Characterization and Verification of Coaxial Open-circuit Primary Standards for Millimeter-wave Vector Network Analyzer Calibration

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Abstract

***Abstract*—This paper presents a new form of primary reference standard suitable for vector network analyzer calibration at millimeter-wave frequencies. The standard comprises a calculable, frequency-dependent, capacitor terminating a section of lossy coaxial line. The standard can be realized in any of the currently available precision coaxial line sizes used at these frequencies. The paper describes the characterization (via electromagnetic modeling and precision dimensional and electrical metrology) and validation (via precision electrical measurements) of these standards. Results are presented for a series of such standards that have been realized in the 1.85 mm line size.**

***Index terms*—primary measurement standards, millimeter-waves, vector network analyzer calibration, coaxial lines.**

I. Introduction

The increasing use of the millimeter-wave part of the electromagnetic spectrum for both commercial and scientific applications is driving the need for reliable measurements to be available at these frequencies. One way to ensure reliable measurements is to use precision coaxial connectors [1] as the reference planes for such measurements. These connectors achieve low insertion and reflection loss and are also very repeatable. As the requirement for measurements has extended into the millimeter-wave range, the design of precision coaxial connectors has also been extended to deal with these higher frequencies. For example, the 1.85 mm connector [2] (operating to at least 65 GHz) was introduced in the 1980s, and the 1 mm connector [3] (operating to at least 110 GHz) was introduced in the 1990s. Both these connectors can now be found on the front panel of precision measuring instruments, such as Vector Network Analyzers (VNAs), and devices that operate at these frequencies.

The introduction of these connector types also requires that standards are available that are fitted with these connectors so that reliable measurements can be made on these VNAs. Such standards can be found in commercially available VNA calibration kits. However, there is also a need for primary reference standards as absolute references for these measurements, to ensure that traceability to the International System of units (SI) can be achieved. To date, the availability of devices that are suitable for use as primary reference standards for these line sizes has been limited. This is because there are serious difficulties in using commercially available standards as such references to provide traceability to SI. This paper discusses these traceability difficulties and goes on to propose a new type of primary reference standard that avoids these difficulties. The paper describes the characterization of the standards using precision dimensional metrology. This is followed by the verification of the standards using precision electrical (VNA) measurements.

The standard comprises a calculable open-circuit (i.e. a frequency-dependent capacitor) terminating a section of lossy coaxial line. Such standards have previously been used successfully at lower RF and microwave frequencies [4, 5]. The challenge is now to realise such standards, with sufficient accuracy and reliability, at millimeter wavelengths in the smaller precision connectors (1.85 mm and 1 mm).

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II. EXISTING COMMERCIAL STANDARDS

The traditional primary reference standard for VNA measurements at microwave frequencies is the unsupported air dielectric coaxial transmission line (or air line, for short) [6-8]. These air lines have been used to calibrate VNAs using calibration schemes such as thru-reflect-line (TRL) [9] to achieve the very highest levels of accuracy required by National Measurement Laboratories [10].

Air lines are well suited as primary reference standards because their electromagnetic properties can be calculated from first principles. These lines comprise two separate parts – a center conductor and an outer conductor. The diameters of these conductors (that define the characteristic impedance of the line) can therefore be determined easily and directly using mechanical measurement techniques (such as pneumatic gauging [11]). This shows that traceability to SI can be demonstrated easily. Air lines are therefore used regularly as primary reference standards at frequencies up to approximately 50 GHz.

However, at frequencies above 50 GHz, the line sizes become very small, i.e. 1.85 mm (for 65 GHz operation) and 1 mm (for 110 GHz operation). This reduction in size causes a number of problems:

(1) The inevitable discontinuities present at each end of the line cause significant unwanted reflections at these higher frequencies;

(2) The lines are difficult to connect due to their small size and the center conductor being unsupported;

(3) The lines are very fragile;

(4) The performance of the lines can degrade rapidly with use, due to their fragility;

(5) The lines are very expensive.

The above difficulties have led some manufacturers to introduce offset short-circuits as standards for these line sizes. Such standards can be found in VNA calibration kits for both the 1.85 mm and 1 mm lines sizes [12, 13]. These standards are used to perform three-known-loads calibrations at each VNA reference plane. However, as potential primary reference standards, these offset short-circuits have two major drawbacks:

(1) They cannot be dismantled and so it is difficult to determine the dimensions (i.e. the diameters and lengths) of the conductors. This means that it is not straightforward to demonstrate (dimensional) traceability to SI for these devices;

(2) Since the devices have fixed connectors, the center conductor will be somewhat recessed with respect to the outer conductor reference plane. Such a recession can cause significant unwanted reflections during VNA calibration, especially at millimeter-wave frequencies.

These difficulties mean that, like air lines, these offset short-circuit devices are not well suited as primary reference standards at frequencies above 50 GHz.

III. OFFSET OPEN-CIRCUITS - FABRICATION

Unsupported air dielectric coaxial line offset open-circuits (or offset open-circuits, for short) represent an alternative form of primary reference standard. They are particularly useful as standards at millimeter-wave frequencies because they do not suffer from the problems described above for air lines and offset short-circuits.

An offset open-circuit standard can be fabricated using a section of precision center conductor of the required length fitted with either a male pin or a female socket, as appropriate. A length of precision outer conductor is then connected that extends sufficiently beyond the point where the center conductor is truncated thus forming an effectively infinite length of circular waveguide below cutoff. This produces a well-defined open-circuit offset by a desired length of line (i.e. the length of line, l, that extends beyond the VNA test port reference plane) – see Figure 1. Note that there is no 'gap' in the center conductor where it joins the VNA test port reference plane. This is because the connections of the center and outer conductors of the offset open-circuit to the VNA test port are made independently. The center conductor of the offset open-circuit can therefore be pushed fully on to the test port center conductor pin (or socket) removing any gap due to the specification tolerance of the VNA test port.[1]

In practice, it is desirable to keep the line length of the offset open-circuit as short as possible. This ensures that the offset section remains acceptably concentric. With this in mind, to date, five offset open-circuits have been manufactured in both male and female configurations. The offset lengths have been chosen to be 5 mm, 6 mm, 7 mm, 8 mm and 9 mm.

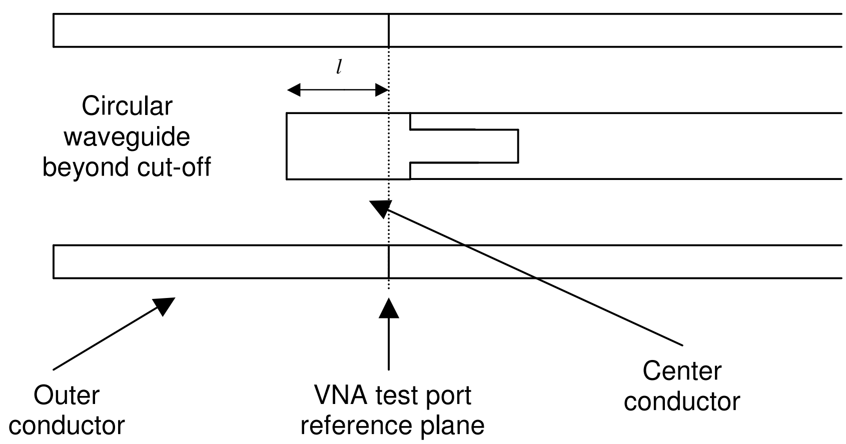

Figure 1: The realization of a calculable coaxial offset open-circuit standard

IV. DIMENSIONAL CHARACTERIZATION

The characterization of an offset open-circuit standard is achieved by determining the mechanical (i.e. dimensional) properties of the conductors of the standard – specifically, the diameters of the center and outer conductors, and, the length and any lack of concentricity of the center conductor. These measurements are described below.

A. Diameter Measurements

The diameters of the center conductors are measured using a Laser Gauge Measurement System (LGMS). Some typical results are shown in Figure 2(a) (for the 5 mm male center conductor) and Figure 2(b) (for the 5 mm female conductor).[2] These measurements show good agreement with the nominal value of 0.803 mm for this center conductor diameter. However, the diameter values in Figure 2(b) show a significant increase (to more than 0.815 mm) at one end of the line. This is the section of the line that contains the slots needed to realize the female socket.

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[1] Note that if the recession of the VNA test port is considerable, then attaching the open-circuit will change the 'appearance' of the test port during calibration. For a recessed test port, there will be a discontinuity (gap) in the center conductor for a device with a fixed connector whereas for the offset open-circuit there will be no gap. It is therefore recommended that a VNA test port is used that has minimal recession (e.g. by using a precision adaptor), thus minimizing this change of 'appearance' effect.

[2] All measurements presented in this paper were made by NMIJ, Japan. A subset of these measurements was also made by NPL, UK. The NPL measurements were used for cross checking purposes.

The uncertainties of these measurements are also shown in these figures. These uncertainties are of the order of ±2 µm (at a level of confidence of 95%) for most of these measurements.

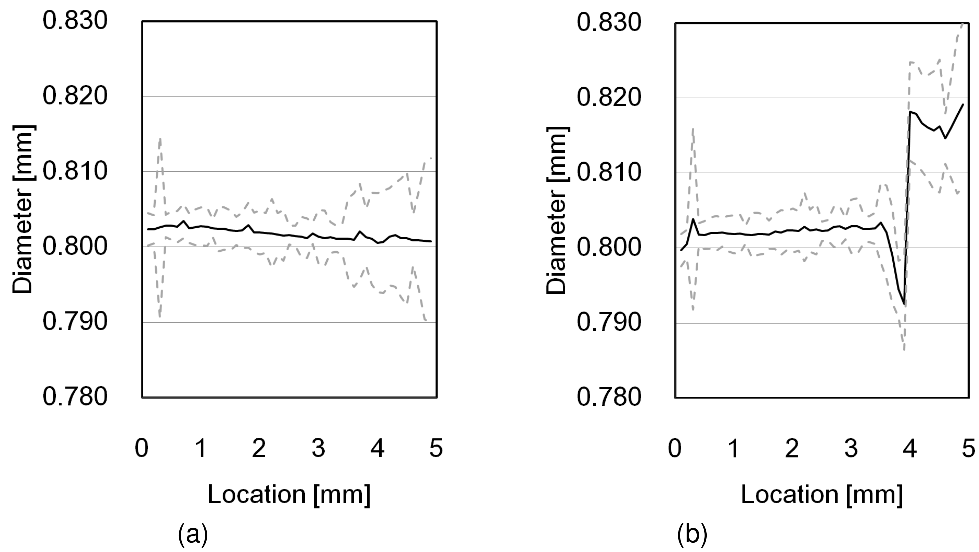

Figure 2: Diameter measurement result of 5 mm long center conductor (a) male (b) female, Black solid lines and gray broken lines indicate average diameter and expanded uncertainty limits. The connector end is located at the 5 mm location.

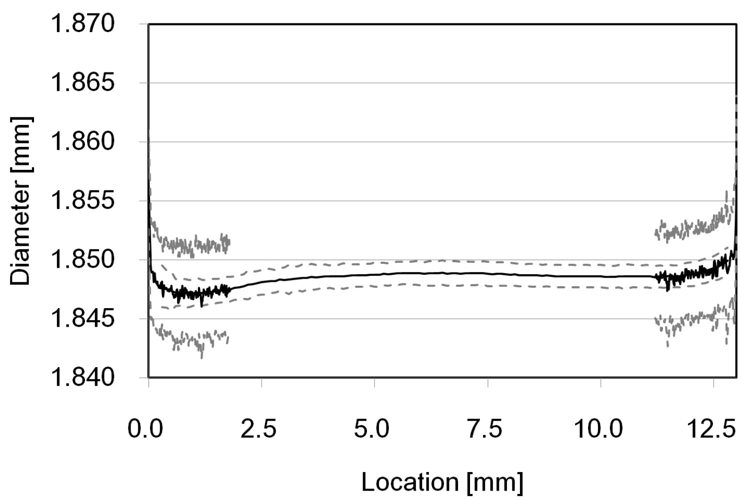

Figure 3: Diameter measurement result of 13 mm long outer conductor, Black solid lines and gray broken lines indicate average diameter and expanded uncertainty limits. The male connector end is located at the 0 mm location.

The internal diameters of the outer conductors are measured using an Air Gauging Measurement System (AGMS) and a three-dimensional Coordinate Measuring Machine (CMM). Some typical results are shown in Figure 3 (for an outer conductor that is 13 mm in length). These measurements show that the diameter of this outer conductor is slightly less than the nominal value of 1.85 mm for the outer conductor diameter. The uncertainties of these measurements are also shown in this figure. These uncertainties are of the order of ±1 µm (at a level of confidence of 95%) for most of these measurements.

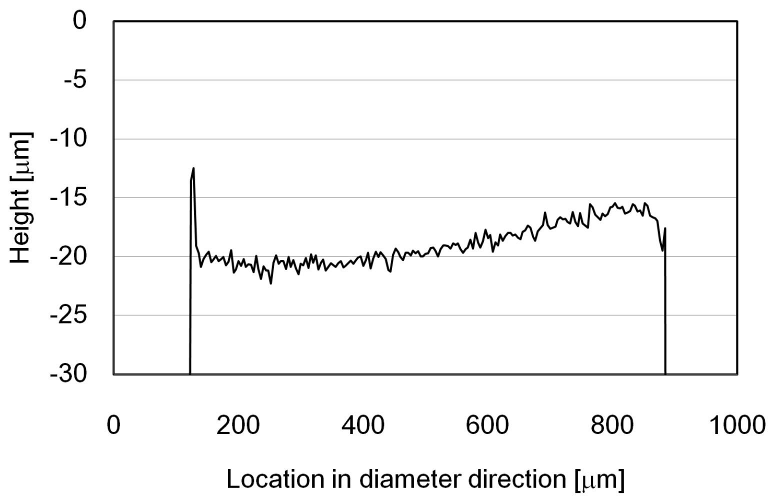

Figure 4: Cross sectional view of the top ('flat') surface of the open-circuit.

B. Length measurement

The lengths of the center conductors are measured using a Laser Displacement Measurement System (LDMS). The cross sectional view of the top ('flat') surface of the open-circuit is also measured using the LDMS [14]. An example is shown in Figure 4. This shows that there is a variation in flatness across this surface of approximately 10 μm. This becomes the major component to the uncertainty for the overall determined length of the center conductor. All measured lengths were within 15 μm of their nominal values. The LDMS is also used to examine the structure of the female center conductor socket.

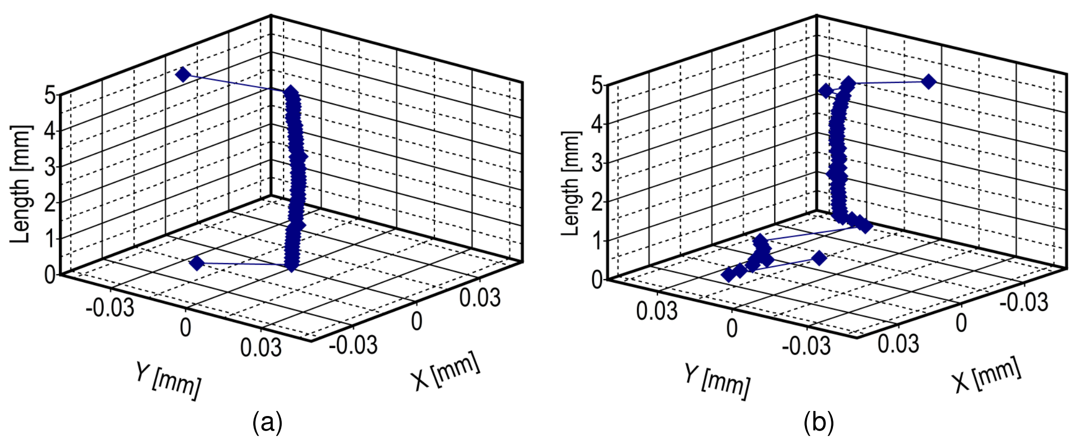

Figure 5: straightness of the center conductor (a) male (b) female. The end of the conductor containing the connector is located at the 0 mm location.

In addition, the straightness of the center conductor is measured using the LGMS and a Mechanical Displacement Measurement System (MDMS). Example measurements are shown in Figure 5(a) (for the 5 mm male center conductor) and Figure 5(b) (for the 5 mm female center conductor).

V. ELECTRICAL VERIFICATION

The verification of an offset open-circuit standard is achieved by measuring the electrical performance of the device when connected to a calibrated VNA using TRL calibration with different lines [15] – specifically, the Voltage Reflection Coefficient (VRC), magnitude and phase, is measured over a broad range of frequencies (to at least 67 GHz). These measurements, and their subsequent use to verify the performance of the realized standard, are described below.

A. Loss Measurement

The measurement of the linear VRC magnitude, $|\Gamma|$, of the offset open-circuits, as a function of frequency, establishes the electrical loss in the standard. Some typical results are shown in Figure 6 (for the 5 mm male offset open-circuit). The observed loss (i.e. $|\Gamma| < 1$) is expected to be due primarily to the finite conductivity (i.e. non-zero resistivity) of the conductors of the line section of the standard. Estimates for the observed resistivity of the conductors of the line section can be obtained from the measured values of $|\Gamma|$ by adapting an expression given in [16]. This is described below.

For a perfectly reflecting open-circuit with offset line length, l, the attenuation constant, α, of the offset line section is related to a VRC, Γ, by:

$$\alpha = \frac{-\log_e |\Gamma|}{2l} \tag{1}$$

It has been shown that [17], to a first-order approximation, the resistivity, ρ, of a line is related to α as follows:

$$\rho \approx \left[\frac{200\alpha b}{1 + (b/a)} \right]^2 \frac{\pi}{\mu_0 f} \tag{2}$$

where a and b are the radii of the line's center and outer conductor, respectively, f is the frequency and μ_0 is the permeability of free-space ($4\pi \times 10^{-7}$ H/m).

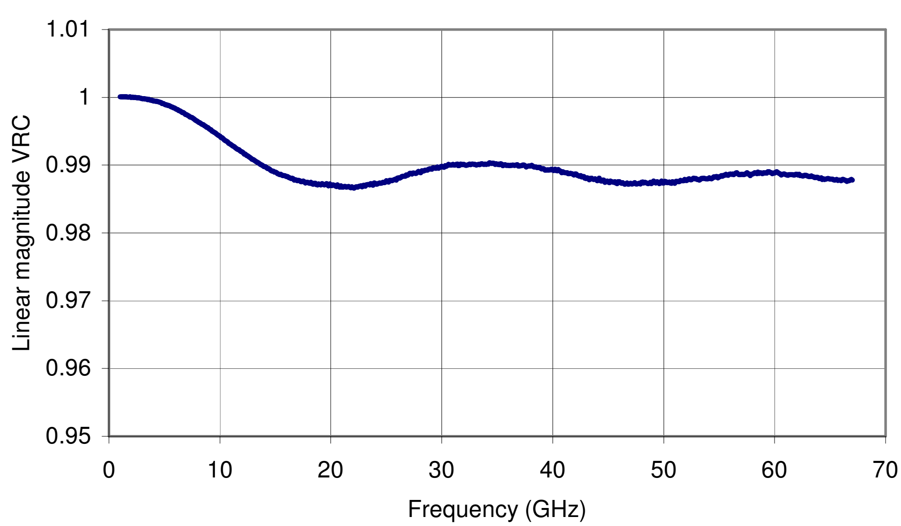

Figure 6: Measured linear magnitude Voltage Reflection Coefficient (VRC), as a function of frequency, for the 5 mm male offset open-circuit

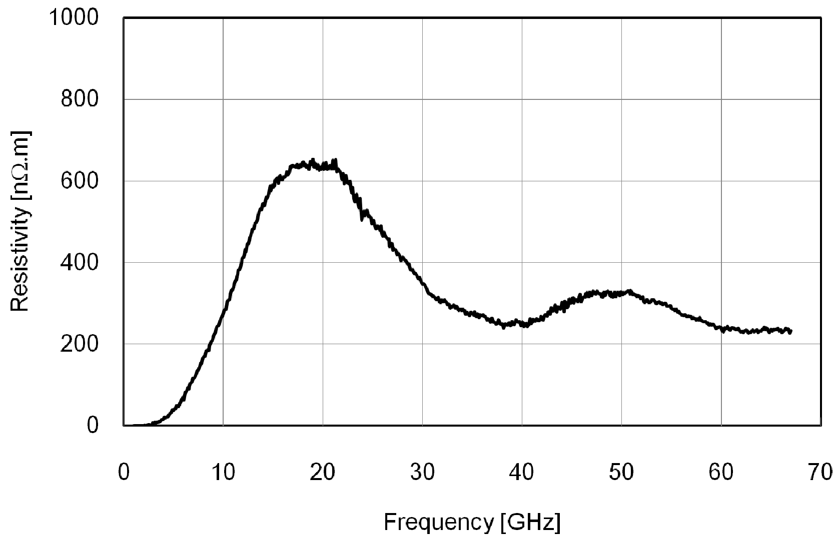

Figure 7: Calculated resistivity, as a function of frequency, for the 5 mm male offset open-circuit

We can therefore use equations (1) and (2) to determine the resistivity of the conductors used for the line section of the offset open-circuit. Figure 7 shows values of resistivity, as a function of frequency, derived from the VRC data shown in Figure 6, for the 5 mm male offset open-circuit. The average value of resistivity for this standard is 290 nΩ.m. This value compares favorably with values determined previously for air lines in the 1.85 mm line size [18, 19].

B. Capacitance Measurement

The shunt capacitance due to the truncation of the center conductor can be estimated from the VRC, Γ, measured at the input of the offset open-circuit, the mechanical dimensions of the open-circuit (radius of the center conductor, *a*, radius of the outer conductor, *b*, and the offset length, *l*) and the resistivity, ρ, of the open-circuit conductors (determined as described in Section *A*). The procedure used to determine the capacitance is as follows:

1. The complex-valued characteristic impedance Z_0 and propagation constant, γ, of the section of lossy coaxial line comprising the open-circuit offset are estimated from the cross-sectional dimensions (*a* and *b*) and resistivity (ρ) using the method described in [20].

2. The measured VRC, Γ, at the input of the open-circuit (normalized to a characteristic impedance of 50 Ω) is renormalized [21] to the characteristic impedance of the lossy line, Z_0, and then transformed a distance, *l*, along the lossy line to the point where the center conductor is truncated according to the following equation $\Gamma_C = \Gamma \exp(2\gamma l)$. When Γ_C is renormalized from Z_0 to 50 Ω, the resulting VRC, Γ_{C0}, has (approximately) unit magnitude and phase θ.

3. The impedance, *Z*, at the plane of truncation of the center conductor is purely capacitive:

$$Z = \frac{1}{j\omega C} = 50\frac{1+\Gamma_{C0}}{1-\Gamma_{C0}} = 50\frac{1+\exp(j\theta)}{1-\exp(j\theta)}$$

where ω is the angular frequency. Hence the open-circuit shunt capacitance, *C*, is given by

$$C = -\frac{1}{50\omega}\tan\frac{\theta}{2}.$$

4. The frequency dependent capacitance, *C*, can be represented by a third-order polynomial:

$$C(f) = C_0 + C_1 f + C_2 f^2 + C_3 f^3.$$

The polynomial coefficients, C_0, C_1, C_2 and C_3, can be estimated by a least-squares polynomial fit to the capacitance data. The uncertainties in the capacitance coefficients and the correlation between them can be estimated from the measured VRC, Γ, and its uncertainty using a Monte-Carlo method as described in [22].

For the male 5 mm offset open-circuit, the phase of the VRC, Γ_{C0}, at the plane where the center conductor is truncated is plotted in Figure 8 and the shunt capacitance, *C*, is plotted in Figure 9. Table 1 presents the polynomial capacitance coefficients with uncertainties derived from the measured VRC[3] and, for comparison, modelled capacitance coefficients taken from [23].

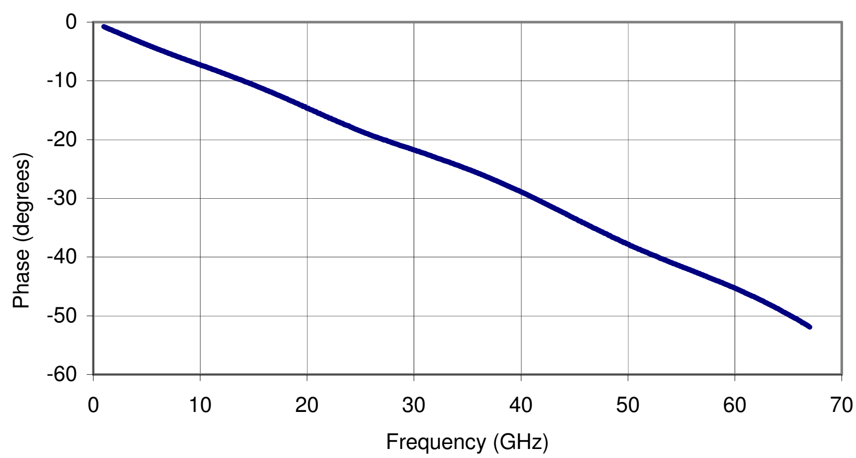

Figure 8: Phase of VRC at plane of truncation of center conductor (normalized to 50 Ω) for male 5 mm offset open-circuit

Table 1: Comparison of measured and modelled capacitance coefficients for the male 5 mm offset open-circuit

Capacitance coefficient	Measured	Modelled
$C_0/10^{-15}$ (F)	(19.99 ± 0.20)	21.05
$C_1/10^{-27}$ (F/Hz)	(13.69 ± 18.76)	4.53
$C_2/10^{-36}$ (F/Hz^2)	(-0.16 ± 0.52)	0.33
$C_3/10^{-45}$ (F/Hz^3)	(0.09 ± 0.04)	0.01

[3] On this occasion, the VNA uncertainties were not derived from complete uncertainty budgets. Therefore, the resulting uncertainties in the capacitance coefficients do not represent overall uncertainties and so will be significantly less than expanded uncertainties quoted at the usual 95 % level of confidence.

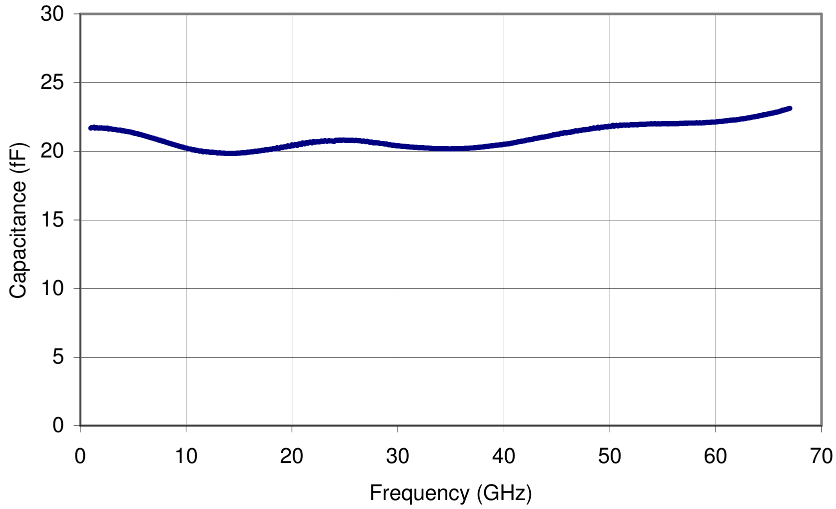

Figure 9: Shunt capacitance at plane of truncation of center conductor (normalized to 50 Ω) for male 5 mm offset open-circuit

VI. Connection Repeatability

Another key performance metric for any measurement standard is the ability to achieve very good connection repeatability. This is particularly true for standards used to calibrate VNAs and also for standards used at millimeter-wave frequencies. Therefore assessments have been made of the connection repeatability of the offset open-circuit standards used during this investigation.

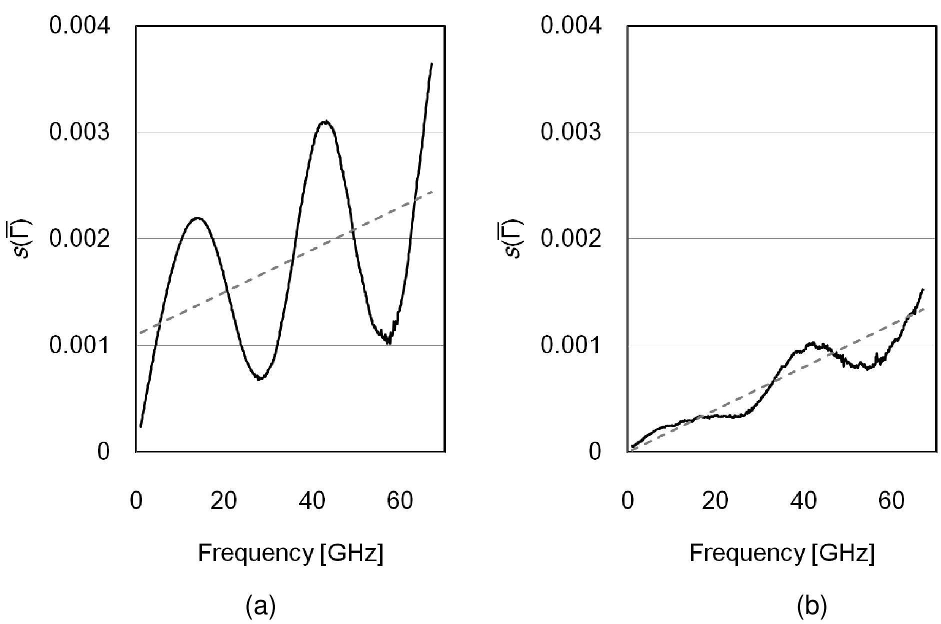

Figure 10: calculated values of $s(\overline{\Gamma})$ for the offset open-circuits (a) male connector (b) female connector. Black solid lines and Gray broken lines indicate value of $s(\overline{\Gamma})$ and fitting function of $s(\overline{\Gamma})$.

One method of measuring and quantifying the repeatability of a device is to calculate the experimental standard deviation in the mean from a series of disconnects and reconnects of the same device to the same instrument test port (performed under essentially the same operating conditions). In the case of a one-port device (such as these offset open-circuits), this calculation can be applied to the measured linear VRC, Γ. For a series of *n* repeat measurements of Γ, the experimental standard deviation in the mean is given by:

$$s(\overline{\Gamma}) = \frac{s(\Gamma_k)}{\sqrt{n}} \tag{3}$$

where

$$s(\Gamma_k) = \sqrt{\frac{1}{(n-1)} \sum_{k=1}^{n} \left| \Gamma_k - \overline{\Gamma} \right|^2} \tag{4}$$

where $\overline{\Gamma}$, the arithmetic mean of the *n* measurements, is given by:

$$\overline{\Gamma} = \overline{\Gamma_{\mathrm{Re}}} + j.\overline{\Gamma_{\mathrm{Im}}} = \frac{1}{n}\left(\sum_{k=1}^{n} \Gamma_{\mathrm{Re}_k} + j \sum_{k=1}^{n} \Gamma_{\mathrm{Im}_k} \right) \tag{5}$$

where Γ_{Re} and Γ_{Im} are the real and imaginary parts of Γ, respectively.

Equations (3) to (5) are used to calculate values of $s(\overline{\Gamma})$ for the offset open-circuits used during this investigation. For example, Figure 10(a) shows a plot of $s(\overline{\Gamma})$, as a function of frequency, for the 5 mm male offset open-circuit and Figure 10(b) shows a similar plot for the 5 mm female offset open-circuit. These figures show that the value of $s(\overline{\Gamma})$ for both types of offset open-circuit can be roughly fitted with a function ($2 \times 10^{-5} f$ [GHz] + *const)*, with *const* being 0 for the male connector and 0.0011 for the female connector.

VII. Summary

This paper has described the characterization and verification of a new form of primary measurement standard suitable for calibrating Vector Network Analyzers at millimeter-wave frequencies – the unsupported air dielectric coaxial line offset open-circuit. The characterization has been achieved by performing a series of high precision dimensional measurements on the conductors that constitute the line section of the standard. These dimensional measurements can be used to determine the electrical performance of the standards over the full bandwidth of operation (i.e. DC to more than 67 GHz). The dimensional measurements also provide traceability to SI – specifically, to the SI Base Unit, the meter.

After characterizing the standards dimensionally, their performance has been verified using electrical measurements (of VRC), made using a VNA. The magnitude of the VRC measurements indicates the loss (due to the non-zero resistivity of the lines' conductors). The phase of the VRC measurements indicates the shunt capacitance of the open-circuit that terminates the line section. The values of resistivity and capacitance are compared with published values and this verifies the performance of these offset open-circuit standards. (The resistivity values are also used to determine the phase constant for the line section in the presence of loss. This forms part of the overall characterization of the standards.)

It is believed that standards of this type will play an important role in providing traceability for measurements made using Vector Network Analyzers in coaxial lines operating at millimeter-wave frequencies.

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