Characterizing a Noninsertable Directional Device Using the NIST Uncertainty Framework

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Abstract — We characterize and provide uncertainties for a noninsertable, directional device over a frequency range of 90 to 100 GHz using the NIST Microwave Uncertainty Framework in conjunction with a commercial vector network analyzer. Our device consists of a chain of components, including a coaxial-to-waveguide adapter, a waveguide band-pass filter, a waveguide low-noise amplifier, a waveguide isolator, and a waveguide taper. With the aforementioned directional components, the well-known adapter removal technique is not adequate on its own for characterizing our device. In this paper, we describe and implement our method, and propagate the uncertainties from the two required calibrations to the characterized device.

Index Terms — Characterize, coaxial, directional, noninsertable, rectangular waveguide, uncertainty, vector network analyzer.

I. INTRODUCTION

Noninsertable devices, such as adapters with the same-sex or different-size coaxial connectors, and microwave probes with one port typically coaxial or rectangular waveguide and the other coplanar waveguide, are commonly encountered in high-frequency applications. Characterizing these devices poses a challenge since they cannot be characterized by use of a single vector network analyzer (VNA) calibration. Several methods [1–5], including the well-known adapter-removal technique [6], have been developed over the years for characterizing noninsertable adapters and probes. However, none of them are adequate on their own when the noninsertable device transmits power in one direction only, such as an isolator or amplifier. In this case, if the device is comprised of a noninsertable adapter connected to an insertable directional component, the adapter can be characterized by use of the adapter removal technique or one of its variants, the insertable directional component can be characterized using a single VNA calibration, and then the overall device may be characterized by cascading the two resultant S -parameter matrices.

Here, we implement this multi-step approach utilizing the NIST Uncertainty Framework [7–9] to propagate uncertainties. The Framework is based on a covariance-matrix description that enables us to capture all of the S -parameter measurement uncertainties and statistical correlations between them [10]. By identifying and modeling the physical error mechanisms in the calibration standards, we can determine the statistical correlations between uncertainties at different

frequencies. These covariance-based uncertainties can then be propagated into the uncertainties of the S -parameters of the noninsertable, directional device. This is particularly valuable when transforming from the frequency domain to the time domain.

In the following sections, we describe our measurement methodology and error mechanisms, and present our results.

II. METHODOLOGY

Our device under test consisted of a chain of components, including a 1 mm coaxial-to-WR-10 waveguide adapter, a WR-8 waveguide band-pass filter (BPF), a WR-8 waveguide low-noise amplifier, a WR-8 waveguide isolator, and a WR-8-to-WR-10 waveguide taper, as shown in Figure 1. This device will be used in conjunction with a characterized photodiode and sampling oscilloscope [11] to calibrate a down-converter.

Because our device is comprised of a noninsertable adapter connected to additional components, two of which are directional, we first characterize the adapter by use of a technique that determines the S -parameters of the adapter from two one-tier calibrations [7]. The first calibration is performed at a reference plane to the left of the adapter (in our case, WR-10 rectangular waveguide) with the adapter connected to port 2, and the second calibration is performed at a reference plane to the right of the adapter (in our case, 1 mm coax) with the adapter connected to port 1, as illustrated in Figure 1. The first estimate for the adapter S -parameters comes from the difference of the left calibration's port 1 error box (port 1 VNA terms only) and the right calibration's port 1 error box (port 1 VNA terms and adapter). The second estimate for the adapter S -parameters comes from the difference of the left calibration's port 2 error box (adapter and port 1 VNA terms) and the right calibration's port 2 error box (port 2 VNA terms only). The two estimates are then averaged.

During the left calibration (in WR-10 rectangular waveguide), we also measure our device chain without the adapter. Using the WR-10 calibration, we can characterize this portion of our device. Then, once the adapter is characterized using the two calibrations, we characterize the overall device by cascading the two resultant S -parameter matrices.

Our WR-10 calibration kit consisted of a flush short, a thru connection, and three delay lines of differing lengths. Using these measurements, along with their respective definitions (i.e., lengths, widths, etc.) and associated uncertainties, listed

in Table I, we calibrated the VNA utilizing the NIST Microwave Uncertainty Framework, which resulted in a set of calibration coefficients along with uncertainties. The Uncertainty Framework [7–9] was employed to construct models for the calibration standards, and was used for propagating the uncertainties to the calibrated DUTs in conjunction with the calibration engine, StatistiCAL™ [12–13], which accommodates most coaxial, waveguide, and on-wafer standards. For our WR-10 calibration, we assumed the thru and flush short to be ideal, while the delay lines were modeled using closed-form expressions for waveguides with finite metal conductivity [14].

Our 1 mm coaxial calibration kit consisted of four offset shorts of differing lengths, an open, a load, and a thru connection. The offset short standards were modeled using closed-form expressions for coaxial lines with finite metal conductivity [15]. Table II lists the offset lengths and associated uncertainties for the short standards, and Table III lists the other sources of uncertainty. Our values and distributions of the uncertainties come from a variety of sources, including previous publications [15], manufacturers’ specifications, and an IEEE standard [16]. We assumed the thru to be ideal, while the load and open models were derived from DC measurements and an offset-short calibration above 20 GHz. The model for the load standard consisted of a rational function, while the model for the open was comprised of a short transmission line terminated with a capacitor. Both models were fit to measured data using a nonlinear least squares procedure [17]. Uncertainties for the load and open models were estimated from the uncertainties in the measurements from which they were derived.

III. RESULTS

Utilizing the NIST Microwave Uncertainty Framework, we were able to characterize our noninsertable, directional device and provide uncertainties that have been propagated through from both calibrations. Figure 2 plots the magnitudes of the calibrated S -parameters of the device over the measured frequency range of 90 to 100 GHz. As expected, the values of the S_{21} transmission terms are very low, while the values of S_{12} are as high as 15.32 dB due to port 2 being on the input side of the amplifier and isolator. Although the amplifier is specified to have a gain of approximately 22 dB, the loss of the other components lowers the overall gain of the device. The values of S_{12} taper off at the lower and higher frequencies due to the bandpass filter, which has a center frequency of 94 GHz. Likewise, the reflection terms on port 2 (S_{22}) are very high at the lower and higher frequencies because of the filter.

Figures 3 and 4 display the magnitudes and 95 % confidence intervals of S_{12} and S_{22} , respectively, from 93 to 96 GHz. Over the entire frequency range, the mean confidence intervals are ± 0.038 dB for S_{12} and ± 0.599 dB for S_{22} . The physical error mechanisms that contribute most to the overall uncertainties are those of the WR-10 line lengths.

TABLE I
PHYSICAL ERROR MECHANISMS FOR THE WR-10 STANDARDS

Mechanism (units)	Value $\pm$ Uncertainty (Distribution)
Thru Length (mm)	0.000 ± 0.005 (Rectangular)
Line 1 Length (mm)	2.105 ± 0.005 (Rectangular)
Line 2 Length (mm)	3.157 ± 0.005 (Rectangular)
Line 3 Length (mm)	4.209 ± 0.005 (Rectangular)
Width (mm)	2.540 ± 0.005 (Rectangular)
Height (mm)	1.270 ± 0.005 (Rectangular)
Metal Resistivity Relative to Cu	2 ± 1 (Rectangular)

TABLE II
LENGTHS AND UNCERTAINTIES OF 1 MM OFFSET SHORT STANDARDS

Offset Short Designation	Female Connector Length (mm) $\pm$ Uncert. (Distribution)	Male Connector Length (mm) $\pm$ Uncert. (Distribution)
Short 1	1.2869 ± 0.008 (Rect.)	1.2883 ± 0.008 (Rect.)
Short 2	1.8119 ± 0.008 (Rect.)	1.8133 ± 0.008 (Rect.)
Short 3	2.4369 ± 0.008 (Rect.)	2.4383 ± 0.008 (Rect.)
Short 4	2.9869 ± 0.008 (Rect.)	2.9883 ± 0.008 (Rect.)

TABLE III
PHYSICAL ERROR MECHANISMS FOR THE 1MM OFFSET SHORTS

Mechanism (units)	Value $\pm$ Uncertainty (Distribution)
Inner Conductor Diameter (mm)	0.434 ± 0.003 (Rectangular)
Outer Conductor Diameter (mm)	1.000 ± 0.005 (Rectangular)
Pin Diameter (mm)	0.250 ± 0.005 (Rectangular)
Pin Length (mm)	0.005 ± 0.005 (Rectangular)
Metal Conductivity (S/m)	$7.3 \times 10^6 \pm 1.7 \times 10^6$ (Rectangular)
Relative Dielectric Constant	1 ± 0 (Rectangular)
Dielectric Loss Tangent	0 ± 0 (Rectangular)

Fig. 1. Measurement set-up for characterizing a noninsertable directional device that consists of a 1 mm coaxial-to-WR-10 waveguide adapter, a WR-8 waveguide band-pass filter, a WR-8 waveguide low-noise amplifier, a WR-8 waveguide isolator, and a WR-8-to-WR-10 waveguide taper.

Fig. 2. Magnitudes of the scattering parameters for the noninsertable directional device.

Fig. 3. Magnitude of S_{12} for the device along with 95 % confidence intervals.

Fig. 4. Magnitude of S_{22} for the device along with 95 % confidence intervals.

IV. CONCLUSION

We have characterized and provided uncertainties for a noninsertable, directional device from 90 to 100 GHz by use of the NIST Microwave Uncertainty Framework. Although other sources of uncertainty may be included in a final uncertainty analysis, we believe these minor additions will not significantly increase the overall uncertainty.

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