Developing Models for a 0.8 mm Coaxial VNA Calibration Kit within the NIST Microwave Uncertainty Framework

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***Abstract* — We developed models for a 0.8 mm coaxial vector network analyzer (VNA) calibration kit within the NIST Microwave Uncertainty Framework. First, we created physical models of commercially-available standards and included error mechanisms in each of the standards' constituent parameters that were utilized to propagate uncertainties. Next, we calibrated a network analyzer with this calibration kit and compared measurements and uncertainties of two verification devices with data provided by the manufacturer. We found the measurements agreed to within their respective uncertainties.**

***Index Terms* — calibration, coaxial, physical models, uncertainty, vector network analyzer, verification.**

I. INTRODUCTION

With the demand for faster data-transfer rates, the wireless industry continues to develop technology in the millimeter-wave (30-300 GHz) spectrum. One potential impediment is the connector interface. Typically, waveguides are used at higher frequencies since they are easier to manufacture and less lossy than coaxial lines. The main disadvantage of waveguides, however, are their limited bandwidths, precluding broadband frequency coverage. As an alternative, 0.8 mm coaxial connectors have recently been developed that provide uninterrupted coverage up to 145 GHz [1-2].

Researchers at the National Institute of Standards and Technology (NIST) are actively pursuing research in millimeter-wave frequencies, including small- and large-signal network analysis, modulated-signal characterization, over-the-air (OTA) testing for advanced cellular applications, antenna metrology, channel measurements and modeling [3], and mismatch correction for electro-optic sampling (EOS).

The EOS system at NIST is the United States' primary standard for high-speed waveform calibration of photodiodes and is traceable to the SI through fundamental physics. A photodiode calibrated using this system serves as a time- and frequency-domain transfer standard and allows for subsequent calibrations of high-speed oscilloscopes, light-wave component analyzers, comb generators, and high-speed modulated signals [4]. To calculate the electrical waveform at the photodiode's coaxial connector from the voltage measured in the coplanar waveguide (CPW) by the EOS system, a change in reference plane is required. This requires vector network analysis to characterize the reflection coefficients of the photodiode and on-wafer resistor, as well as the scattering-parameters (*S*-parameters) of the probe head. Currently, the EOS system is limited to 110 GHz due to the 1.0 mm coaxial connectors on the photodiode and probe head. If these two devices were fitted with 0.8 mm coaxial connectors and characterized with correlated uncertainties, the EOS system could provide calibrated photodiodes at frequencies up to 145 GHz.

With extending the EOS capabilities as one of our prime motivators, we utilized the NIST Microwave Uncertainty Framework (MUF) [5] to develop physical models of a commercially-available 0.8 mm coaxial calibrations kit. The MUF utilizes parallel sensitivity and Monte-Carlo analyses, and enables us to capture and propagate the significant *S*-parameter measurement uncertainties and statistical correlations among them [6]. By identifying and modeling the physical error mechanisms in the calibration standards, we can determine the uncertainties in *S*-parameters, including their cross-frequency correlations. These uncertainties can then be propagated to measurements of devices under test. In the following sections, we describe our methodology in further detail, and compare measurements and uncertainty estimates made on two verification devices with data provided by the manufacturer.

II. MODEL DEVELOPMENT

Our commercial 0.8 mm calibration kit consisted of two sets of standards – male and female offset opens, offset shorts, and loads (OSL) for frequency coverage up to 80 GHz, and three pairs of offset shorts (SSS) with differing lengths for frequency coverage between 80 GHz and 145 GHz [7]. The manufacturer included dimensions and uncertainties for the offset lengths and inner and outer conductor diameters, as well as polynomial models for each of the standards.

Using the MUF, we constructed our own physical models of the calibration standards with closed-form expressions for coaxial lines of finite metal conductivity [8]. The MUF was also used for automatically propagating the uncertainties to the calibrated verification devices in conjunction with the calibration engine, StatistiCAL [9-10], which utilizes a "mix-and-match" philosophy to VNA calibrations.

In our previous work with Type-N, 3.5 mm, and 2.4 mm coaxial calibrations standards, we have compared our physical models to measurements of the standards performed with an independent multiline thru-reflect-line (TRL) calibration [11-12]. Since we do not have access to any 0.8 mm airlines, we were unable to do so here. However, we did compare our physical models to the manufacturer's polynomial models and optimized our inductances and capacitances to match the frequency responses of the manufacturer's standards, especially with regards to the phase delays.

The low-band (< 80 GHz) OSL standards were modeled with the values and uncertainties (standard errors) listed in Tables I and II. Table I lists the physical error mechanisms related to the inner and outer conductors and pins of the offset transmission lines, and Table II lists the physical error mechanisms specific to the pairs of opens, shorts, and loads. The high-band (80 GHz to 145 GHz) offset-short (SSS) standards were modeled with the values and uncertainties listed in Tables I and III. Table III lists the physical error mechanisms specific to the offset shorts. The thru connection was modeled as a zero-length transmission line and included error mechanisms.

Table I. Physical error mechanisms of the 0.8 mm calibration standards.

Mechanism (units)	**Value ± Uncertainty**
Inner Conductor Diameter (mm)	0.347 ± 0.003
Outer Conductor Diameter (mm)	0.8 ± 0.003
Pin Diameter (mm)	0.2 ± 0.003
Pin Depth (mm)	-0.010 ± 0.005
Metal Conductivity (S/m)	$6\times10^6 \pm 5\times10^6$
Relative Dielectric Constant	1.000535 ± 0
Dielectric Loss Tangent	0 ± 0

Table II. Physical error mechanisms of the 0.8 mm OSL standards.

Mechanism (units)	**Value ± Uncertainty**
OPEN	
Male Offset Length (mm)	1.2 ± 0.013
Male Capacitance (pF)	0.012 ± 0.002
Male Conductance (1/Ω)	0 ± 0
Female Offset Length (mm)	1.2 ± 0.013
Female Capacitance (pF)	0.0124 ± 0.002
Female Conductance (1/Ω)	0 ± 0
SHORT	
Male Offset Length (mm)	1.2 ± 0.013
Male Inductance (nH)	0.0042 ± 0.002
Male Resistance (Ω)	0 ± 0.1
Female Offset Length (mm)	1.2 ± 0.013
Female Inductance (nH)	0.0042 ± 0.002
Female Resistance (Ω)	0 ± 0.1
LOAD	
Male Resistance (Ω)	50.2 ± 0.1
Male Inductance (nH)	0.006 ± 0.002
Male Shunt Capacitance (pF)	0.0001 ± 0
Female Resistance (Ω)	50.2 ± 0.1
Female Inductance (nH)	0.010 ± 0.002
Female Capacitance (pF)	0.0001 ± 0

Table III. Physical error mechanisms of the 0.8 mm SSS standards.

Mechanism (units)	**Value ± Uncertainty**
SHORT 1	
Male Offset Length (mm)	1.2 ± 0.013
Male Inductance (nH)	0.005 ± 0.002
Male Resistance (Ω)	0 ± 0.1
Female Offset Length (mm)	1.2 ± 0.013
Female Inductance (nH)	0.0057 ± 0.002
Female Resistance (Ω)	0 ± 0.1
SHORT 2	
Male Offset Length (mm)	1.63 ± 0.013
Male Inductance (nH)	0.007 ± 0.002
Male Resistance (Ω)	0 ± 0.1
Female Offset Length (mm)	1.63 ± 0.013
Female Inductance (nH)	0.00535 ± 0.002
Female Resistance (Ω)	0 ± 0.1
SHORT 3	
Male Offset Length (mm)	2.06 ± 0.013
Male Inductance (nH)	0.002 ± 0.002
Male Resistance (Ω)	0 ± 0.1
Female Offset Length (mm)	2.06 ± 0.013
Female Inductance (nH)	0.0005 ± 0.0005
Female Resistance (Ω)	0 ± 0.1

III. Measurement Comparison

Figure 1 illustrates our VNA measurement configuration. One VNA, equipped with 1 mm test ports, enabled us to make measurements at frequencies up to 110 GHz (200 MHz spacing, 20 Hz IF bandwidth, and -10 dBm output power), and the other VNA, equipped with WR-8 test ports, allowed us to measure at frequencies between 90 GHz and 140 GHz (100 MHz spacing, 10 Hz IF bandwidth, and -10 dBm output power). Both VNAs were equipped with 0.8 mm adapters (Port 1 being female and Port 2 being male). Even though our OSL standards (low-band) were specified by the manufacturer up to only 80 GHz, we used them to 110 GHz since our VNA equipped with 1 mm test ports had the capability to measure these frequencies. Our SSS standards (high-band) were measured from 90 GHz to 140 GHz using the VNA equipped with WR-8 test ports. Thus, the two calibrations overlapped between 90 GHz and 110 GHz.

Figures 2-5 show calibrated *S*-parameters and corresponding confidence bounds calculated for the two verification devices – a Beatty line and a matched airline. The dark red curves correspond to the manufacturer's values using the OSLT calibration up to 80 GHz, and the light red curves correspond to the manufacturer's values using the SSST calibration from 80 GHz to 140 GHz. The dark blue curves correspond to our measured values using the OSLT calibration up to 110 GHz, and the light blue curves correspond to our measured values using the SSST calibration from 90 GHz to 140 GHz. The dashed curves correspond to confidence bounds, in our case at 95% intervals.

In Figures 2-5, we see that our measurements appear to be noisier than those provided by the manufacturer. This may be in part due to our frequency spacing being 100 or 200 MHz and the manufacturer's being 1 GHz. Our confidence intervals were also smaller in general but did not include a repeatability component. The manufacturer stated their confidence intervals were "extremely conservative" and "include a large budget for cable flex and connector repeatability."

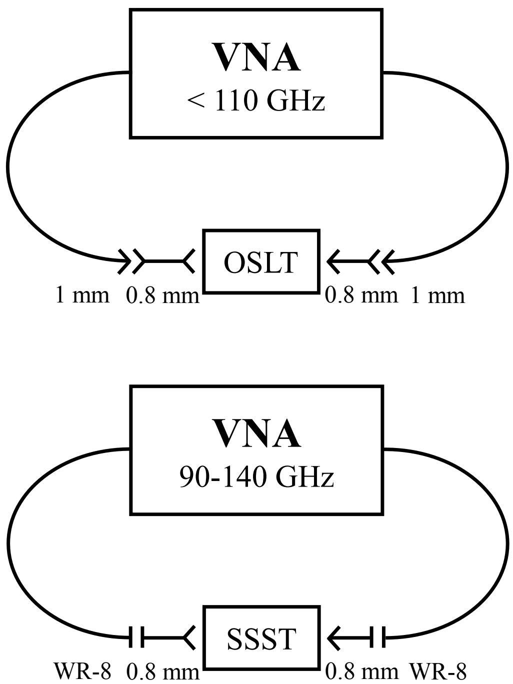

Figure 1. VNA measurement configuration.

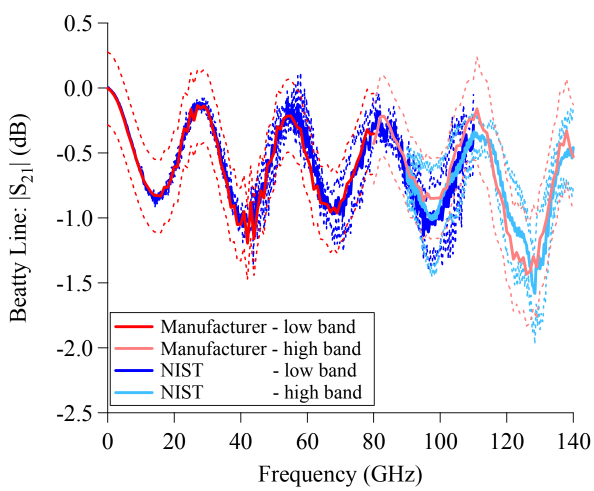

Fig. 2. Measurements and confidence intervals of the Beatty line's transmission coefficients.

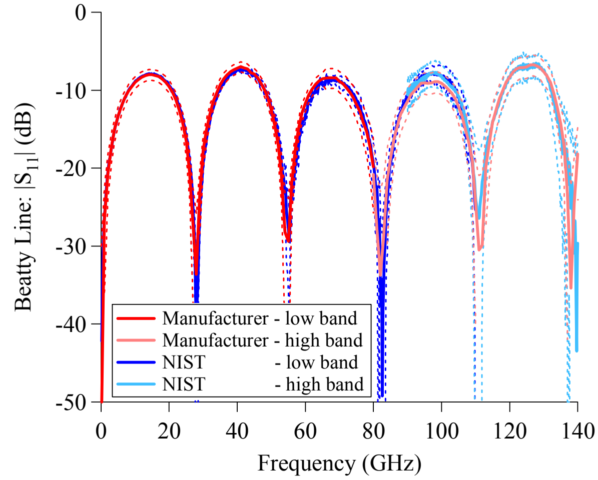

Fig. 3. Measurements and confidence intervals of the Beatty's lines reflection coefficients.

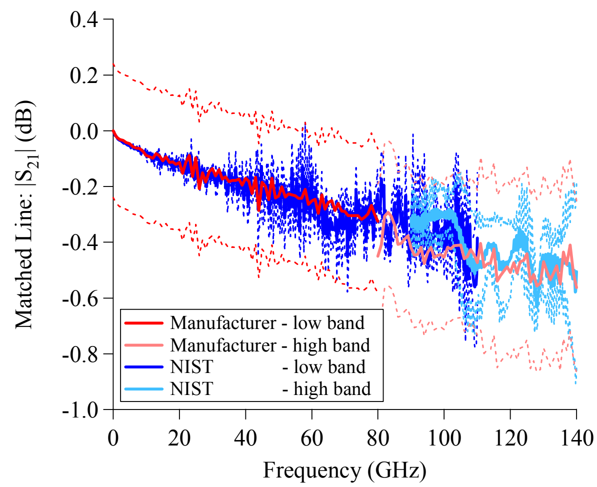

Fig. 4. Measurements and confidence intervals of the matched line's transmission coefficients.

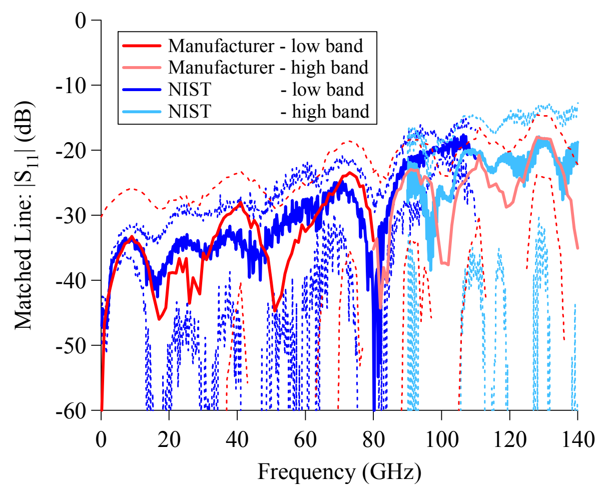

Fig. 5. Measurements and confidence intervals of the matched line reflection coefficients.

Nonetheless, the variations between our measurements and the manufacturer's agreed to within their respective confidence intervals at most frequencies. Some discrepancies may be attributed to connector repeatability, and the different calibration algorithms and standard definitions. Additionally, our measurements on the two VNAs agreed to within their respective confidence intervals for the overlapping frequencies between 90 GHz and 110 GHz, as illustrated in Figures 6-7, which zoom in on the areas from Figures 2 and 4, respectively.

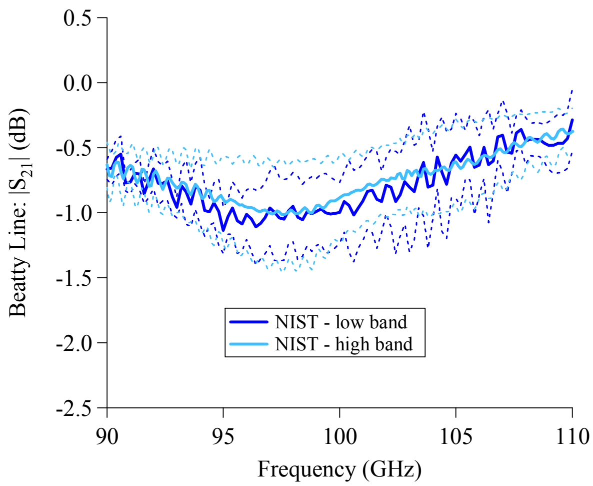

Fig 6. Comparing NIST measurements of the Beatty line's transmission coefficients from 90 GHz to 110 GHz.

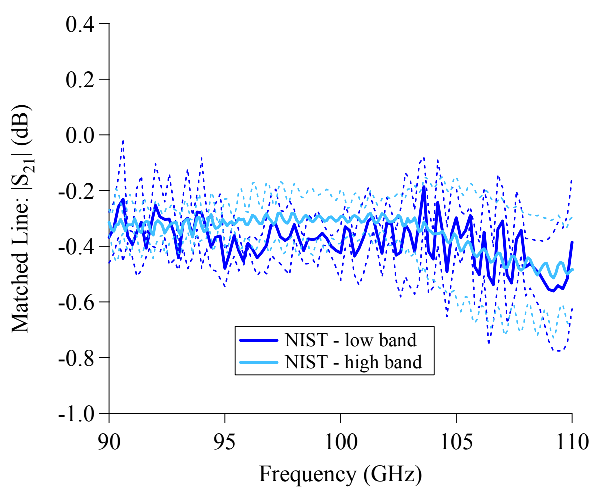

Figure 7. Comparing NIST measurements of the matched line's transmission coefficients from 90 GHz to 110 GHz.

IV. Conclusions

We have developed physical models of a 0.8 mm coaxial calibration kit for vector network analyzers that support calibration algorithms within the NIST Microwave Uncertainty Framework. After calibrating a network analyzer with this calibration kit and comparing measurements and uncertainties of two verification devices with data provided by the manufacturer, we found the measurements agreed to within their respective uncertainties.

Future work in this area includes a study of connector repeatability and developing an approach for achieving traceability. Traceability would require that the OSL standards be measured with a more fundamental calibration, such as multiline TRL or SSST, where dimensional tolerances are traceable to NIST. Then, the resulting measurements from the fundamental calibration would be used as models for the OSL standards.

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