URSI GASS 2020, Rome, Italy, 29 August - 5 September 2020

Design of Verification Standards for *S*-parameter Measurements from 110 GHz to 170 GHz

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Abstract

This paper describes a new waveguide verification kit has been introduced recently to provide high repeatable and high stable scattering parameter measurements in the frequency range from 110 GHz to 170 GHz. The verification kit consists of three two-port mismatches with flat frequency response, two precision fixed attenuators and a new designed waveguide section. The verification kit can be used as a primary standard for *S*-parameters. Traceability to the International System of units (SI) is achieved via dimensional measurements of the waveguide aperture or precision calibration by the national attenuation standards. This paper describes the design method of the verification kit, both simulation and measurement results are presented. Furthermore, the uncertainty of measurement results is estimated in this paper.

1.Introduction

Vector-network-analyzers (VNA) are widely used to measure components and sub-assemblies. It can measure *S*-parameters rapidly with a great accuracy. When a calibration has been performed, we need to use verification kits to check the performance of the VNA. These kits contain devices, such as transmission magnitude standards, transmission phase standards and reflect magnitude standards, whose characteristics are precisely and independently known. When these devices are measured, the difference between the displayed results and the known values indicates the level of measurement accuracy. If its characteristics are calculated by other basic parameters, it can be used as the primary standard of the *S*-parameter.

Recently, there has been a significant growth interesting in the use of VNA in the higher millimeter-wave range[1], such as from 110 GHz to 170 GHz. So the verification kits used in these regions has received more and more attention. In the frequency range below 110 GHz, commercial verification kits are available, such as W11645A provided by Keysight and 27710 provided by Flann, which cover the frequency from 75 GHz to 110 GHz. However, in the frequency beyond 110 GHz, there is no specific model available in the catalog. In this paper we designed a new verification kits for VNA in the frequency range from 110 GHz to 170 GHz. The verification kit consists of three two-port mismatches, two precision fixed attenuators and a new designed waveguide section, which are used as reflect magnitude standards, transmission magnitude standards and transmission phase standards respectively. It can provide accurate, stable and repeatable *S*-parameters, it can trace to the International System of units (SI) by precision calibration by the national standards and dimensional measurements of the waveguide sections. So it can be used as a primary standard for *S*-parameters measurement. The traceability path of the 110GHz~170GHz *S*-parameter is shown in Figure 1.

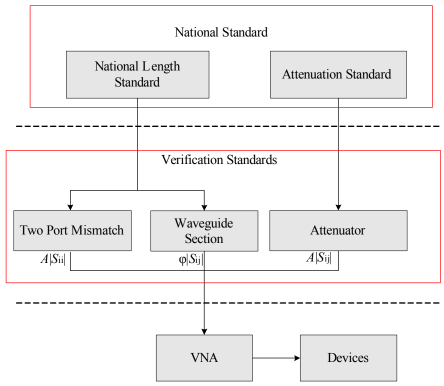


Figure 1. Traceability path of the 110GHz~170GHz *S*-parameter.

2.Design of Verification Standards

The primary standard for *S*-parameter measurement can be traced to International System of units, which is the most important requirement. So at the beginning of design, traceability has the highest priority, followed by stability and repeatability. The two-port mismatch and matched waveguide section are used as the reflection amplitude standard ($A|S_{ii}|$) and transmission phase standard ($\varphi|S_{ij}|$), respectively, which can be traced to the national length standard. The precision attenuator is used as the transmission amplitude standard ($A|S_{ij}|$), which can be traced to the national attenuation standard. In order to ensure the stability and repeatability, WM-1651 waveguide is used as the match waveguide, and IEEE1785.2a flange is used as the waveguide flange.

The matched waveguide section is used as the transmission phase standard, which should cover the phase range from -180 ° to +180 ° . In the lower frequency, W11645A in 75GHz~110GHz for example, which is realized by a uniform matched waveguide section with 50mm-lengths. However in the 110GHz~170GHz band, the waveguide section with 50mm-length will produce a multi-period phase shift as shown in the left side of Figure 2, which is not conductive to the transmission phase verificy of the VNA. Moreover, the waveguide and flange of the long waveguide section need to be processed separately, so the accuracy of tracing to the length will be reduced. In this paper, we design a new waveguide section with the shortest length to cover the phase range from -180° to +180° . The simulation result is shown in the right side of figure 2. As can be seen from the figure, it will not produce multi-period phase. The waveguide section is only a few millimeter thick, and the waveguide and flange are machined together, which can greatly improve the accuracy of its length traceability. The machining model is shown in Figure 3. In the design, because it is a matched waveguide section, the waveguide aperture height, *b*, and the waveguide aperture width, *a*, is the same as that of the standard waveguide (*a*=1.651mm, *b*=0.826mm, in the WM-1651 waveguide). The phase introduced by the phase standard can be calculated as follow:

$$\varphi = 2\pi l / \lambda_g \tag{1}$$

Where l is the thickness of the waveguide section, λ_g is the wavelength in the waveguide. Make the phase introduced at the initial frequency(110GHz) equal to 285° (which is -75° in the range of -180° to +180° displayed by the VNA), the thickness, l, of the section can be calculated to be 3.822mm. Then, with this value as the initial value, the thickness, l, is optimized and simulated. If it does not cover a phase change from -180° to +180° in the full band, increase the value l until the phase range is just covered.

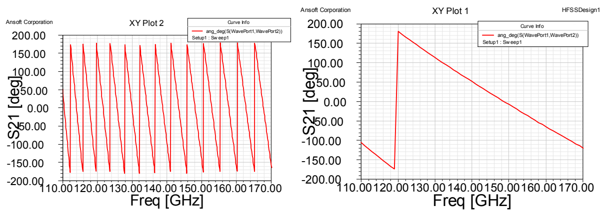


Figure 2. Simulation results of the match waveguide section with different length (left l=50mm, right l=3.822mm).

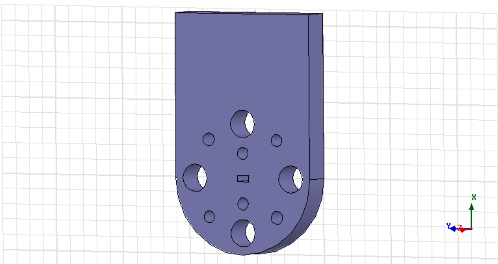


Figure 3. Machining model of the transmission phase standard.

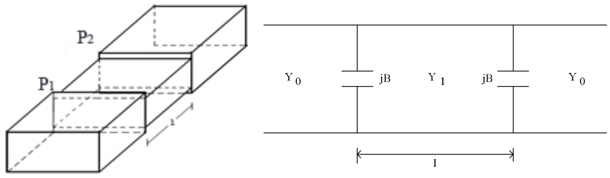
The three two-port mismatches waveguide sections with nominal VSWR 1.1, 1.5 and 2.0 are working as the reflect magnitude standards. The design parameters of the two-port mismatch waveguide section are mainly the dimensions of waveguide aperture and thickness. In the traditional design, the design model and equivalent circuit are shown in Figure 4. The thickness of the mismatch is quarter-wave-length ($1/4\lambda_g$) at the mid-frequency of the waveguide band, and the waveguide aperture width, *a*, is the same as that of the standard waveguide in the design frequency band. Then waveguide aperture height, *b*, is reduced to form the different VSWR. For the different aperture height, *b*, the corresponding reflection coefficient, S_{11}, can be calculated as follow:

$$S_{11} = \frac{(1+r-jBr)(1-\frac{1}{r}-jB)e^{-2\gamma l}+(1-r-jBr)(1+\frac{1}{r}+jB)}{(1-r+jBr)(1-\frac{1}{r}-jB)e^{-2\gamma l}+(1+r+jBr)(1+\frac{1}{r}+jB)} \tag{2}$$

Where l is the thickness of the waveguide section, γ is the propagation constant, $r=Y_1/Y_0$ is the ratio of admittance, B is the step capacitance due to the discontinuity of the waveguide, which can be calculated as:

$$\frac{B}{Y_0} = \frac{2b}{\lambda_g} \ln \csc\left(\frac{\pi b'}{2b}\right) \tag{3}$$

Where b is waveguide aperture height of the standard waveguide; b' is waveguide aperture height of the mismatch waveguide; λ_g is the wavelength in the waveguide.



(a) (b)

Figure 4. (a) Design model and (b) equivalent circuit of the mismatch waveguide section.

The parameters of the mismatch designed by the traditional method are shown in Table 1. The simulation results of the mismatch with a nominal VSWR of 2.0 are shown in the dotted line in Figure 5. As can be seen from the figure, the frequency response of the mismatch fluctuates greatly. In order to reduce the fluctuation of the frequency response, a new design method is adopted, which is similar to the reference [2], which reducing the waveguide aperture height, *b*, increasing the waveguide aperture width, *a*, decreasing the thickness, *l*, as the same time. The parameter of the mismatch designed according to the new method are shown in Table 2, and the simulation results of the mismatch with the nominal VSWR of 2.0 are shown in the solid line in figure 5. It can be seen from the figure that its frequency response has been significantly improved.

Table 1. Dimensional design of the mismatch with the traditional method (Unit: mm)

VSWR	*a*	*b*	*l*
1.10	1.6510	0.784	0.640
1.50	1.6510	0.660	0.640
2.00	1.6510	0.580	0.640

Table 2. Dimensional design of the mismatch with the new method (Unit: mm)

VSWR	*a*	*b*	*l*
1.10	1.656	0.787	0.640
1.50	1.795	0.690	0.473
2.00	2.140	0.620	0.488

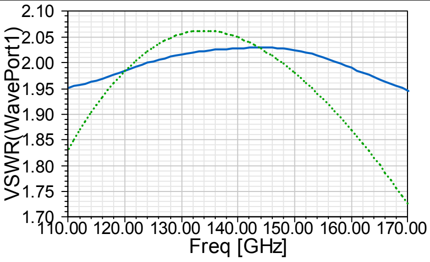


Figure 5. Simulation results of the mismatch waveguide with nominal VSWR 2.0 with different method (the dotted line is the traditional design, and the solid line is the new design)

The two precision fixed attenuators with nominal insert loss of 20dB and 40dB are working as the transmission magnitude standards. It realized by a directional coupler, and the aperture of the coupling hole conforms to the Chebyshev distribution. The distance between the holes is one quarter wavelength of the center frequency, which is *d*=0.728mm. The absorbing materials are added to port 2 and port 4 of the coupler, respectively, converting the coupler into a two port device. The internal structure of the attenuator is shown in Figure 6.

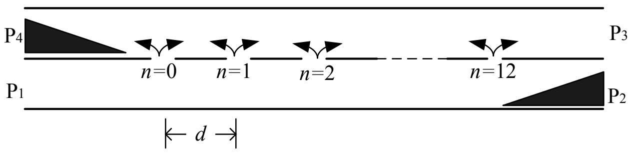


Figure 6. The internal structure of the attenuator.

3. Determination of theoretical value

The verification standard after processing is shown in Figure 7, including the mismatch waveguide designed by the two methods, the new designed matched waveguide section and two precision attenuators with different attenuation. Send the mismatch waveguide and the matched waveguide to National Institute of Metrology, China, for dimension traceability. The dimension and uncertainty of the device after traceability are shown in Table 3.

According to the dimensional measurement results in Table 3, the theoretical values of transmission phase and reflection amplitude can be determined by formula (1) to (3), combined with electromagnetic simulation.

The theoretical value of the transmission amplitude standard is obtained from the attenuation measurement system, which based on the IF substitution method as shown in Figure 8, it employs an inductive voltage divider (IVD) working at 10 kHz as a reference standard.

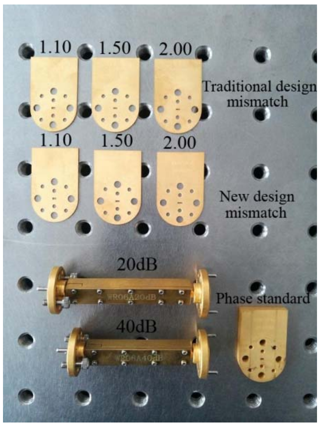


Figure 7. Photos of the processed verification standard.

Table 3. Dimensional measurement results of aperture size and thickness of the mismatch waveguide and match section (Unit: mm)

Device	*a*	*b*	*l*	*U* （*k*=2）
Match section	1.657	0.822	3.834	0.003
1.10 N-mismatch	1.649	0.784	0.644	0.003
1.50 N-mismatch	1.788	0.684	0.473	0.003
2.00 N-mismatch	2.136	0.618	0.501	0.003
1.10 T-mismatch	1.647	0.779	0.661	0.003
1.50 T-mismatch	1.646	0.655	0.654	0.003
2.00 T-mismatch	1.648	0.574	0.649	0.003

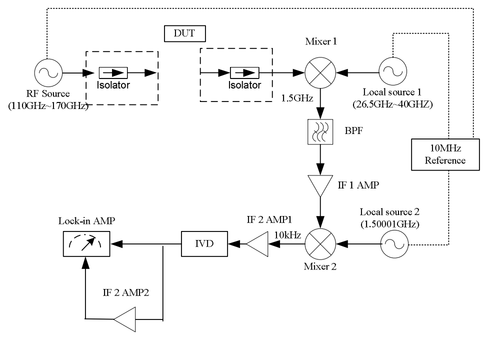


Figure 8. Block diagram of the attenuation measurement system

4. Uncertainty estimates

The approach used to establish the uncertainty in the determination of theoretical value follows the procedures given in [3]. The dominate source of the transmission phase and reflection amplitude uncertainty contains worst-case errors due to aperture height tolerance, worst-case errors due to aperture width tolerance, worst-case errors due to length tolerance. Due to the special processing technology, the waveguide aperture is almost a perfectly rectangular waveguide without corner radius, as shown in Figure 8. These measurement errors are predicted from electromagnetic theory according to the values suggested in the IEEE std 1785.1-2012 standard and electromagnetic simulation of tolerance in the Table 3 [4]. The dominate source of the transmission magnitude uncertainty contains receiver nonlinearity, detection noise, leakage, inductive voltage divider (IVD) error and repeatability. We assumed that the factors were uncorrelated. Uncertainties are combined using root-sum-of-the-squares (RSS) method to yield the standard system uncertainty. The expanded system uncertainty is $U = ku$, where k is the coverage factor and we have set k=2. The expanded uncertainty of the result for the 20dB and 40dB attenuator is found to be 0.03dB and 0.07 dB respectively. And the expanded uncertainty of the theoretical value predicted by the electromagnetic model for the transmission phase standard and reflect magnitude standard is found to be less than 1° and 3% of the VSWR, respectively, for the full band from 110GHz to 170GHz.

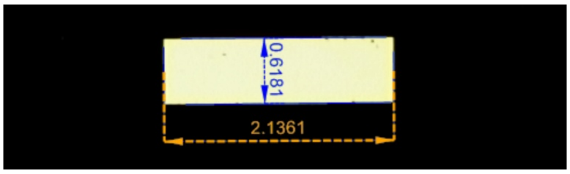


Figure 8. Waveguide aperture of the mismatch waveguide (VSWR2.0) seen through a microscope

5. System verification for vector network analyzer

Using verification standards achieves system verification for a VNA from Keysight Technologies and a ZC-170 frequency extension module from Rohde&Schwarz Company. All results presented in this paper have been taken with IF bandwidth 10Hz and averaging factor 1, after calibrated by Thru-Reflect-Line (TRL) calibration. The system configuration is shown in Figure 9, air floating optical table and the precise guide rail are used to ensure the connection repeatability.

Figure 9. The system configuration of the test.

Figure 10 show plots of the measured reflect magnitude, transmission magnitude and transmission phase, as a function of frequency, for the designed verification standards. Also shown in Figure 10 are the values predicted by the electromagnetic model. The uncertainty intervals for the modeled values combined with the VNA can be used to verify the measured values - i.e. the measured values are verified when they fall within the range of values established by the uncertainty intervals.

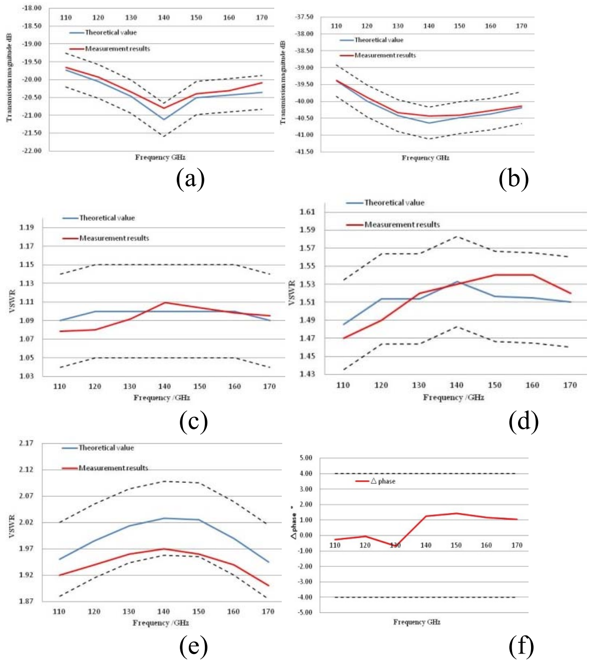


Figure 10. Results of system verification for VNA with (a)20dB attenuator ,(b)40dB attenuator,(c)1.10VSWR mismatch,(d)1.50VSWR mismatch, (e)2.00VSWR mismatch, and (f)$\Delta\varphi$ of the match section.

6. Conclusion

This paper describes the new designed waveguide verification standards in the frequency from 110GHz to 170GHz. It can provide accurate, stable and repeatable S-parameters, it can trace to the International System of units (SI) by dimensional measurements of the waveguide sections and precision calibration by the national standards. By using the verification standards, the performance of a VNA can be verified.

7 References

[1]. Wilson, Alan;Salter, Martin;Ridler, Nick;Pollard, Roger;Clarke, Roland, "Traceability to National Standards for S-parameter Measurements of Waveguide Devices from 110 GHz to 170 GHz," *Microwave Measurement Conference, 2009. 73rd ARFTG*, 2009.

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[4] IEEE Standard 1785.1-2012, "IEEE P1785: IEEE Standard for Rectangular Metallic Waveguides and Their Interfaces for Frequencies of 110 GHz and Above-Part 1: Frequency Bands and Waveguide Dimensions".