

Reconfigurable Waveguide for Vector Network Analyzer Verification

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Abstract—A novel simple approach to the verification process for millimeter-wave vector network analyzer waveguide calibration is reported using a single reconfigurable component verification kit. Conventional techniques require multiple verification components and these only exist commercially for operation up to 110 GHz. At millimeter-wave frequencies, the use of multiple components can lead to significant errors due to imperfections in waveguide flange misalignments during the multiple component connections. The reconfigurable component is designed so that its electrical properties can be changed quickly to a broad range of predetermined values without introducing additional errors due to changes in flange alignment. Once connected, the component can be reconfigured to introduce relative changes in the reflected and transmitted signals. For millimeter-wave metrology, where mechanical precision is of paramount importance, this single-component verification approach represents an attractive solution. A proof-of-concept verification process is described, based on full-wave electromagnetic modeling, hardware implementation, and validation measurements using standard WR-15 waveguide (50–75 GHz).

Index Terms—Measurement, millimeter-wave, reconfigurable, rectangular waveguide, verification, vector network analyzer (VNA).

I. INTRODUCTION

THE exponential growth in the commercial exploitation of the millimeter-wave frequency range [1]–[5] requires continual improvements in metrology. One important piece of measurement equipment is the vector network analyzer (VNA), which must be first calibrated before any device-under-test measurements can be performed. However, of equal importance is

the calibration verification process. In rectangular waveguide, the measurement setup (i.e., calibration and its verification) is a relatively slow manual process when compared to rapid automated RF on-wafer approaches [6]. Being a manual process, requiring multiple matings of rectangular waveguide flanges, mechanical misalignments can introduce errors in verification measurements [7], which become more pronounced as frequency increases into the millimeter-wave frequency range. Thus, the ability of these devices to act as independent transferable verification components will be significantly compromised at these higher frequencies due to interactions between multiple random misalignment errors, including those due to the inevitable imperfections in different end-users' test ports. Errors in verification measurements could lead to a false conclusion concerning the quality of the calibration, which, in turn, may lead to an unnecessary and time-consuming re-calibration.

In addition to calibration kits, millimeter-wave instrumentation manufacturers can also provide independent verification kits. However, in rectangular waveguide, verification kits are only commercially available for operation up to 110 GHz. A typical waveguide verification kit contains four distinct components: two fixed attenuators (e.g., 20 and 50 dB), a standard low-loss thru section, and a half-height impedance mismatch section. The thru and half-height sections can be accurately characterized by classical electromagnetic theory, while the fixed attenuators must be pre-characterized through traceable measurements. The quality of the verification components can be subsequently checked against the performance of the associated models to ensure that the known electrical behavior is maintained.

With conventional verification kits, components are permanently fixed, i.e., their electrical behavior cannot be changed once they have been connected to the VNA. On the other hand, p-i-n diodes [8] and radio frequency microelectromechanical systems (RF MEMS) switches can be used for implementing an electronically reconfigurable verification kit. However, p-i-n diode circuits suffer from poor performance and are much more difficult to integrate at higher millimeter-wave and sub-millimeter-wave frequencies. RF MEMS switches can perform better, but still suffer from the problem of electromagnetic interactions with the biasing arrays and also introduce a large cost overhead.

A single-component verification kit, consisting of a reconfigurable section of rectangular waveguide that can introduce a broad range of known values in the voltage-wave reflection and transmission coefficients, represents a novel simple approach.

One approach to creating a reconfigurable waveguide section is to pattern its broad walls with holes so that metal pins can

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be inserted through the complete waveguide section, similar to the way pins are inserted into a “voodoo doll”—hence, we use the term “voodoo-waveguide” to describe this type of artifact. This concept was recently introduced in [9]. These pins will perturb the electromagnetic behavior within the waveguide section, giving rise to predictable and repeatable changes in reflection and transmission coefficients.

This paper describes a reconfigurable “voodoo-waveguide” device, realized in WR-15 waveguide (50–75 GHz). This millimeter-wave band was chosen because structures can be easily machined without the need for using more expensive micromachining technologies [10].

The “voodoo-waveguide” device is designed using commercially available full-wave numerical simulation software (CST Microwave Studio). An example device is then fabricated in accordance with the proposed design with the quality of the device fabrication process being checked using high-precision dimensional metrology. The device is then characterized in terms of its electrical S -parameters over the full waveguide band using high-precision electromagnetic measurements (in this work, provided by the National Physical Laboratory (NPL), Teddington, Middlesex, U.K.). This electrical characterization provides the reference data for the device that can then be compared with other sets of measurement data, e.g., produced by other measurement system configurations. The outcome from this comparison verifies (or not, as the case may be) the other measurement system configurations.

A proof-of-concept verification process is described in detail in this paper whereby the reference data is produced by the NPL, using the U.K.’s primary national standard measurement facility. This reference data is then used to verify two sets of measurement data produced using short/offset-short/load/thru (SOLT) calibrations: one of the calibrations utilizes a well-matched calibration load whereas the other calibration deliberately uses a poorly matched load. This helps demonstrate the ability of the method to determine both a good quality and a poor quality calibration. Although, on this occasion, the reference data is provided by the NPL, such reference data can be provided by any suitably reliable measurement laboratory (e.g., a laboratory accredited to the ISO/IEC 17025 international standard [11]). This is of particular relevance when this technique is used by end-users for routine verification of waveguide VNAs.

The proof-of-concept verification process that is described clearly demonstrates that this new approach to calibration verification can quickly reveal whether a calibrated VNA is operating within expected performance metrics.

II. RECONFIGURABLE VOODOO-WAVEGUIDE DESIGN

The behavior of a reconfigurable “voodoo-waveguide” is first investigated theoretically using a full-wave simulator (CST MWS). The design of the reconfigurable voodoo-waveguide structure chosen on this occasion is shown in Fig. 1, having five pins/holes to demonstrate the single-component verification concept.

For example, with reference to Fig. 1(a), hole h_4 is placed at the center of the waveguide (along both the x - and y -directions),

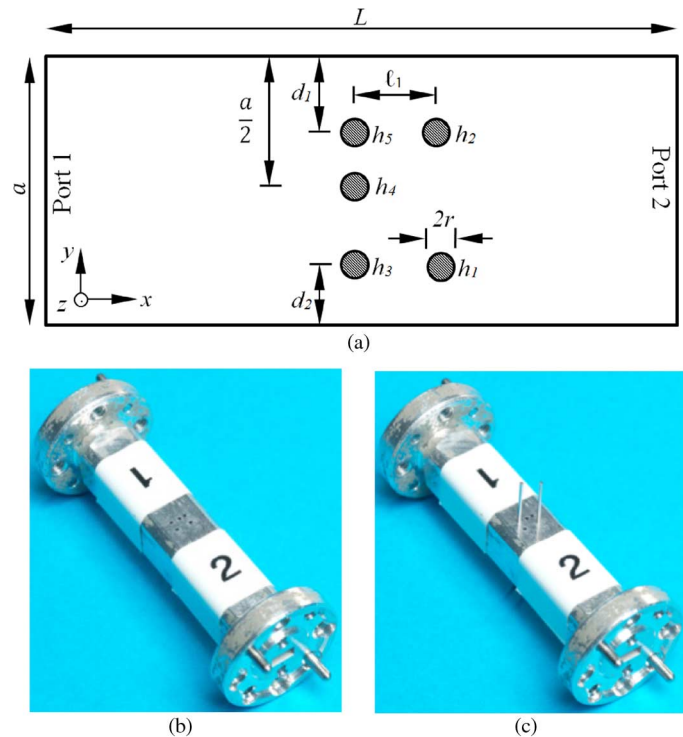


Fig. 1. Reconfigurable voodoo-waveguide structure. (a) Design plan view. The shaded areas represent the position of the holes (nominal dimensions are $L = 50$ mm, $d_1 = 1.0$ mm, $d_2 = 0.5$ mm, $l_1 = 1.5$ mm, and $r = 0.25$ mm). (b) Machined structure with no pins inserted and (c) machined structure with two pins inserted all the way through.

where the electric field is at a maximum for the fundamental TE_{10}^x mode, resulting in the highest level of interaction when a pin is inserted. Similarly, h_3 and h_5 are located in-line with h_4 (along the y -direction), with an offset d_2 and d_1 from the adjacent sidewalls, respectively. As a result, different levels of interference can be achieved to create predetermined changes in the reflection and transmission coefficients. Additionally, holes h_1 and h_2 are in-line with h_3 and h_5 (along the x -direction), respectively, to provide phase offsets. With five holes, there are 32 discrete combinations that can be selected, giving a wide range of verification measurements—this is in contrast to the four possible states offered by commercial verification kits. For convenience, on this occasion, all pins have the same diameter of 500 μm , which needs to match the size of the holes, so that there is adequate electrical contact and sufficiently low leakage of electromagnetic radiation. With the gap between the pins and holes being of the order of a few micrometers, and hence, much smaller than the guided wavelength, the radiation effects can be neglected (i.e., electrostatic limit). Although there might be some leakage effects (i.e., a quasi-TEM mode is still supported in the pin-hole air gap), this is automatically taken into account by the pin insertion repeatability and associated statistical analysis. As a result, acceptable repeatability of the states of the “voodoo-waveguide” is obtained.

For simplicity, the waveguide is only operated in its fundamental TE_{10}^x mode (with E_z , H_x , and H_y being nonzero) so that all higher order modes are cutoff. With the pins placed vertically (i.e., parallel to the electric field E_z), currents are induced along the pins, resulting in a strong interaction with propagating

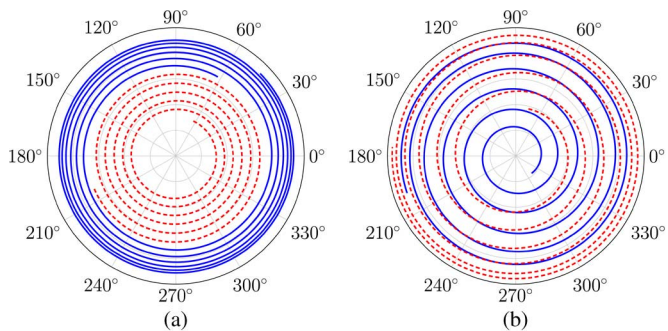


Fig. 2. Simulated reflection (solid blue in online version) and transmission (dashed red in online version) characteristics for the reconfigurable voodoo-waveguide structure with pins filling the holes. (a) h_1 and h_2 . (b) h_1 and h_5 .

fields. This would not be the case if the pins were placed horizontally. Simple single- and double-pin discontinuities located in the E -plane have been studied analytically [12], [13].

As an example, the reflection and transmission characteristics of the reconfigurable voodoo-waveguide structure incorporating two pins is shown in Fig. 2 for two different pin combinations. Polar plot responses exhibit a spiral frequency response (for both reflection and transmission measurements), which is unique to the reconfigurable voodoo structure. This demonstrates that this single-component verification kit should be sufficient for most practical applications. Having values spread out across most of the scattering (S)-parameter planes provides a comprehensive verification for the VNA's reflection and transmission measurements, as will be discussed in detail in the following sections.

Next, a prototype device based on the initial design is fabricated, as shown in Fig. 1(b) and (c). The holes are made by electrical discharge machining using a computer-controlled process. A spark from a copper rod placed in close proximity to the aluminum waveguide surface repeatedly vaporizes a small part of the waveguide near the copper rod. The vertical line of holes h_3 , h_4 , and h_5 is nominally midway between the waveguide end ports. Fig. 1(b) and (c) shows the finished rectangular waveguide, having internal aperture dimensions $a \times b = 3.76 \times 1.88 \text{ mm}^2$ (corresponding to WR-15 [14]), with symmetrical holes drilled on both broad walls. Through the holes, high-speed steel cylindrical pins can penetrate through the waveguide walls.

III. EXPERIMENTAL VALIDATION

A. Reconfigurable Structure Dimensional Measurements

In order to verify successful manufacture of the reconfigurable voodoo-waveguide structure, it is important to check the positions of the pin insertion holes at the micrometer level of accuracy. This becomes more important at higher frequencies.

The position of the pin insertion holes, with respect to waveguide datum features, was determined using a coordinate measuring machine (CMM) at the NPL. The intra-hole positions were determined using a Zeiss F25 small-component CMM, fitted with a 125- μm -diameter ball-ended probing stylus, as shown in Fig. 3(a).

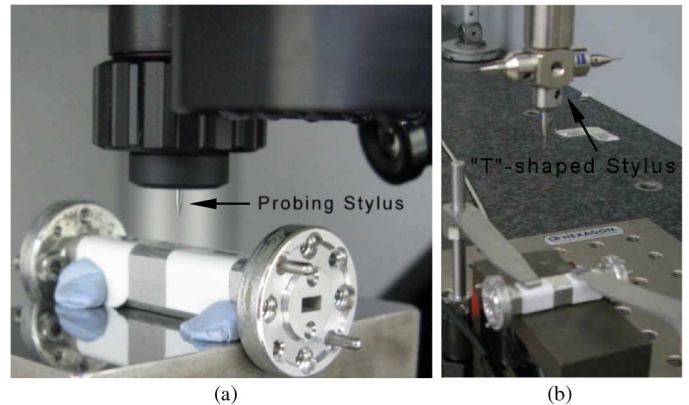


Fig. 3. Experimental setup for determining hole positions using: (a) Zeiss F25 small-component CMM and (b) Zeiss Universal Precision Measuring Center CMM.

The x - y surface of each hole was contacted at 16 different locations and a Gaussian best fit circle fitted to the measurement data. A first local coordinate system (CS1) was set up using the center of h_4 as the origin, and the center location of the other four holes were established with respect to this evaluated feature. The position of h_4 , with respect to the waveguide end faces (the port end planes) and outer sidewalls, was also determined. Since the pattern of holes is nonsymmetric, the ports are labeled 1 and 2, to avoid any ambiguity in their identification. All measurements were repeated five times, as part of the process of determining the repeatability of the dimensional measurements.

The position of the waveguide's inner sidewalls, with respect to the outer sidewalls, was determined using a Zeiss Universal Precision Measuring Center (UPMC) CMM fitted with a "T"-shaped stylus array [see Fig. 3(b)], each stylus having a 600- μm -diameter ball-ended tip. In this case, a second local coordinate system (CS2) was set up using designated waveguide datum features. This was then used as the global coordinate system. The Port 1 aperture was defined as the $x = 0$ plane, and one internal sidewall defined as the $y = 0$ plane, as indicated in Fig. 1(a), with the origin at $x = y = 0$. The latter is designated as the wall adjacent to holes h_1 and h_3 . Since it was not possible to make contact with the inside of any sidewall, along the length of the waveguide, 24 points corresponding to the inside of this sidewall were determined at each end of the waveguide with Gaussian best fit planes fitted to the data. A mean plane was constructed from the part planes at both ends to define the $y = 0$ plane. The external position of the sidewall, with respect to the $y = 0$ plane, was then determined. Finally, the center coordinates of all holes were transposed and evaluated in CS2. Again, measurements were repeated five times to determine the repeatability of the measurements.

The coordinates of the hole centers, with respect to coordinate system CS2, are given in Table I, together with the location of the Port 1/Port 2 apertures (i.e., the overall length of the reconfigurable voodoo-waveguide structure). The measurement uncertainty of the data is estimated to be $\pm 0.25 \mu\text{m}$ for the intra-hole positions and $\pm 250 \mu\text{m}$ for the center coordinates of h_4 . The larger uncertainty, in the latter case, is due primarily to the lower accuracy of the UPMC CMM. The holes were only

TABLE I
HOLE LOCATIONS (IN MILLIMETERS) WITH RESPECT TO THE ORIGIN FOR CS2

	h_1	h_2	h_3	h_4	h_5	Length
x	26.428	26.449	24.940	24.955	24.940	49.979
y	0.465	2.713	0.459	1.835	2.713	—
diam.	0.501	0.514	0.507	0.520	0.509	—

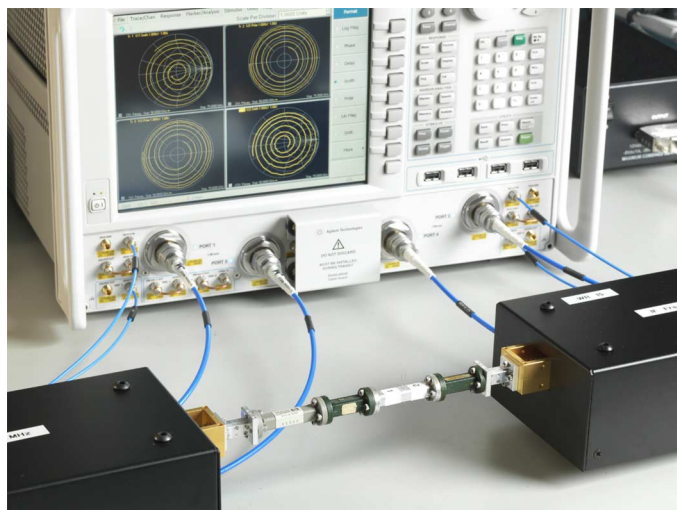


Fig. 4. Experimental setup for measuring the frequency response of the reconfigurable voodoo-waveguide structure.

measured from the top side of the waveguide with the assumption that there is perfect symmetry between the top and bottom sides such that the pins stand perfectly vertical.

B. Electrical Measurements Methodology

The electrical measurements were also made at the NPL using an Agilent Technologies PNA-X VNA and a pair of Virginia Diodes Inc. waveguide extender heads. These extender heads are fitted with standard WR-15 waveguide test ports [14] and enable the VNA to make measurements across the full frequency range of interest (50–75 GHz), as shown in Fig. 4.

Traceable calibration standards were used for accurate S -parameter measurements, with reference planes at the waveguide test ports, by performing a thru-reflect-line (TRL) calibration [15]. This calibration employed WR-15 waveguide standards: thru connection (T), a flush short-circuit connected, in turn, to each test port (R) and a quarter-wavelength delay line section of waveguide (L). The calibration was performed using an in-house calibration algorithm, employing a seven-term error-correction routine [16]. The overall setup (i.e., VNA, primary standards, and calibration algorithm) is referred to as the NPL primary impedance microwave measurement system (PIMMS) [17], [18]. This is the U.K.'s primary national standard system for S -parameter measurements. The realization of this system for millimeter-wave waveguide measurements has been previously described [19].

PIMMS also determines the uncertainty in the S -parameter measurements. This is achieved following internationally

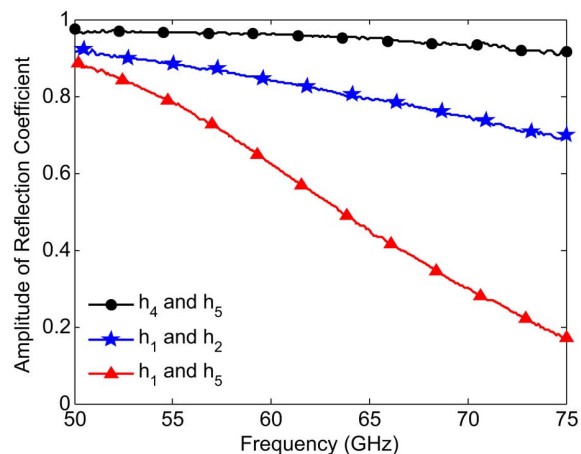


Fig. 5. Measured amplitude of voltage-wave reflection coefficient for various pin configurations.

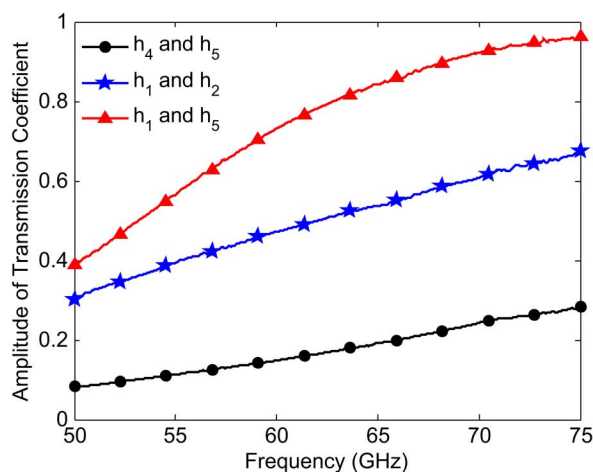


Fig. 6. Measured amplitude of voltage-wave transmission coefficient for various pin configurations.

agreed guidelines [20] with minor modifications to accommodate the complex-valued (i.e., vector) nature of the S -parameter measurands [21]. Uncertainties using PIMMS for measurements of the linear magnitude of transmission coefficients range typically from 0.001 to 0.002 [18] for a nominal transmission of 0.1 (i.e., 20 dB) in this waveguide band. Similarly, uncertainties for measurements of the linear magnitude of reflection coefficients range typically from 0.005 to 0.006 [18] for low reflecting devices in this waveguide band.

C. Reconfigurable Structure Electrical Measurements

The voltage-wave reflection and transmission coefficients of the reconfigurable voodoo-waveguide structure were first measured in order to obtain the reference data for the device. With our design, which has 32 different pin combinations, not all combinations had sufficiently distinct and useful characteristics. Some of the most illustrative combinations are shown in Figs. 5 and 6.

As can be seen, the reconfigurable nature of the structure allows a diverse range of reflection and transmission values. The same behavior is also observed as spirals in the measurement complex planes, as shown in Fig. 2. This diverse range has the

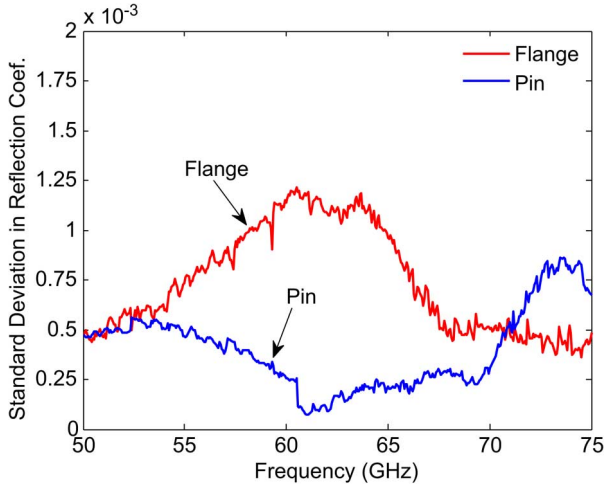


Fig. 7. Experimental standard deviation in reflection coefficient.

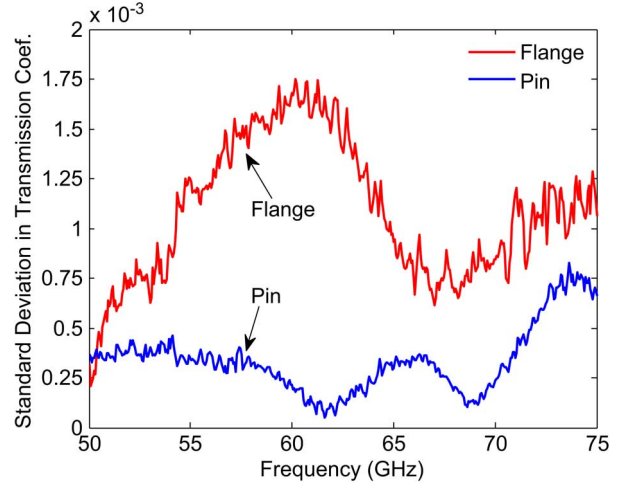


Fig. 8. Experimental standard deviation in transmission coefficient.

advantage that most parts of the S -parameter complex planes can be verified, and hence, more detailed information about the quality of calibration can be obtained. This contrasts with the behavior of most commercial verification kit components (i.e., attenuators and waveguide sections) that only provide relatively flat magnitude frequency responses (corresponding to circles in the measurement complex planes).

In order to verify the repeatability of the reconfigurable voodoo-waveguide device, two independent studies were undertaken in order to decompose the random errors introduced by flange misalignments and pin insertion misalignments. First, the waveguide is connected/disconnected $N = 10$ times while the pin configuration is fixed (h_1 and h_2 are filled) in order to expose the errors due to flange misalignments only. A rapid method of assessing these repeatability effects is by using a simple statistical analysis—specifically, the standard deviation (SD) can be defined as

$$\text{SD} = \sqrt{\frac{1}{N-1} \sum_{k=1}^N |S_{ij,k} - \bar{S}_{ij}|^2} \quad (1)$$

where $\bar{S}_{ij} = (1/N) \sum_{k=1}^N S_{ij,k}$ is the mean value. As shown in Figs. 7 and 8, even at this relatively low frequency band and with a prototype not made using high-precision machining, the flange repeatability is generally larger than the pin insertion repeatability.

D. Calibration Verification Proof of Concept

Having characterized, using the PIMMS electrical measurements, the proposed reconfigurable voodoo-waveguide structure, it is now possible to demonstrate its value as a single-component verification kit. With the NPL PIMMS software, it is difficult to deliberately adjust the quality of a given calibration. Therefore, the widely used SOLT calibration method was used to enable a deliberately poor calibration to be introduced into the investigation. Usually, a high-quality well-matched load standard can produce a linear reflection coefficient magnitude of less than 0.01 (corresponding to a return loss of 40 dB), at millimeter-wave frequencies, as shown in Fig. 9.

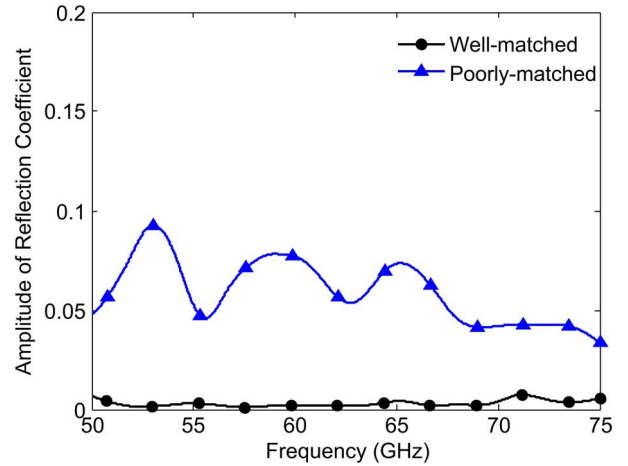


Fig. 9. Measured responses for a well-matched load standard (black) and a poorly matched load standard (blue in online version).

After performing a good calibration, using a well-matched load standard, the reconfigurable voodoo-waveguide structure was connected to the VNA test ports. The measured reflection and transmission coefficients were then compared with the NPL reference measurements obtained from PIMMS. The error vector magnitude, given by $|S_{ij}^{\text{TRL}} - S_{ij}^{\text{SOLT}}|$, can be used as a measure of equivalence between the two sets of measurements. This is shown in Fig. 10. Next, a deliberately poor calibration was performed using a load standard having a significant impedance mismatch (i.e., with a linear reflection coefficient of between 0.05–0.1, as shown in Fig. 9, corresponding to a worst case return loss of 20 dB) to produce a calibration that is unacceptable for most practical applications. This is a typical scenario when a “standard” may have been poorly treated during its working life time, and its level of performance degradation may not be obvious to the user. The single-component voodoo-waveguide verification kit is then reconnected and its reflection and transmission measured. As seen in Fig. 10, the error vector magnitude with poor calibration is significantly larger than for the good calibration.

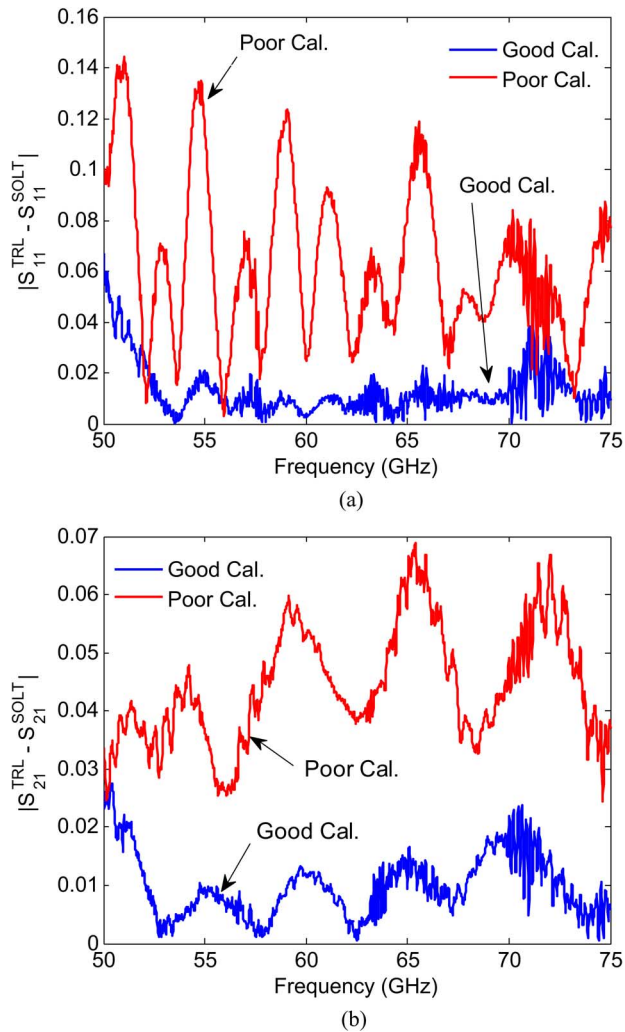


Fig. 10. Error vector magnitude in: (a) reflection and (b) transmission coefficients. The plots correspond to the case where pins are inserted into h_1 and h_2 .

A visual inspection of the plots in Fig. 10 immediately shows the problem with a poor calibration (due to the poor quality of the calibration load standard). This clearly indicates that the calibration being verified is of unacceptable quality, and thus successfully demonstrates the proof-of-concept for a single-component verification kit. For completeness, the average error across frequency, calculated using the Euclidean norm by

$$s_{ij}^e = \frac{\| \mathbf{s}_{ij}^{\text{SOLT}} - \mathbf{s}_{ij}^{\text{TRL}} \|_2}{\| \mathbf{s}_{ij}^{\text{TRL}} \|_2} \cdot 100\% \quad (2)$$

for the pin configurations shown in Fig. 5 is given in Table II. Generally, agreement between the test data (in this case, the data produced using the SOLT calibration) and the reference data (produced using PIMMS) is considered acceptable when the error vector magnitude is less than the combined expanded uncertainties for both test and reference data. These uncertainties will vary according to the type of calibration used for the VNA, the frequencies at which the measurements are made, and

TABLE II
AVERAGE PERCENTAGE ERROR, CALCULATED USING THE EUCLIDEAN NORM, IN REFLECTION AND TRANSMISSION COEFFICIENTS FOR GOOD- AND POOR-QUALITY CALIBRATIONS

Coef.	Reflection			Transmission		
	h_1 and h_2	h_1 and h_5	h_4 and h_5	h_1 and h_2	h_1 and h_5	h_4 and h_5
Good	2.1	2.4	2.4	2.4	1.7	6.3
Poor	8.4	11.7	8.5	8.9	4.1	10.3

the nominal values of the S -parameters being measured. Therefore, the uncertainties in both test and reference data need to be evaluated for each measurement situation under consideration.

It should be stated that these results have also been validated using a commercially available multi-component WR-15 verification kit. As expected, both kits were able to successfully distinguish between good and poor calibrations, enabling the end-user to either accept or reject the calibration.

IV. DISCUSSION AND CONCLUSION

A simple approach in the verification process for VNA waveguide calibration at millimeter-wave frequencies has been reported using a single-component verification kit. The strength of the proposed reconfigurable voodoo-waveguide structure is that it can easily be transformed from having a very good impedance match (when all pins are removed) to varying degrees of mismatch (by inserting different combinations of pins). Furthermore, the different pin combinations also provide varying degrees of attenuation (i.e., higher levels of attenuation are achieved when more pins are introduced). Therefore, there is a wide dynamic range of operation in both the reflection and transmission coefficient domains.

Conventional multi-component commercial waveguide verification kits are currently only available at frequencies up to 110 GHz. If such kits are made available at higher frequencies, then the necessary multiple flange connections will make them susceptible to measurement errors due to the inevitable mechanical misalignments of the waveguide interfaces. In contrast, a single-component verification kit based on introducing changes in reflection and transmission coefficients will inherently exhibit smaller errors at higher frequencies, while its reconfigurability offers a broader selection of predetermined electrical characteristics. Moreover, the time taken to reconfigure the compact verification kit is significantly reduced.

For millimeter-wave metrology, where mechanical precision is of paramount importance, this single-component verification approach represents an attractive solution. For example, the rectangular waveguide verification kit could be implemented using RF MEMS technology [10], possibly using paraffin wax microactuator technology [22], [23].

A proof-of-concept verification process has been described, based on simulations, hardware implementation, and validation measurements through comparison with reference measurements using standard WR-15 waveguide (50–75 GHz). While a relatively low millimeter-wave band has been used here, for convenience, it is believed that the same technique can be

adopted to provide calibration verification for VNAs operating at submillimeter-wave frequencies.

At higher frequencies, more sophisticated state-of-the-art machining is required for improved mechanical tolerances. With current machining technologies, hole/pin accuracies of $\lesssim 1 \mu\text{m}$ is possible. This level of accuracy is required for example at 500 GHz, where holes diameters of 100 μm could be used and is greater than the flange repeatability tolerances. Moreover, the accuracy issues associated with the hole/pin are subject to current technology limitations, and therefore, as new technologies evolve, it is likely that even higher frequency devices with better accuracies will be feasible. In this work, we have not used sophisticated machining techniques, as this is not required for our frequency range, but has the potential for much higher frequency bands. Since it has been demonstrated that the pin insertion repeatability is significantly less than the waveguide flange connection repeatability, the authors consider that this verification method can be applied to high-precision measurements, in a similar way to existing commercial verification kits.

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