurement consisted of only one error network. Originally, this network was described as a matrix of four *S*-parameters.

Measurement Assurance

Although traceability provides arguably the most acceptable method for assuring a given measurement, it is not always possible to provide such traceability for all types and ranges of measurement. This is particularly true of modern VNAs that offer many different measurement formats (e.g., logarithmic or linear; single-ended or differential; frequency- or time-domain; etc.) often over very wide dynamic ranges (sometimes up to 100 dB or more). Under these circumstances, the measurement community benefits from the use of additional assurance techniques to validate results from VNAs.

The first major contribution to this area was the introduction of verification standards and kits for VNAs [74], [75]. These verification kits can be measured routinely by the end-user and compared with reference values supplied by the manufacturer. The kits can also be returned periodically to the manufacturer, who checks the reference values. This provides a high degree of measurement assurance for the end-users. Verification kits have since been produced in many of the different types of connectors used by the industry, as well as in waveguide.

Another activity that has been very valuable to measurement practitioners in our industry is the user groups that have been set up over the years. These groups have enabled the key measurement issues, at any given time, to be identified, discussed, and resolved. Probably the first such user group set up by RF and microwave specialists was the Automatic RF Techniques Group (ARFTG), www.arftg.org , which was established back in 1972 [76]. ARFTG is a technical organization interested in all aspects of RF and microwave test and measurement. The group is still very active today, and continues to evolve in response to the many developing needs of the RF and microwave community. For example, a recent development within ARFTG has been the establishment of a Nonlinear Vector Network Analyser (NVNA) Users' Forum. This informal group meets three times each year - during the Spring ARFTG conference (which is itself part of Microwave Week), the Fall ARFTG Symposium, and European Microwave Week.

Other user groups of interest to the VNA community include ARMMS (www.armms.org)—the RF and Microwave Society—and ANAMET (www.npl.co.uk/anamet)—the RF and Microwave Metrology Club. Like ARFTG, these groups meet twice each year to discuss issues of relevance to each group.

An activity that some of these user groups undertakes is to provide the opportunity to participate in measurement comparison programs (MCPs). These are programs that allow many participants to make measurements of the same devices that travel between the participating laboratories [77], [78] (see Figure A). The results of the measurements of these traveling standards are compared to indicate the overall equivalence (or not) of the results. Such exercises are extremely useful for identifying serious errors that may be present in measurements made by any of the participants. Comparisons can also be undertaken in areas of measurement where traceability may not yet exist (e.g., time-domain measurements [79]).

All of the above processes—local auditing using verification kits, interactions with user groups, participation in MCPs—provide measurement assurance which complements that provided by classical traceability processes. Ultimately, for the very highest level of measurement assurance, one should consider traceability of measurement along with one or more of these other processes.

Figure A. *Type-N travelling standards used for the ARFTG MCP.*

However, it turned out that only the coefficients S_{11} and S_{22} and the product $S_{21}S_{12}$ were needed for further error correction. As a result, the three-term error model replaced the matrix consisting of four S-parameters where the coefficients e_{00}, e_{11}, and e_{01} are E_D (directivity), E_S (source match), and E_R (reflection tracking), respectively (Figure 4) [18]. Today, the three-term error model is still the most common representation of one-port calibration and error correction procedures.

Following from the above, the eight-term model represented the bidirectional system for automated measurements of two-port devices under test (DUTs) (Figure 5). The S-parameter-based model [Figure 5(a)] required all four coefficients (S_{11}, S_{12}, S_{21}, and S_{22}) to be known for each error adapter. The error correction of the transmission measurements included two factors $S_{21}^{(1)}S_{12}^{(2)}$ and $S_{21}^{(2)}S_{12}^{(1)}$ for the forward and reverse directions, respectively [8]. These factors were addressed as coefficients E_T in the error terms representation [Figure 5(b)] [19].

Alternative unidirectional test sets did not include an internal switch for redirecting the incident measurement signal between measurement ports. They allowed the DUT to be characterized in one direction only (for its S_{11} and S_{21} parameters). As introduced in [18], such a system can be described by only five error terms. An additional term represents the signal leakage between the measurement ports, thus extending the model to six parameters [18], [20] (see Figure 6).

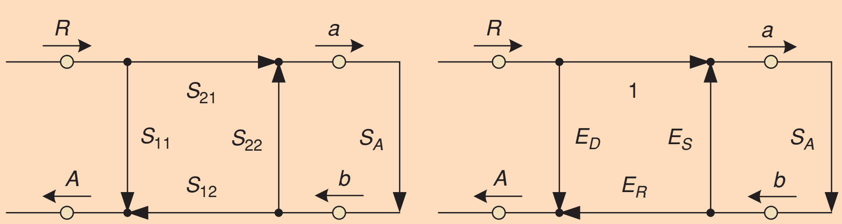
The leakage terms (also called *crosstalk terms*) were later added to the eight-term model, one for each measurement direction, increasing the number of the error coefficients in general to ten [21].

The 8(10)- and 5(6)-term error models were in use for almost ten years without significant modification. [Note that here and elsewhere in the article, the number in parentheses represents the number of error terms, including any leakage terms (E_X). These terms are optional parameters that may not fully represent the crosstalk (as discussed further in this article) and thus we do not count it in our nomenclature.] Within any model, the error terms need to be defined for each measurement frequency point and saved in the VNA memory. Therefore, an extension of the error model, including the use of additional error terms, or development of a unified error model for different test sets were not commercially viable options. (At that time, the cost of computer memory was still a major design consideration.)

Rapid progress in semiconductor technologies at the end of the 1970s significantly expanded the availability of low-cost read/write memory modules as well as mass storage devices embedded in measuring instruments. This greatly extended the capabilities of VNA error modeling. The measurement system description was unified and the 10(12)-term model was introduced for commercial VNAs independent of the test set configuration [19] (see Figure 7). This error model became the standard model for the description of systematic measurement errors of a

(a) (b)

Figure 3. *(a) An example of a state-of-the-art 300-mm RF and microwave wafer-level measurement system. The system includes: the EMI-shielded and light-tight automated probe system with integrated thermal management and automated RF calibration, a VNA, RF cables, and RF wafer probes. (b) The set of coplanar calibration standards (a calibration substrate) is used for the calibration of the system.*



(a) (b)

The relationship between the actual S_A and the measured S_M=A/R S-parameter of the DUT is given by

$$S_{11A} = \frac{S_{11M} - E_D}{E_S(S_{11M} - E_D) + E_R}$$

Figure 4. *The one-port three-term error model in (a)* S-Parameter *and (b) error terms representation.*

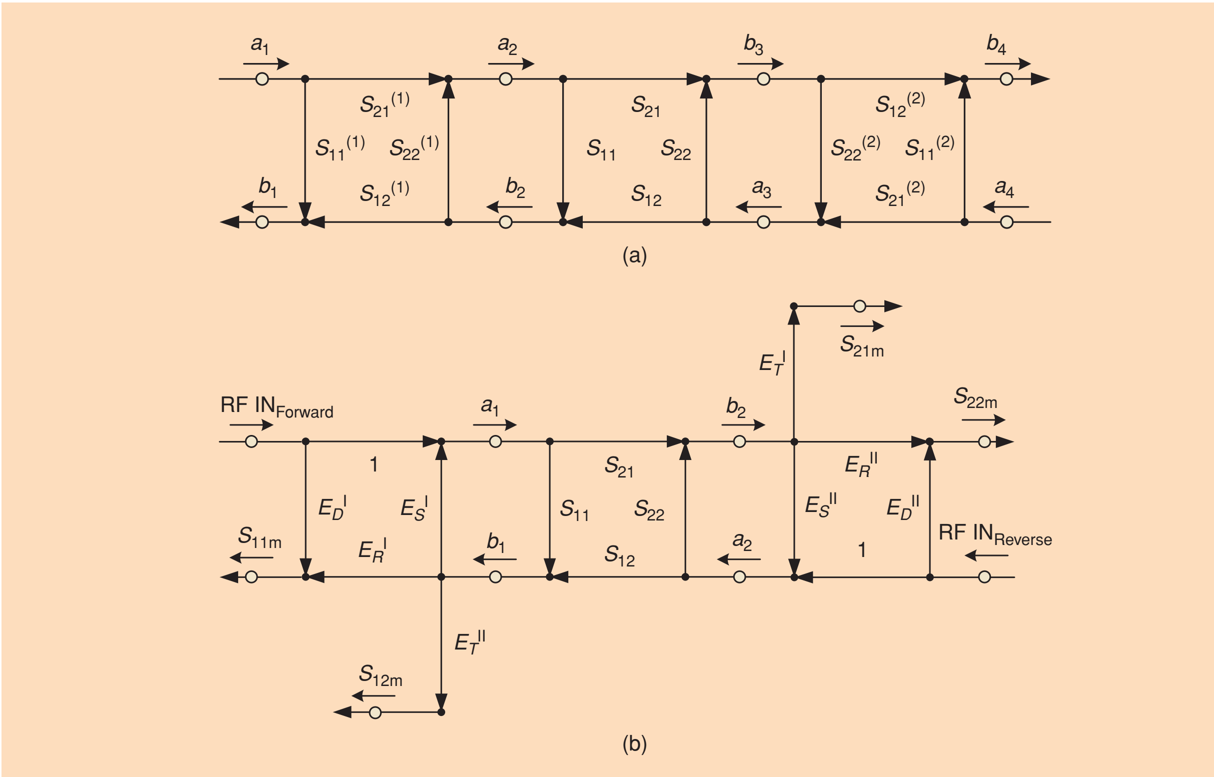


Figure 5. *The eight-term error model of a two-port VNA in (a)* S*-Parameter and (b) error terms representations. The unknown DUT* [S] *is connected between the error adapters. Prime and double-prime parameters correspond to the forward and reverse measurement directions, respectively.*

two-port VNA. It is implemented in all modern measurement instruments.

The equations for the relationship between the measured and actual S-parameter of a two-port DUT were given in [19] and [22]. However, these equations are somewhat bulky. An alternative simplified approach was introduced in [23]. For the measurement system, the relationship between the measured, m, waves and the incident, a, and reflected/transmitted waves, b, at the DUT can be found using the scattering parameter definition:

$$\begin{pmatrix} m_2^I \\ a_1^I \end{pmatrix} = \begin{pmatrix} E_D^I & E_R^I \\ 1 & E_D^I \end{pmatrix} \begin{pmatrix} m_1^I \\ b_1^I \end{pmatrix}. \tag{1}$$

From (1) and Figure 7, the incident a_1^I, a_2^I, reflected b_1^I, and transmitted b_2^I waves at the DUT are

$$a_1^I = m_1^I + \frac{E_S^I}{E_R^I}\left(m_2^I - E_D^I m_1^I\right),$$
$$b_1^I = \frac{1}{E_R^I}\left(m_2^I - E_D^I m_1^I\right),$$
$$b_2^I = \frac{m_4^I}{E_T^I}, \quad a_2^I = \frac{E_L^I m_4^I}{E_T^I}. \tag{2}$$

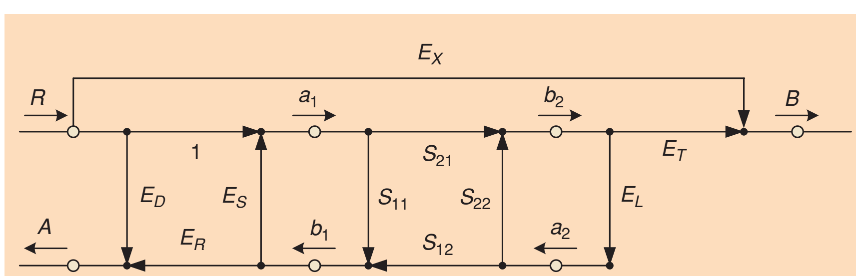


Figure 6. *The five-term unidirectional error model, represented by the error coefficients* E_D, E_S, E_R, E_L, *and* E_T. *The leakage coefficient* E_X *is an optional parameter.*

The parameters $a_1^{II}, a_2^{II}, b_1^{II}$, and b_2^{II} can be found in a similar way, taking into account the switch in its other position. Once the wave parameters a and b are defined, the following matrix can be formed:

$$\begin{pmatrix} b_1^I & b_1^{II} \\ b_2^I & b_2^{II} \end{pmatrix} = \begin{pmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{pmatrix} \begin{pmatrix} a_1^I & a_1^{II} \\ a_2^I & a_2^{II} \end{pmatrix}, \tag{3}$$

or, in short,

$$[K] = [Sx][L]. \tag{4}$$

Finally, the S-parameters of the DUT can be found by

$$[Sx] = [K][L]^{-1}. \tag{5}$$

Cascade Matrix T-Parameter Representation

The ten-term model, as described above and shown in Figure 8, represents the systematic measurement errors in terms of effective *S*-parameters. A different concept was introduced by engineers from Tektronix in 1975 [24]. They proposed describing the systematic measurement errors of a two-port system as two error boxes, characterized by transmission (*T*) parameters (Figure 9). Their model included eight error terms. However, as it was later demonstrated in [12] and [25], only seven error terms are needed for further error correction. To distinguish this approach from the old *S*-parameter-based eight-term model [8], it is usually referred to as the *seven-term model*.

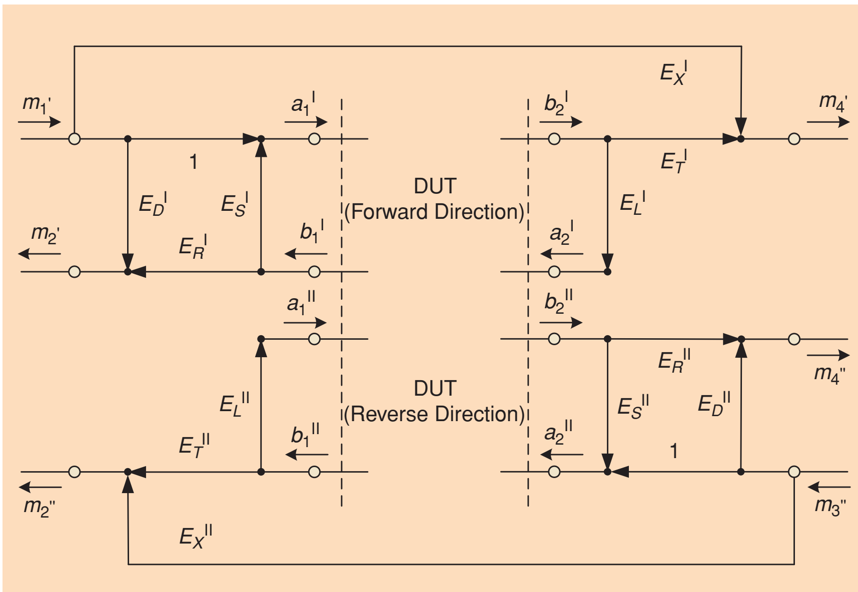


Figure 7. *The 10(12)-term error model for two-port bidirectional* S*-parameter measurements. The error coefficients* E *represent the relationship between waves,* m*, measured by the ideal VNA receivers and incident,* a*, and transmitted/reflected waves,* b*, at the DUT plane. Prime and double-prime parameters correspond to the forward and reverse measurement directions, respectively.*

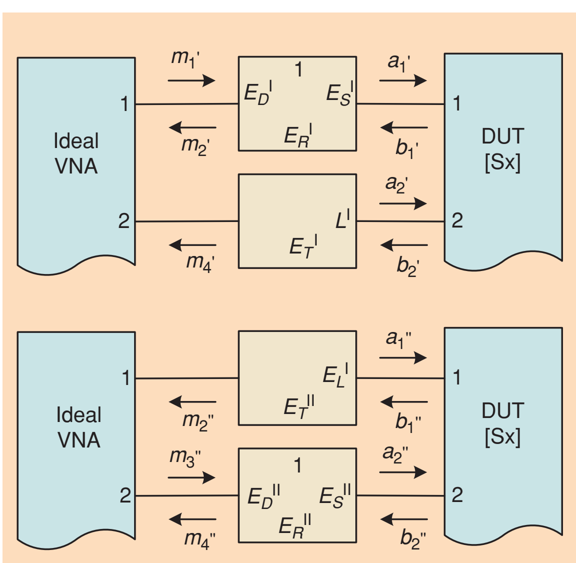


Figure 8. *Block diagram of a two-port VNA described by the ten-term model for the first and second state of the switch.*

Impact of VNA Measurement Receivers

It is common to relate the ten-term error model with the reference channel hardware concept of the VNA. The reference channel VNA has one reference receiver for detecting the incident signal and several measurement receivers, one for each VNA port. Thus, for the *n*-port system, the total number of receivers, *k*, is: $k = n + 1$, where *n* is the number of measurement ports (Figure 10).

The application of the seven-term model requires a VNA built on a so-called double-reflectometer principle: every measurement port is related with the individual reference and measurement receivers. For instance, the two-port double-reflectometer VNA uses four measurement receivers (Figure 11). In general, the number of measurement receivers *k* for a multiport double-reflectometer is $k = 2n$, where *n* is the number of system measurement ports.

Figure 11 shows a physical model of the systematic errors for a four-receiver VNA where $[Tx]$ is a measured DUT and $[A]$ and $[B]$ are the error boxes. The latter describe measurement systematic errors. The values $m_1 \ldots m_4$ represent waves measured by ideal receivers.

It is straightforward to show that the relationship between $m_1 \ldots m_4$, incident (a_1, a_2), and reflected or transmitted (b_1, b_2) signals is:

$$\begin{pmatrix} m_1' & m_1'' \\ m_2' & m_2'' \end{pmatrix} = \begin{pmatrix} A_{11} & A_{12} \\ A_{21} & A_{22} \end{pmatrix} \begin{pmatrix} T_{11} & T_{12} \\ T_{21} & T_{22} \end{pmatrix} \times \begin{pmatrix} B_{11} & B_{12} \\ B_{21} & B_{22} \end{pmatrix}^{-1} \begin{pmatrix} m_3' & m_3'' \\ m_4' & m_4'' \end{pmatrix}, \quad (6)$$

where: $m_1' \ldots m_4'$ and $m_1'' \ldots m_4''$ are the measured values in forward and reverse directions, respectively. $T_{11} \ldots T_{22}$ are defined as the transmission parameters of a measured DUT. Alternatively, in shortened form,

$$M = ATB^{-1}, \quad (7)$$

where measurement matrix *M* is

$$M = \begin{pmatrix} m_1' & m_1'' \\ m_2' & m_2'' \end{pmatrix} \begin{pmatrix} m_3' & m_3'' \\ m_4' & m_4'' \end{pmatrix}^{-1}. \tag{8}$$

Finally, the T-parameters of the DUT are given by

$$T_X = A^{-1} M_x B. \tag{9}$$

Conversion of Error Models

Both seven-term and ten-term error models are used to describe the double-reflectometer VNA. If required, a seven-term model can be converted into a ten-term model. Several approaches have been published giving different conversion equations [22], [26]–[28]. These equations are slightly different, but are based on the same physical principle. The differences stem from the authors' notation used for the seven-term model elements, e.g., using the inverse of matrix [B]. Such conversion techniques are implemented in many double-reflectometer VNAs today.

There were also attempts to apply the seven-term model for the reference receiver VNA [29]. In fact, this assumes that the source match equals the load match of the test set, which holds only in the case of an ideal test set switch. For a real system, this assumption may lead to intolerable measurement inaccuracy, especially for highly reflective DUTs [30]. Only the ten-term model can guarantee the entire description of the reference receiver VNA.

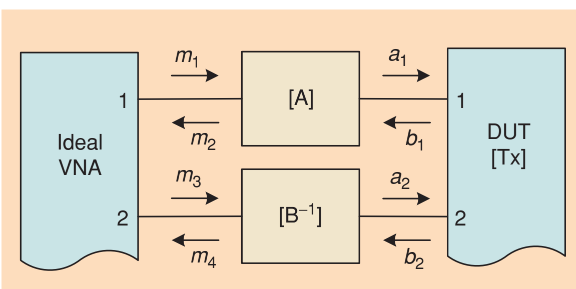


Figure 9. *Block diagram of a two-port VNA described by the cascade matrix representation (seven-term model).*

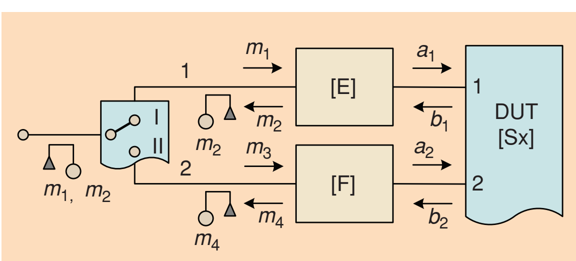


Figure 10. *Block diagram of VNA based on the reference channel architecture. It shows one reference receiver for incident signals* m_1 *and* m_3*, the signal source switch, the measurement receivers for signals* m_2 *and* m_4*, and the ten-term error model matrices* [E] *and* [F].

Multiport Measurements and Signal Leakage Problems

As noted above, even the first error models of a VNA included special error term(s) to address the influence of one system measurement port on another (i.e. the so-called leakage term, E_X). The leakage term was simply defined as a transmission coefficient between VNA ports being perfectly matched. This definition holds only for those cases when the DUT has input and output impedances equal to the system impedance. When measuring other devices, the application of a leakage term defined in such a way degrades the measurement accuracy.

Further measurement experiments and practical experiences revealed that the leakage can have a very complicated nature. It is generally insufficient to use just one or two error terms to correctly represent this phenomenon. Clearly, another description of systematic measurement errors was required.

Such a concept was introduced by Speciale and Franzen in 1977 [31]. The systematic measurement errors of the n-port VNA were represented by a $2n$-port virtual error network, connected with its n-ports to the DUT and its other n-ports to the ideal, error-free VNA. The error network consists of $(2n)^2$ coefficients and describes all possible influences of the measurement ports on each other. In fact, one error term can be set to be a free parameter and the error model can be normalized with respect to this term. That is, only $4n^2 - 1$ coefficients are linearly independent from each other. Thus, these error terms completely describe such a system [32].

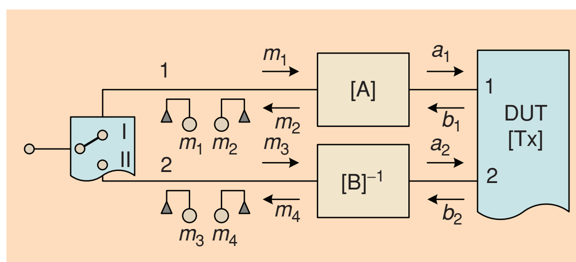


Figure 11. *Block diagram of VNA based on the double-reflectometer architecture. It shows the reference receivers,* m_1, m_3*; the signal source switch; the measurement receivers,* m_2 *and* m_4*; and the seven-term error model matrices* [A] *and* [B].

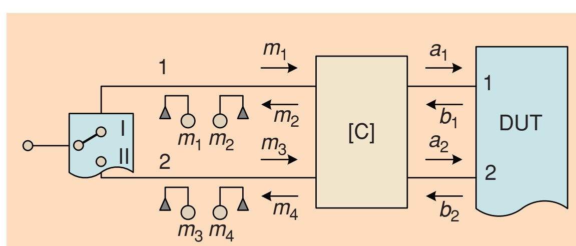


Figure 12. *Block diagram of the leaky VNA based on the double-reflectometer architecture. For the two-port system, the matrix* [C] *includes 15 error coefficients.*

The $4n^2-1$ model is only valid for VNAs built upon the double-reflectometer concept (with $2n$ measurement receivers, Figure 12). However, it was demonstrated much later that the full error model of a reference channel VNA (with $n+1$ reference receivers) can also be defined (Figure 13). This includes significantly more error terms: e.g., 22 coefficients for a two-port VNA, compared with 15 coefficients for a two-port double-reflectometer VNA [33].

The error models including crosstalk describe the measurement system in a more general way. They can be easily transformed to their equivalent, crosstalk-free models by setting the crosstalk error coefficients to zero. Thus, the reduction of the 22-term model (for an $n+1$ measurement receiver VNA) leads to a $(2n^2+n)$-term crosstalk-free model (i.e., a ten-term model for the two-port case). Omitting the influence of the crosstalk from the $2n$ measurement receiver VNA ($4n^2-1$-term model) gives the $(4n-1)$-term model (i.e., a seven-term model for the two-port case).

Partly Leaky Model

For some applications, the signal leakage between different measurement ports of a multiport system is not the same. For example, the multiport wafer-level measurement system configured with dual wafer probes (two ports per probe) shows a strong crosstalk between in-side (in-probe) ports, whereas the side-by-side (probe-to-probe) port influence is much lower. For such cases, it is feasible to include only those crosstalk coefficients in the system error model that most affect the measurement results.

The solution for the four-port measurement system was introduced in [34]. In this case, the error network is split into two parts. Each covers the in-side ports only (e.g., one network [$C1$] for Ports 1 and 2 and a separate network [$C2$] for Ports 3 and 4, as shown in Figure 14). This approach significantly simplifies the description of the measurement system by reducing the number of error terms from $4n^2-1$ to $2n^2-1$, where n is the number of VNA ports. Thus, only 31 error coefficients (for the partly leaky model) are needed, instead of 63 error coefficients (for the fully leaky model), when describing a four-port VNA.

Once the error model is known, the error terms can be calculated with the help of the calibration procedure. Various calibration methods have been developed over the 40-year history of vector network analysis. Some of these methods became standard de facto methods, while others were just intermediate steps towards improving the accuracy of S-parameter measurements.

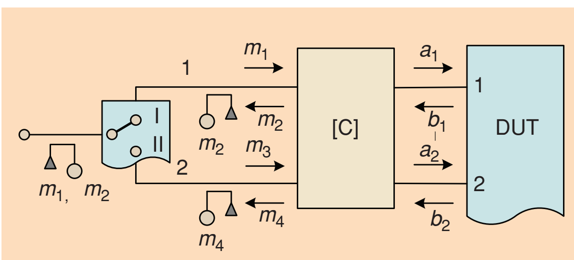


Figure 13. *Block diagram of the leaky VNA based on the reference channel architecture. For the two-port system, the matrix* [C] *includes 22 error coefficients.*

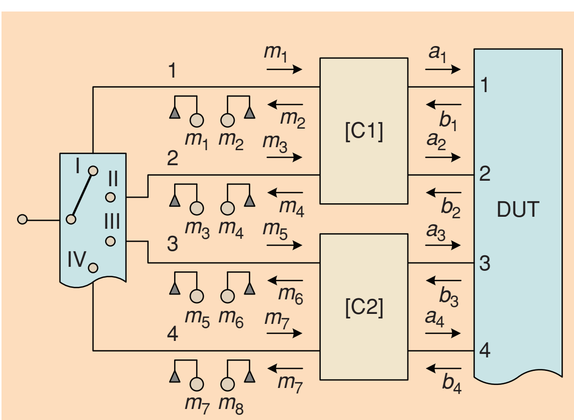


Figure 14. *A model of the double-reflectometer VNA allowing leakage between Ports 1 and 2 and between Ports 3 and 4.*

Calibration Procedures

First Iteration Solutions

Calibrating early VNAs was a lengthy and tedious process. Straightforward calculations of the required error terms as well as the error correction of the measured S-parameters of a DUT were not readily available at that time. Engineers were forced to rely on numerous variations of numerical and iterative procedures, e.g., [8].

First Explicit Solution

A significant advance was made in 1971 by Kruppa and Sodomsky [35]. For the first time, an explicit solution for calibrating a two-port VNA described by the eight-term model was introduced. This solution used three reflection standards (open, short, and match load termination) at each VNA port and two ports connected together (thru standard). Using the measurements of the open, short, and load at individual VNA ports, the three error terms S_{11}, S_{22}, and $S_{21}S_{12}$ (E_D, E_S and E_R) were defined for each port. The T_{21} and T_{12} terms were calculated from the forward and reverse transmission measurements of the thru standard, respectively (as shown in Figure 5).

The same work also introduced simple equations to perform a straightforward correction of the DUT's four S-parameters for the systematic measurement errors. Therefore, the need for lengthy iterative numerical calculations of error terms and error-corrected S-parameters was resolved.

This explicit approach was further modified for different test sets (error models) [20], [21] and, finally, the ten-term explicit calibration solution was introduced commercially by Hewlett-Packard in 1978 [19]. Since that time, this calibration procedure has become very popular under the name short-open-load-thru (SOLT) or thru-open-short-match (TOSM). Today, the SOLT calibration is a well-established technique that is implemented on all modern VNAs.

The accuracy of the SOLT procedure depends critically on the fabrication and modeling tolerances of the calibration standards (i.e., the lumped open, short, and load elements). Since the accuracy of these standards degrades with frequency, it remained a challenge to achieve reliable measurement results at high frequencies. Additional procedures, such as improving the calibration standard models (i.e., [36], [37]) or the use of standards initially characterized with respect to the reference calibration [38], can enhance the accuracy of the SOLT method.

Self-Calibration—TRL

The introduction of the TRL calibration (another variant of this is LRL) procedure by Engen and Hoer in 1974 was the next significant step in the development of VNA calibration theory [12]. For the first time, there was a method not requiring all standards to be either ideal or fully known. Using the redundancy of measurement results (an advantage of the double-reflectometer VNA and seven-term error model), TRL was able to define the originally unknown parameters of calibration standards like the reflection coefficient of the reflection standard and the propagation constant of the line standard. This new principle of calibrating a VNA with partly known standards was later called *self-calibration*.

Another advantage of the TRL technique is that it becomes possible to achieve real calibration and measurement traceability using well-defined air-isolated line standards. However, TRL is frequency limited. This restriction can be overcome by including additional line standards and applying a statistical analysis of the redundant measurement information (similar statistical techniques, such as weighted least squares [39] and generalized distance registration [40], have also been applied to one-port VNA calibration schemes resulting in a significant improvement in the overall accuracy of measurement), making TRL the accuracy benchmark per se [41]–[43].

TABLE 1. General requirements for the calibration standards.

Standard	Requirements
N1	Four known parameters (fully known)
N2	Minimum two known parameters
N3	Minimum one known parameter

Self-Calibration—Further Developments

After the introduction of the TRL self-calibration methods, many other different self-calibration procedures were developed. The measurement information redundancy obtained from the double-reflectometer VNA and its seven-term error model gives some calibration freedom: one or more standards may be partly unknown. This useful feature helps to define new calibration methods and optimize them for different applications.

For instance, the calculation of matrices [A] and [B] in Figure 9 can be performed by measuring three different two-port standards N_1, N_2, and N_3 instead of the DUT [T] in (7)

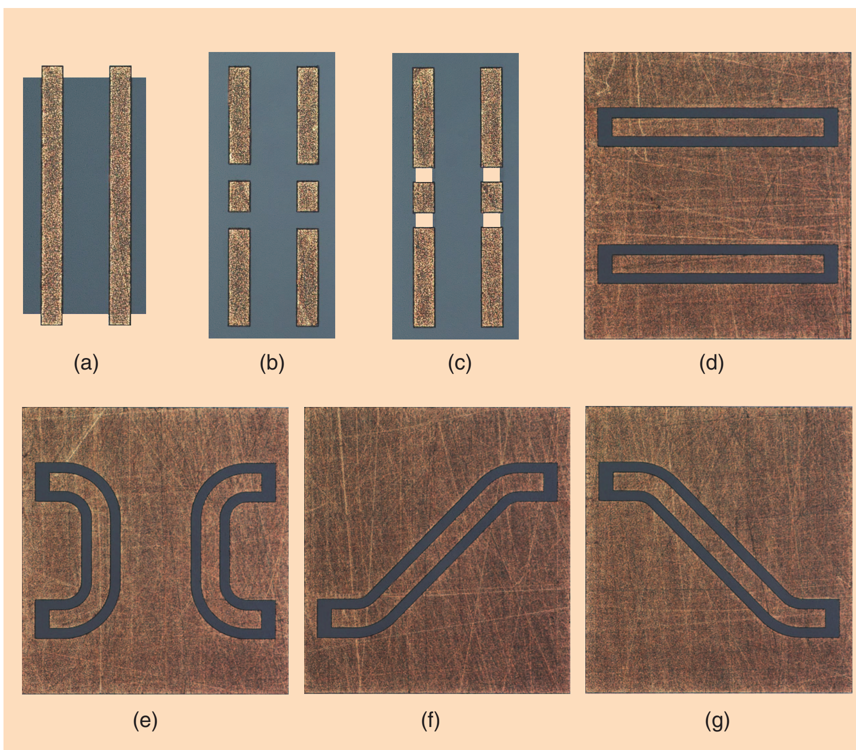


Figure 15. *Example of the commercially available (CSR) coplanar calibration standards: (a) paired shorts, (b) paired opens, (c) paired loads, (d) dual in-line thru lines, (e) dual loop-back thru lines, and, (f)–(g) cross-over thru lines. Such standards are used for most popular wafer-level calibration procedures.*

$$M_i = AN_iB^{-1}, (i = 1 \ldots 3). \quad (10)$$

To characterize the system completely [as in (6)], only seven unknowns have to be found from the 12 equations in (9). This redundancy produces general requirements to the calibration standards (Table 1) and makes it possible to derive many different calibration procedures [25], [44]–[46].

Reflection and transmission standards are addressed by the self-calibration procedure in two ways:

- one measurement of one known parameter (e.g., the reflection coefficient of a standard defines one error term)
- two measurements of the one unknown parameter taken under different conditions (e.g., the reflection coefficient of the same one-port standard measured at two VNA ports) give one error term.

Self-calibration requires seven error terms to be defined. In general cases, this can be met by any arbitrary combination of known and partly known standards (Figure 15). Today, TRL, line-reflect-match (LRM) [also often called thru-reflect-match (TRM) or thru-match-reflect (TMR)], short-open-load-reciprocal two-port (SOLR), quick-short-open-load-thru (QSOLT), and line-reflect-reflect-match (LRRM) are the most popular self-calibration procedures covering a very wide variety of applications.

Conventional and Improved LRM Procedures

The LRM method [47] was developed to resolve the frequency bandwidth limitation of conventional TRL. Instead of the line standard (or a set of different lines), it employed two one-port match (load) elements. Theoretically, LRM can be considered as a broadband calibration procedure. However, good calibration accuracy of commercially available LRM can be guaranteed only if using purely resistive, highly symmetrical 50Ω loads. This requirement is very difficult to achieve, especially at the wafer level. Some further improvements—like LRM, available from NIST [48], and line-reflect-match, advanced (LRM+) [49]—addressed this main drawback of conventional LRM.

SOLR

The SOLR method does not require the complete knowledge of the thru standard [50]. In fact, any passive two-port element providing a symmetrical (forward/reverse) transmission coefficient (reciprocal) can be used for the calibration. SOLR is very helpful for setups where implementation of the thru is impractical: e.g., for coaxial applications when measurement ports have the same sex, or rectangular port configurations at the wafer-level. The accuracy of the SOLR method strongly depends on the one-port standards (open, short, load), which have to be either ideal or fully known.

QSOLT

Like SOLT, the QSOLT procedure expects all standards to be fully known. However, it removes the need to measure the one-port standards at the second VNA port [51], [52]. This feature dramatically reduces the time spent on reconnecting and remeasuring the standards. However, it should be noted that a VNA calibrated with the QSOLT method exhibits significant measurement errors at its second port, i.e., the port that did not have the one-port standards connected to it during calibration [53].

LRRM

The LRRM procedure was the first method that was developed explicitly to address the needs of wafer-level applications. It was designed to resolve the restrictions of the planar lumped load, such as potential asymmetry and the frequency dependence of its impedance [54]. However, like QSOLT, it measures the load standards at only one VNA port. For some applications, this may lead to less reliable measurement results at the second VNA port [55].

Table 2 gives a brief comparison of these popular self-calibration procedures for the following criteria:

- type of calibration standards
- use of standards
- definition of error term (ET) from reflection and transmission measurements
- products obtained from the redundancy information.

Calibration of the Leaky System

Obviously, calibrating a leaky system (e.g., described by the 15-term models) requires an extended number of standards and/or calibration measurements. An iterative solution for the 15-term model was presented in [56]. It proposed four fully known two-port standards: one standard was the thru, while the remaining three standards were combinations of match-match, open-short, and short-open elements. As shown later in [57], the use of only four fully known two-port standards leads to an undetermined system of equations and, ultimately, a reduction in calibration accuracy. At least five such standards are required.

The explicit calibration and some self-calibration solutions for the 15-term model have been presented [57]–[60]. Also, the work in [33] gave a solution for the reference channel system (i.e., the 22-term model). Finally, the general self-calibration match-unknown-reflect-network (MURN) method for a leaky system was presented with eight unknown parameters of standards [58].

Multiport Cases and Hybridization

The fact that both ten-term and seven-term system descriptions can be applied to the multiport reflectometer VNA gives the user enough flexibility in choosing the most appropriate calibration method for his or her measurement system applications. Since the seven-term calibration procedures are insensitive to inaccuracies in some standards, this often makes them the preferred choice (e.g., [61], [62]).

When calibrating the seven-term system, selected error terms can be calculated using different methods. For instance, one can perform a hybrid calibration with a combination of SOLR and LRM [63] or another method [64]. This approach has benefits when some thru standards are difficult to characterize (e.g., at wafer level). However, hybrid methods may have limitations concerning the calibration dynamic range because they are based on the seven-term model [65].

An alternative way of integrating the advantages of different calibration procedures has been proposed by [66] and [67] with the generalized reflect-reflect-match-thru, advanced (GRRMT+) multiport solution. In contrast to hybrid calibrations, the GRRMT+ procedure uses the seven-term-based self-calibration LRM+ and SOLR procedures to calculate the accurate behavior of the partly known standards (i.e., the reflects and the thrus). Once all calibration standards are fully known, error terms are

TABLE 2. Comparison of TRL, LRM, SOLR, QSOLT, and LRRM calibration procedures.

	TRL		LRM/LRM+		SOLR		QSOLT		LRRM	
	Port 1	Port 2	Port 1	Port 2	Port 1	Port 2	Port 1	Port 2	Port 1	Port 2
Transmission Standards										
THRU Four Known S-parameters	☑ (4 ET)		☑ (4 ET)		×		☑ (4 ET)		☑ (4 ET)	
LINE Known: S_{11}, S_{22} Unknown: S_{21}, S_{12}	☑ (2 ET)		×		×		×		×	
RECIPROCAL Known: $S_{21} = S_{12}$, Known for $+/-90$ Degree Unknown: S_{11}, S_{22}	×		×		☑ (1ET)		×		×	
Sum of Error Terms Defined from Transmission Measurements	6		4		1		4		4	
Reflection Standards										
	Port 1	Port 2	Port 1	Port 2	Port 1	Port 2	Port 1	Port 2	Port 1	Port 2
OPEN One Known Per Port	×	×	×	×	☑ (1 ET)	☑ (1 ET)	☑ (1 ET)	×	×	×
SHORT One Known Per Port	×	×	×	×	☑ (1 ET)	☑ (1 ET)	☑ (1 ET)	×	×	×
LOAD One Known Per Port	×	×	☑ (1 ET)	☑ (1 ET)	☑ (1 ET)	☑ (1 ET)	☑ (1 ET)	×	☑ (1 ET)	×
REFLECT $S_{11}, = S_{22}$, Known for $+/-90$ Degree One Known for Two Ports	☑ (1 ET)		☑ (1 ET)		×		×		☑ (as open) (1 ET) ☑ (as short) (1 ET)	
Sum of Error Terms Defined From Reflection Measurements	1		3		6		3		3	
Self-Calibration Product	Reflection Coefficient of the Reflect Propagation Constant of the Line		Reflection Coefficient of the Reflect		S-Parameters of the Reciprocal		No		Reflection Coefficient of both Reflects	

calculated by the modified GSOLT procedure with non-ideal, but known, standards. Thus, the limitations of the multiport ten-term, multiport seven-term, and hybrid methods are overcome all in one procedure.

Future Perspectives

In the last four decades, we have observed remarkable advances in microwave measurement instrumentation as well as in calibration and error correction methodologies. This significantly influenced the evolution of high-frequency semiconductor devices. Precise measurement results are crucial for understanding the real performance of a DUT, verifying its model, and improving its design. Thus, progress in the *S*-parameter measurement methods accelerated the development of, for example, high-performance telecommunication and defense systems.

Today's progress in wireless technologies and high-frequency broadband applications and the requirements for low power consumption, reduced electro-magnetic interferences, increased sensitivity, and increased data transfer rates drive the development of high-frequency passive and active differential devices. Therefore, the improvement of measurement systems is integral for providing broadband differential driving signals.

The first multiport VNAs enabling true differential measurement are already commercially available [68], [69]. Some methods for correcting systematic measurement errors have recently been published [70], [71]. These methods represent modifications of existing approaches for single-ended systems. The next significant step in calibration and error correction theory could well be the introduction of true-differential error models and calibration standards. New straightforward true-differential calibration methods will drastically simplify the calibration process. It will bring the accuracy of measurement and characterization of differential devices to new levels.

References

[1] B.O. Weinschel, "Air-filled coaxial lines as absolute impedance standards," *Microwave J.*, pp. 47–50, vo, 7, Apr. 1964.

[2] I.A. Harris and R.E. Spinney, "The realization of high-frequency impedance standards using air-spaced coaxial lines," *IEEE Trans. Instrum. Meas.*, vol. 13, no. 4, pp. 265–272, 1964.

[3] L. Essen and K.D. Froome, "The refractive indices and dielectric constants of air and its principal constituents at 24,000 Mc/s," *Proc. Phys. Soc.*, vol. 64B, no. 10, 1951, pp. 862–875.

[4] K.H. Wong, "Using precision coaxial air dielectric transmission lines as calibration and verification standards," *Microwave J.*, vol. 31, pp. 83–92, Dec. 1988.

[5] A.E. Sanderson, "A radically new coaxial connector for high-precision measurements," *GR Experimenter*, vol. 37, pp. 1–6, Feb.–Mar. 1963.

[6] F.R. Huber and H. Neubauer, "The Dezifix connector—A sexless precision connector for microwave techniques," *Microwave J.*, vol. VI, pp. 79–85, June 1963.

[7] G-IM Subcommittee, "IEEE standard for precision coaxial connectors," *IEEE Trans. Instrum. Meas.*, vol. 17, no. 3, pp. 204–204, 1968.

[8] R.A. Hackborn, "An automatic network analyzer system," *Microwave J.*, vol. 11, pp. 45–52, May 1968.

[9] S.F. Adam, "A new precision automatic microwave measurement system," *IEEE Trans. Instrum. Meas.*, vol. 17, no. 4, pp. 308–313, 1968.

[10] S.F. Adam, G.R. Kirkpatrick, N.J. Sladek, and S.T. Bruno, "A high performance 3.5 mm connector to 34 GHz," *Microwave J.*, vol. 19, pp. 50–54, July 1976.

[11] K. Howell and K. Wong, "DC to 110 GHz measurements in coax using the 1 mm connector," *Microwave J.*, vol. 42, pp. 22–34, July 1999.

[12] G.F. Engen and C.A. Hoer, "Thru-reflect-line: An improved technique for calibrating the dual six-port automatic network analyzer," *IEEE Trans. Microwave Theory Tech.*, vol. 27, no. 12, pp. 987–993, 1979.

[13] C.A. Hoer and G.F. Engen, "On-line accuracy assessment for the dual six-port ANA: extension to nonmating connectors," *IEEE Trans. Instrum. Meas.*, vol. 36, pp. 524–529, June 1987.

[14] G.F. Engen, "The six-port reflectometer: An alternative network analyzer," *IEEE Trans. Microwave Theory Tech.*, vol. 25, no. 12, pp. 1075–1080, 1977.

[15] D. Williams, R. Marks, K. Phillips, and T. Miers, "Progress toward MMIC on-wafer standards," in *Proc. 36th ARFTG Microwave Measurements Conf.-Fall*, 1990, pp. 73–83.

[16] D.J. Bannister and M. Perkins, "Traceability for on-wafer S-parameter," *IEE Proc. Science, Measurement and Technology*, vol. 139, 1992, no. 5, pp. 232–234.

[17] *International Vocabulary of Basic and General Terms Used in Metrology*, 2nd Ed. International Organization for Standardization, Geneva, Switzerland, 1993.

[18] B.P. Hand, "Developing accuracy specifications for automatic network analyzer systems," *Hewlett-Packard J.*, vol. 21, pp. 16–19, Feb. 1972.

[19] J. Fitzpatrick, "Error models for system measurement," *Microwave J.*, vol. 21, pp. 63–66, May 1978.

[20] S. Rehnmark, "On the calibration process of automatic network analyzer systems (short papers)," *IEEE Trans. Microwave Theory Tech.*, vol. 22, no. 4, pp. 457–458, 1974.

[21] H.V. Shurmer, "Calibration procedure for computer-corrected s parameter characterisation of devices mounted in microstrip," *Electronics Lett.*, vol. 9, no. 14, pp. 323–324, 1973.

[22] D. Rytting, "Advances in microwave error correction techniques," in *Proc. Hewlett-Packard RF and Microwave Measurement Symp. and Exhibition*, June 1987, pp. 6201-6302.

[23] H. Heuermann, "GSOLT: The calibration procedure for all multi-port vector network analyzers," in *MTT-S Int. Microwave Symp. Dig.*, 2003, pp. 1815–1818.

[24] N.R. Franzen and R.A. Speciale, "A new procedure for system calibration and error removal in automated S-parameter measurements," in *Proc. 5th European Microwave Conf.*, 1975, pp. 69–73.

[25] H.J. Eul and B. Schiek, "A generalized theory and new calibration procedures for network analyzer self-calibration," *IEEE Trans. Microwave Theory Tech.*, vol. 39, no. 4, pp. 724–731, 1991.

[26] R.B. Marks, "Formulations of the basic vector network analyzer error model including switch-terms," in *Proc. 50th ARFTG Microwave Measurements Conf.-Fall*, 1997, pp. 115–126.

[27] S. Vandenberghe, D. Schreurs, G. Carchon, B. Nauwelaers, and W. De Raedt, "Identifying error-box parameters from the twelve-term vector network analyzer error model," in *Proc. 60th ARFTG Microwave Measurements Conf.-Fall*, 2002, pp. 157–165.

[28] H.J. Eul, "Methoden zur Kalibrierung von heterodynen und homodynen Netzwerkanalysatoren," Ruhr-Universitaet, Bochum, 1990.

[29] "In-fixture microstrip device measurements using TRL* calibration," Hewlett-Packard Company, Santa Clara, CA, 1991.

[30] D. Zelinka and M. Shaw, "A comparative study of TOSL, TRL, and TRL* network analyzer calibration techniques, using microstrip test fixtures," in *Proc. 46th ARFTG Microwave Measurements Conf.-Fall*, 1995, pp. 9–18.

[31] R.A. Speciale and N.R. Franzen, "Super-TSD, a generalization of the TSD network analyzer calibration procedure, covering n-port measurements with leakage," in *MTT-S Int. Microwave Symp. Dig.*, 1977, pp. 114–117.

[32] V. Teppati and A. Ferrero, "On-wafer calibration algorithm for partially leaky multiport vector network analyzers," *IEEE Trans. Microwave Theory Tech.*, vol. 53, no. 11, pp. 3665–3671, 2005.

[33] H. Heuermann and B. Schiek, "Results of network analyzer measurements with leakage errors-corrected with direct calibration techniques," *IEEE Trans. Instrum. Meas.*, vol. 46, no. 5, pp. 1120–1127, 1997.

[34] V. Teppati, A. Ferrero, D. Parena, and U. Pisani, "A simple calibration algorithm for partially leaky model multiport vector network analyzers," in *Proc. 65th ARFTG Microwave Measurements Conf.-Spring*, 2005, pp. 5-9.

[35] W. Kruppa and K.F. Sodomsky, "An explicit solution for the scattering parameters of a linear two-port measured with an imperfect test set," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-19, no. 1, pp. 122–123, 1971.

[36] S. Padmanabhan, P. Kirby, J. Daniel, and L. Dunleavy, "Accurate broadband on-wafer SOLT calibrations with complex load and thru models," in *Proc. 61st ARFTG Microwave Measurements Conf.-Spring*, 2003, pp. 5–10.

[37] D. Blackham and K. Wong, "Latest advances in VNA accuracy enhancements," *Microwave J.*, vol. 48, pp. 78-94, July 2005.

[38] N. Ridler and N. Nazoa, "Using simple calibration load models to improve accuracy of vector network analyser measurements," in *Proc. 67th ARFTG Microwave Measurements Conf.-Spring*, 2006, pp. 104–110.

[39] D. Blackham, "Application of weighted least squares to OSL vector error correction," in *Proc. 61st ARFTG Microwave Measurements Conf.-Spring*, 2003, pp. 11-21.

[40] M.J. Salter, N.M. Ridler, and P.M. Harris, "Over-determined calibration schemes for RF network analysers employing generalised distance regression," in *Proc. 62nd ARFTG Microwave Measurements Conf.-Fall*, 2003, pp. 127–142.

[41] R.B. Marks, "A multiline method of network analyzer calibration," *IEEE Trans. Microwave Theory Tech.*, vol. 39, no. 7, pp. 1205–1215, 1991.

[42] D.F. Williams, J.C.M. Wang, and U. Arz, "An optimal vector-network-analyzer calibration algorithm," *IEEE Trans. Microwave Theory Tech.*, vol. 51, no. 12, pp. 2391–2401, 2003.

[43] D.F. Williams, R.B. Marks, and A. Davidson, "Comparison of on-wafer calibrations," in *Proc. 38th ARFTG Microwave Measurements Conf.-Fall*, 1991, pp. 68–81.

[44] K.J. Silvonen, "A general approach to network analyzer calibration," *IEEE Trans. Microwave Theory Tech.*, vol. 40, no. 4, pp. 754–759, 1992.

[45] H. Heuermann and B. Schiek, "A generalization of the Txx network analyzer self-calibration procedure," in *Proc. 22nd European Microwave Conf.*, 1992, pp. 907–912.

[46] H. Heuermann and B. Schiek, "Robust algorithms for Txx network analyzer self-calibration procedures," *IEEE Trans. Instrum. Meas.*, vol. 43, no. 1, pp. 18–23, 1994.

[47] H.J. Eul and B. Schiek, "Thru-match-reflect: One result of a rigorous theory for de-embedding and network analyzer calibration," in *Proc. 18th European Microwave Conf.*, 1988, pp. 909–914.

[48] D.F. Williams and R.B. Marks, "LRM probe-tip calibrations using nonideal standards," *IEEE Trans. Microwave Theory Tech.*, vol. 43, no. 2, pp. 466–469, 1995.

[49] R. Doerner and A. Rumiantsev, "Verification of the wafer-level LRM+ calibration technique for GaAs applications up to 110 GHz," in *Proc. 65th ARFTG Microwave Measurements Conf.-Spring*, 2005, pp. 15-19.

[50] A. Ferrero and U. Pisani, "Two-port network analyzer calibration using an unknown 'thru'," *IEEE Microwave Guided Wave Lett.*, vol. 2, no. 12, pp. 505–507, 1992.

[51] A. Ferrero and U. Pisani, "QSOLT: A new fast calibration algorithm for two port S parameter measurements," in *Proc. 38th ARFTG Microwave Measurements Conf.-Fall*, 1991, pp. 15–24.

[52] H.J. Eul and B. Schiek, "Reducing the number of calibration standards for network analyzer calibration," *IEEE Trans. Instrum. Meas.*, vol. 40, no. 4, pp. 732–735, 1991.

[53] J.A. Jargon, R.B. Marks, and D.K. Rytting, "Robust SOLT and alternative calibrations for four-sampler vector network analyzers," *IEEE Trans. Microwave Theory Tech.*, vol. 47, no. 10, pp. 2008–2013, 1999.

[54] A. Davidson, K. Jones, and E. Strid, "LRM and LRRM calibrations with automatic determination of load inductance," in *Proc. 36th ARFTG Microwave Measurements Conf.-Fall*, 1990, pp. 57–63.

[55] R. Doerner, "Evaluation of wafer-level LRRM and LRM+ calibration techniques," in *Proc. 69th ARFTG Microwave Measurements Conf.-Spring*, 2007, pp. 86-89.

[56] J.V. Butler, D.K. Rytting, M.F. Iskander, R.D. Pollard, and M.A. Vanden Bossche, "16-term error model and calibration procedure for on-wafer network analysis measurements," *IEEE Trans. Microwave Theory Tech.*, vol. 39, no. 12, pp. 2211–2217, 1991.

[57] K.J. Silvonen, "Calibration of 16-term error model [microwave measurement]," *Electronics Lett.*, vol. 29, no. 17, pp. 1544–1545, 1993.

[58] H. Heuermann and B. Schiek, "15-term self-calibration methods for the error-correction of on-wafer measurements," *IEEE Trans. Instrum. Meas.*, vol. 46, no. 5, pp. 1105–1110, 1997.

[59] H. Heuermann and B. Schiek, "Results of network analyzer measurements with leakage errors corrected with the TMS-15-term procedure," in *IEEE MTT-S Int. Microwave Symp. Dig.*, 1994, vol. 3, pp. 1361–1364.

[60] K. Silvonen, "LMR 16—A self-calibration procedure for a leaky network analyzer," *IEEE Trans. Microwave Theory Tech.*, vol. 45, no. 7, pp. 1041–1049, 1997.

[61] A. Ferrero, U. Pisani, and K.J. Kerwin, "A new implementation of a multiport automatic network analyzer," *IEEE Trans. Microwave Theory Tech.*, vol. 40, no. 11, pp. 2078–2085, 1992.

[62] J. Martens, "Multiport SOLR calibrations: Performance and an analysis of some standards dependencies," in *Proc. 62nd ARFTG Microwave Measurements Conf.-Fall*, 2003, pp. 205–213.

[63] J. Martens, D. Judge, and J. Bigelow, "VNA calibration modifications and hybridizations for simplified high frequency multiport/differential measurements," in *ARMMS Conf. Dig.*, Apr. 2005.

[64] L. Hayden, "A hybrid probe tip calibration of multiport vector network analyzers," in *Proc. 68th ARFTG Microwave Measurements Conf.-Fall*, 2006, pp. 176-183.

[65] H. Heuermann, "Multi-port calibration techniques for differential parameter measurements with network analyzers," in *Proc. European Microwave Conf., Rohde and Schwarz Workshop*, Oct. 2003, pp. 1-6.

[66] H. Heuermann, A. Rumiantsev, and S. Schott, "Advanced on-wafer multiport calibration methods for mono- and mixed-mode device characterization," in *Proc. 63rd ARFTG Microwave Measurements Conf.-Spring*, 2004, pp. 91–96.

[67] A. Rumiantsev, H. Heuermann, and S. Schott, "A robust broadband calibration method for wafer-level characterization of multiport devices," in *Proc. 69th ARFTG Microwave Measurements Conf.-Spring*, 2007, pp. 56-60.

[68] *ZVA Vector Network Analyzer*, Rohde and Schwartz, Munich, Germany, 2007.

[69] "Dual-source 4-port network analyzers true-mode stimulus application (TMSA)," Agilent, Santa Clara, CA, 2007.

[70] J. Simon, "True differential stimulus gives additional insight into nonlinear amplifier behavior," in *Proc. 69th Microwave Measurements Conf.-Spring*, 2007, pp. 33-41.

[71] J. Dunsmore, K. Anderson, and D. Blackham, "Complete pure-mode balanced measurement system," in *Proc. 2007 IEEE/MTT-S Int. Microwave Symp.*, 2007, pp. 1485–1488.

[72] *General Requirements for the Competence of Testing and Calibration Laboratories*, vol. ISO/IEC 17025:2005, 2005.

[73] R.A. Dudley and N.M. Ridler, "Traceability via the Internet for microwave measurements using vector network analyzers," *IEEE Trans. Instrum. Meas.*, vol. 52, no. 1, pp. 130–134, 2003.

[74] R.W. Beatty, "Calculated and measured S11, S21, and group delay for simple types of coaxial and rectangular waveguide two-port standards," *NBS Tech. Note 657*, Boulder, CO, Dec. 1974.

[75] M.A. Maury Jr. and G.R. Simpson, "Two-port verification standards in 3.5 mm and 7 mm for vector network analyzers," *Microwave J.*, vol. 27, pp. 101–110, June 1984.

[76] R. Tucker, "The history of the Automatic RF Techniques Group," *IEEE Microwave Mag.*, vol. 8, no. 4, pp. 69–74, 2007.

[77] R.A. Ginley, "Confidence in VNA measurements," *IEEE Microwave Mag.*, vol. 8, no. 4, pp. 54–58, 2007.

[78] G.D. Jones and N.M. Ridler, "Comparison assesses the quality of network measurements," *Microwaves & RF*, vol. 34, pp. 101–104, Jan. 1995.

[79] M.J. Maddock and N.M. Ridler, "ANAMET-991: TDNA measurement comparison exercise," ANAMET, Teddington, U.K., Rep. 031, 2001.