Application Note

Anritsu Advancing beyond

Probe-Tip Power Calibrations with the Broadband ME7838 VNA Systems

While VNA systems typically have accurately calibrated power at their test ports (and usually allow user power calibrations to augment that accuracy), it is often asked how to calibrate available/delivered power at the probe tip for on-wafer measurements. This can be important to assure linear operation of the DUT or to conduct power-indexed measurements such as gain compression/AM-AM/AM-PM or distortion measurements. Power calibrations of incedent signals are of particular importance when characterizing and verifying small-signal models of mmWave devices, such as SiGe HBT or others. SiGe HBT requires the input signals as small as -30 dBm or less and linerarly calibrated in the entire frequency range. Such devices are easily driven to saturation and thus, the measured characteristics can lead to extracting inaccurate or wrong device model parameters. While on-wafer power sensors are being developed and studied, there is still often a need to link to a traceable coaxial or waveguide sensor. This note will discuss methods for transferring the sensor-based calibration to the probe tip using user power calibrations and power embedding/de-embedding. The focus of some of the discussion will be the ME7838G/G4 220 GHz system used with the MPI T220A probes but most of the concepts are generally applicable to other broadband and banded millimeter-wave (mmWave) installations.

Power Calibration Reference Planes

The most general case of the calibration/transfer sequence is shown in Figure 1. An adapter may be needed between the sensor and the module (that is not used when connecting to the probe) and this adapter would be de-embedded to move the reference plane from the traceable power sensor to the module interface. This de-embedding is done using the known (from the manufacturer or from direct measurement) S-parameters of the adapter. Then the reference plane is moved to the probe tip using the known (from the manufacturer or from measurement) S-parameters of the probe. It is principally the insertion loss of the adapter/probe that is used for the de-embedding/embedding process but some methods make use of the reflection data as well.

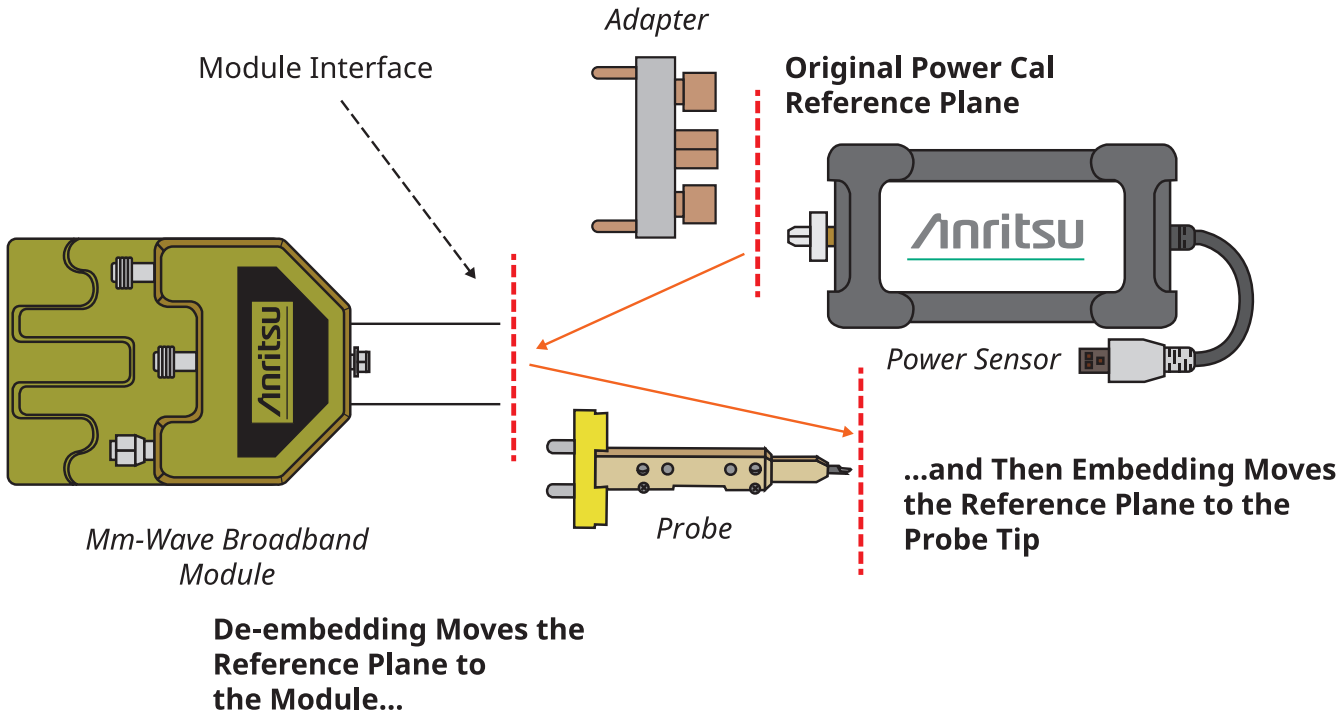

Figure 1. The General Case of Transferring the Power Reference Plane from a Power Sensor to the mmWave Module and to the Probe Tip is Shown Here. The Adapter Shown is not Needed in All Cases

The effect of this process on the measurement varies greatly with frequency. At 110 GHz, common probe insertion losses may be in the 1-2 dB range so ignoring this process will have that order of effect on the delivered power accuracy. At 220 GHz, some representative probe losses are closer to 4 dB so the effect may be more noticeable. An example plot of the loss for a TITAN™ Probe model T220A from MPI Corporation covering to 220 GHz is shown in Figure 2.

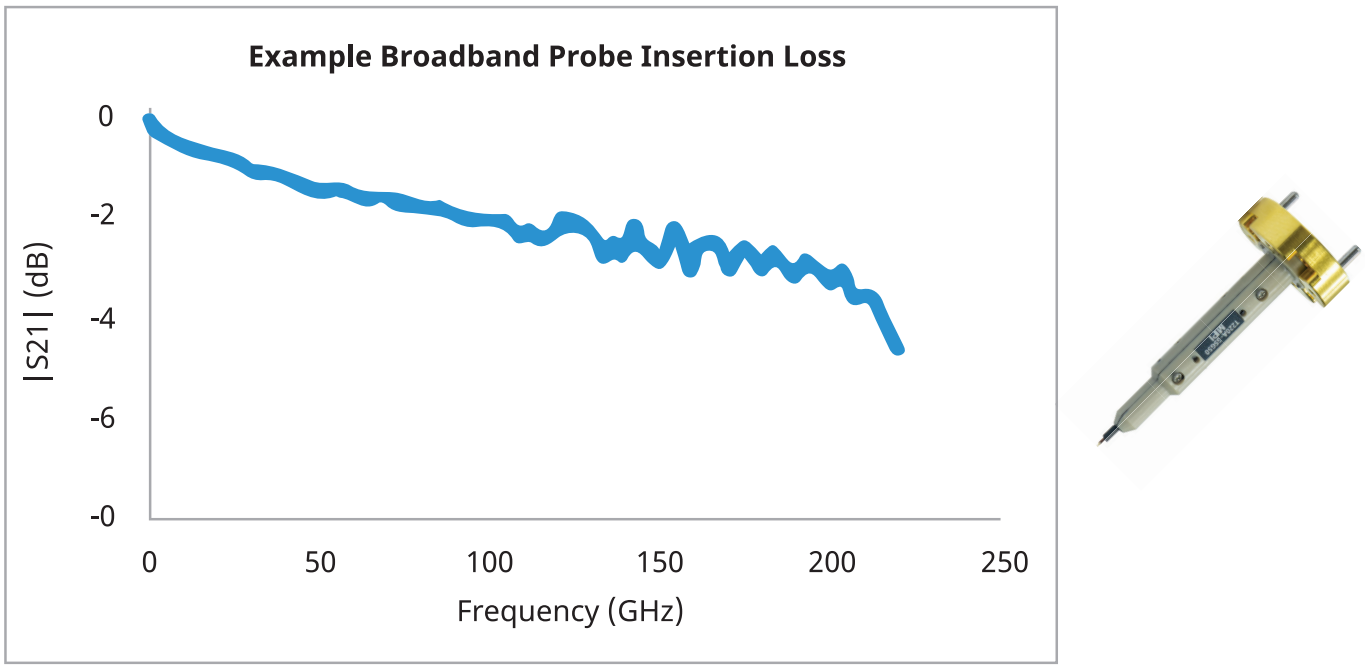

Figure 2. An Example Plot of Probe Insertion Loss Over the Frequency Range of the ME7838G is Shown Here (MPI T220A, also Shown)

Adapter losses vary as well with some typical values being on the order of 0.5 dB at 110 GHz (for 1 mm and 0.8 mm connector types) to 2 dB at 220 GHz. For the VectorStar Broadband ME7838G VNA system, appropriate adapters are required to cover the full 220 GHz range (required by the use of both coaxial and waveguide power sensors) and the concatenated insertion loss plot of these different adapters is shown in Figure 3.

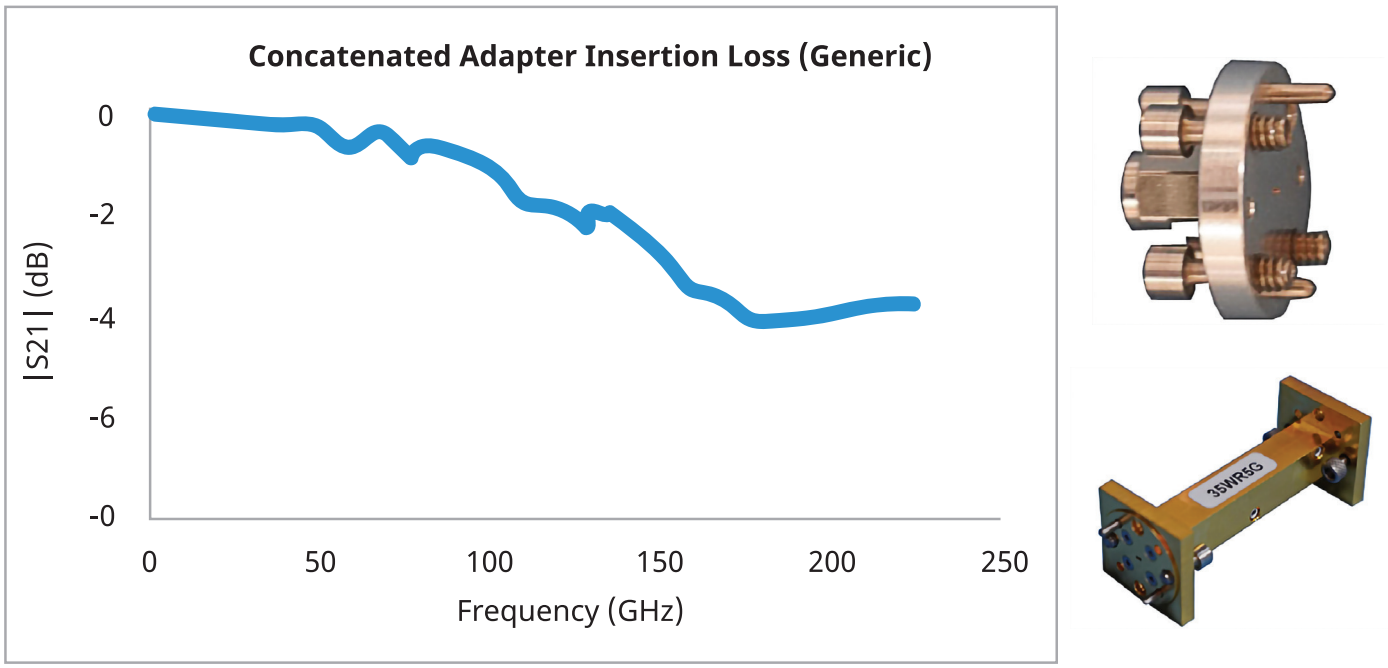

Figure 3. An Example Plot of the Insertion Loss of the Combined 33WG50 and 35WR5G Adapters (Concatenated in Frequency) is Shown Here Along with Images of the Adapters

How is the Calibration/Transfer Executed?

As would be expected from the previous section, there are two main parts to the process: the user power calibration and then the power de-embedding/embedding. On the instrument user interface, these tasks are all executed from a few menus as suggested in Figure 4.

The target power for the port in question is defined and 'perform cal' is then selected. The target power must, of course, be in the available power range of the instrument taking into account the adapter loss to the sensor. One may be able to calibrate above the specified maximum power of the instrument but it is not guaranteed and the calibration might terminate with an error in that case. If a power sweep (instead of a frequency sweep) is being calibrated, there will be both a target start power and a target stop power to enter.

Depending on the frequency range of the calibration (in a frequency sweep), more than one power sensor will need to be connected. The instrument will scan the communication busses when the calibration starts to make sure that a collection of sensors adequate to cover the frequency range are available. If not, the calibration will terminate with an error. When multiple combinations of sensors are available, the instrument has a priority tree to decide which sensor to use for which frequencies. Appendix A contains some details on the allowed sensors and their characteristics. When a different sensor needs to be connected, the system will prompt the user for a sensor change with a dialog box.

The 'network extraction' submenu is used for de-embedding the adapter or if needed, multiple adapters, and embedding probes (these buttons are only available when a user power calibration exists). The buttons shown in Figure 4 are for loading the .s2p file(s) describing the component(s). If an adapter to the sensor was not needed, then of course the de-embedding step can be skipped. The frequency ranges of the .s2p files do not have to match the current sweep range exactly. Interpolation will be used for calibration frequencies within the range of the files and flat-line extrapolation will be used for frequencies outside of the file range. Extrapolation for frequencies well outside the file range may be highly inaccurate and should be done cautiously. Usually, the adapter and probe losses are slowly changing with frequency so interpolation errors are generally modest (few tenths of a dB nominal).

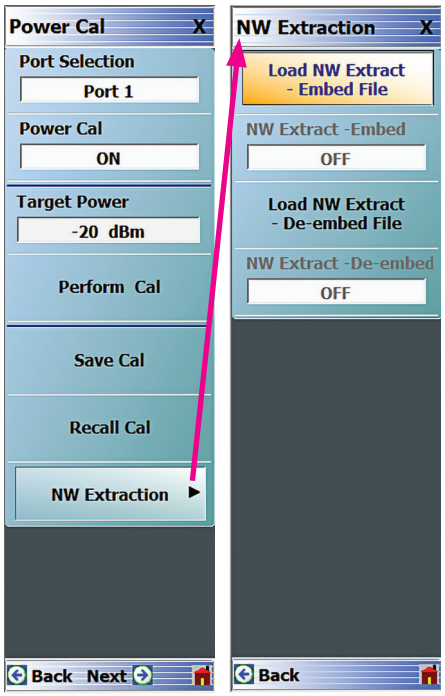

Figure 4. The User Power Calibration Menu and the Corresponding Network Extraction Submenu are Shown Here in the Case of a Frequency Sweep

Once the file(s) is(are) loaded, the extraction can be turned on or off. When both are off, the original user power calibration is what will be applied. When appropriate extraction files are loaded and activated, the power menu entries will reflect the power available at the probe tip.

How are the Adapter/Probe Files Obtained?

Both adapters and probes may be provided with S-parameter data in the form of .s2p files which makes this step simpler. In the case of adapters for the VectorStar Broadband ME7838x VNA systems, generic .s2p files are provided with the software installation and, for the 220 GHz VectorStar Broadband ME7838G system, even a concatenated file containing all of the adapters for a full range calibration is available. For the probes, such as the T220A probe, S-parameter data is also available upon request.

If no such data is available, there are a variety of measurement processes available to help. Some information on probe characterization is available in the Anritsu application note “Generating an .s2p File for a 220 GHz Probe with the VectorStar ME7838G Vector Network Analyzer” (application note 11410-01163). There is also considerable information in the VectorStar™ Calibration and Measurement Guide (particularly chapters 9 and 24 where network extraction is discussed). In general, these processes use the connection of standards of some kind at the non-module side of the adapter/probe to allow the S-parameters of the adapter/probe to be extracted. Some of these methods make added assumptions about the structure (such as reciprocity and localized reflections) that common probes and adapters all satisfy. These ‘higher assumption’ methods benefit from reduced constraints on the standards connections.

Examples and Measurement Implications

Consider an example sweep setup covering 150 - 220 GHz using the VectorStar Broadband ME7838G system. A user power calibration was performed with a target value of -25 dBm using an Anritsu 35WR5G adapter and a G band power sensor. The adapter was then de-embedded and the wafer probe embedded. A plot of the VNA measurement of a1/1 is shown in Figure 5. Effectively, a receiver calibration has been applied to this data so, just after calibration and before embedding and de-embedding, the response was a flat line at -25 dBm. With embedding and de-embedding applied, the VNA has to change its drive levels relative to the original calibration to achieve the target power at the new reference plane. Since, in this case, the probe has slightly more insertion loss than the adapter, the VNA drive level must be higher to achieve -25 dBm at the probe tip. The amount of increased drive (to achieve the -25 dBm at the probe tip) is highest at 220 GHz and reaches about 2.5 dB at that frequency. In lower frequency ranges and with lower frequency systems, these drive excursions are normally smaller.

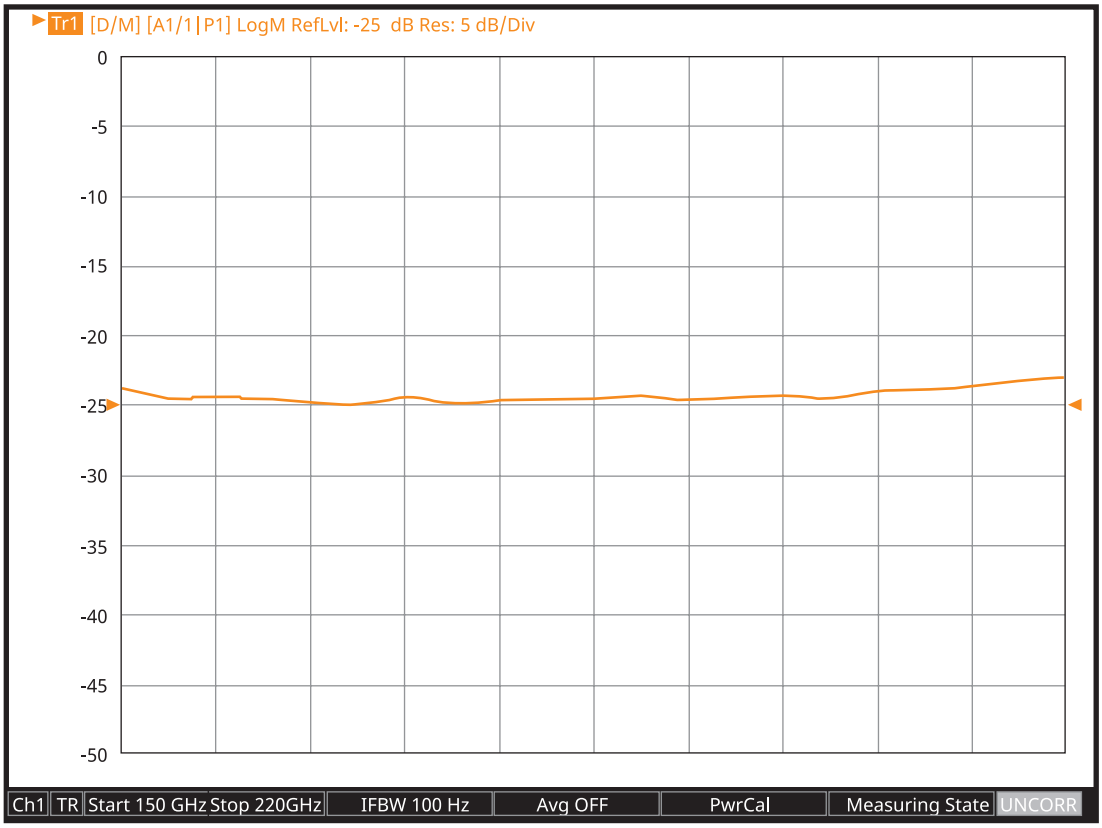

Figure 5. A Plot of Reference Signal Level (a1/1|P1) after the Embedding/De-Embedding Sequence Relative to the Original Calibration at -25 dBm

As an example of measurement impact, consider the analysis of input referred gain compression of a W-band amplifier. At each frequency of the measurement of the example amplifier, the power is increased until |S21| decreases from the low power value by 1 dB and the calibrated drive power is recorded at that point. If probe losses (or other losses after the power calibration reference plane) are not taken into account, the instrument will think an artificially high power at the DUT was required to reach the compression point. By properly referring the power calibration to the DUT plane, a more accurate reading on the compression point may be possible. The results with and without the reference plane transfer are shown in Figure 6 for the example amplifier measurement. Not surprisingly, the difference is essentially that of the probe loss since the 'no power de-embedding curve' is based on the factory power calibration at the module interface.

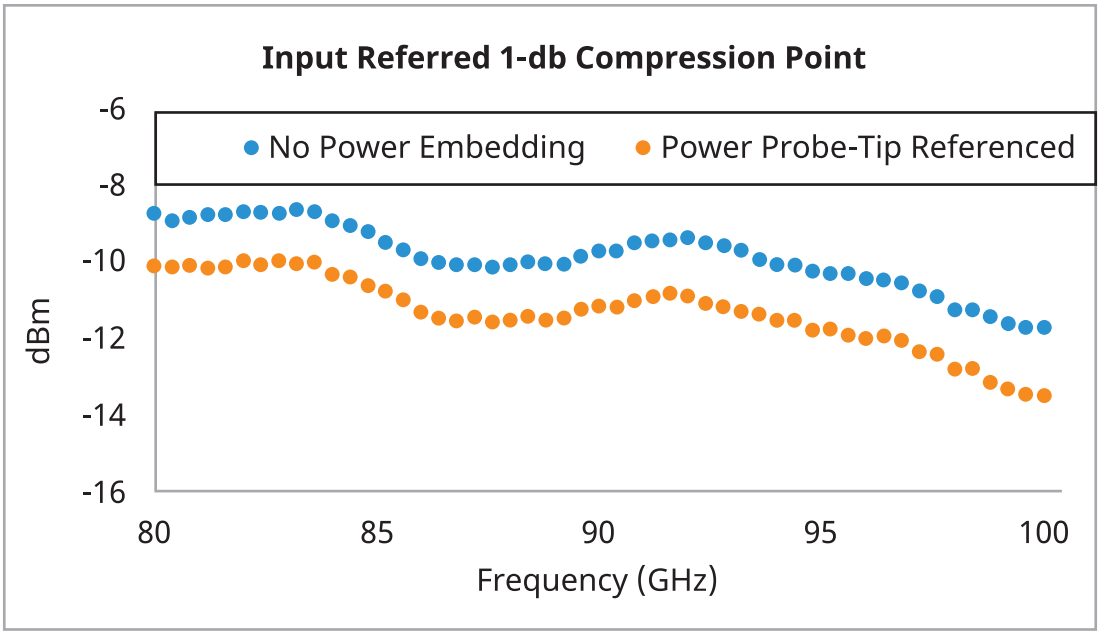

Figure 6. The Effect of Transferring the Power Calibration Reference Plane on an Input Referred Gain Compression Measurement is Plotted Here for an Example Amplifier

While beyond the scope of this application note, the uncertainties in a measurement like that discussed above is often of interest. Assuming the linearity of the instrument is good enough (less than 0.05 dB compression for the example measurement), this measurement is essentially limited by that of power calibration accuracy. A significant factor at higher mm-wave frequencies is often that of the sensor itself (which includes its calibration accuracy, linearity and mismatch effects during connection to the module) and this may be dB-scale in some cases above 125 GHz. The transfer process incurs additional uncertainty of the S-parameter measurements of the probe (impacted by the base calibration kit, the extraction method, and repeatability primarily) and repeatability effects at the probe/module interface.

Summary

Power calibrations to the probe tip can be critical for some active device measurements and processes exist to perform user power calibrations with traceable sensors and transfer that accuracy from the sensor interface to the probe tip using knowledge of the probe (and any adapters that may be needed). The magnitude of the power change from performing this process varies with the probes and the frequencies involved but can exceed several dB at 200+ GHz.

Appendix A: Which Power Meters and Adapters to Use?

Depending on the frequency range being calibrated, there are a number of permutations of power meters/sensors that can be used. The below section covers the 220 GHz range of the ME7838G but the obvious subset of sensors are used for lower frequency systems. The available selections include:

Anritsu SC7770 sensor: (using the ML2438 series of meters) 70 kHz-70 GHz, V(M) connector – usually adapted to 1mm (F).

W-band sensor: Keysight W8486A sensor (using the 437B, N1914 and other meters); nominally 75-110 GHz but can be traceably characterized over 70-125 GHz, WR-10 waveguide – usually adapted to 1mm (F).

Anritsu PowerMaster 110 GHz Broadband sensor: MA24510A Power Analyzer, 9 kHz to 110 GHz, 1mm connector (M) – usually adapted to 1mm (F). This is a USB sensor.

110 GHz 110 GHz Broadband sensor: Rhode and Schwarz NRP110TWG and succeeding sensors (using the NRP2 meter), 9 kHz-110 GHz, 1mm (M) connector – usually adapted to 1mm (F).

D band sensor: Elva WR06/20 sensor (using the DPM-1 meter), 110-170 GHz (generally used above 125 GHz), WR-06 waveguide.

G band sensor: Elva WR05/20 sensor (using the DPM-1 meter), 140-220 GHz (generally used above 170 GHz), WR-05 waveguide.

The VNA has a preference table of which sensors it will use for a given band and it identifies which meters are present on the GPIB bus when the calibration is initiated. The preferences (since the coverage of the above sensors overlap) are based on minimizing the number of sensor connections required and minimizing uncertainties (since some of the sensors have generically higher measurement uncertainties than others). Before each segment, the calibration routine will ask that a specific sensor be connected to the desired calibration plane. If the current frequency range cannot be covered by any combination of the meters/sensors currently on the GPIB bus, an error dialog will be generated. The PowerMaster sensor is a USB sensor that must be manually selected when initiating the calibration and it will take precedence (over its frequency range) when selected.

Examples:

1. 10 MHz to 125 GHz calibration range
   a. First alternate: Broadband sensor + W band sensor
   b. Second alternate: Anritsu SC7770 Sensor + W band sensor
   c. Third alternate: Broadband sensor + D band sensor

2. 70 kHz to 220 GHz calibration range
   a. First alternate: Broadband sensor + W band sensor + D band sensor + G band sensor
   b. Second alternate: Anritsu SC7770 Sensor + W band sensor + D band sensor + G band sensor
   c. Third alternate: Broadband sensor + D band sensor + G band sensor

3. 70 GHz to 220 GHz calibration range
   a. First alternate: W band sensor + D band sensor + G band sensor
   b. Second alternate: Broadband sensor + D band sensor + G band sensor

4. 110 GHz CW range
   a. First alternate: Broadband sensor (overridden by the PowerMaster sensor if that was selected and is available)
   b. Second alternate: W band sensor
   c. Third alternate: D band sensor

Since the MA25400A module has the 0.6 mm coaxial flange interface, the sensors need to be adapted to it. Some possible ways of doing this:

Anritsu SC7770, W-band and 110 GHz broadband sensors: These usually already are adapted to 1 mm (F) for use with the ME7838AX/EX/D systems but an additional adapter (33WG50) is needed to connect to the MA25400A for the ME7838G.

D-band sensor: An adapter to 0.8mm is used with the ME7838D systems but we use this sensor to 170 GHz with the ME7838G so a different adapter is used to connect this sensor to the ME7838G. An adapter to WR6 (35WR6GB) is available for this purpose (covers 110-170 GHz) and the WR5 adapter can also be used (35WR5G). One may wonder about the WR5 choice but we generally only use this sensor above 125 GHz and the WR6 cutoff frequency is ~ 115 GHz. This 'mismatch' of guide sizes causes a mild discontinuity as shown below but the induced error (less than a few tenths of a dB) is considerably less than the ~15% basic power sensor calibration error.

G-band sensor: The 35WR5G adapter is used to connect the sensor to the MA25400A module.

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