Windowing UWB microwave, mm-wave multi-port S-parameter measurements using open-ended excess electrical length

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Abstract: Multi-port measurements are a big challenge in circuits' verification, especially when the frequency increases. This study presents a new technique for measuring S-parameters of multi-port ultra-wideband (UWB) microwave and mm-wave circuits. The concepts are based on direct or indirect applying modulated UWB impulse radio in desired bandwidth to the one port of the modified multi-port circuit and gathering the reflected signal in the same port and the output signal in the second port in time domain, and the other ports are left opened with a special designed added electrical length. Then by applying intelligent windowing in time domain to the gathering data, and using fast Fourier transform, the desired S-parameters are extracted. Validation of this technique is verified by design and fabrication of a three-port UWB Wilkinson power divider in 22–30 GHz. The simulation and measurement results of the reflection and transmission S-parameters by using this new technique are very close to those are extracted with the conventional vector network analysers S-parameters measurements and show the ability and the accuracy of this technique.

1 Introduction

For multi-port devices with their ports more than vector network analysers (VNAs) ports, the other ports must be matched to the reference port. This can be done using coaxial loads, wideband antennas or lumped loads in the desired frequency. At high operating frequencies, spurious effects such as radiations with antenna matching, assembly problems and discontinuity in lumped loads, and transition effects in measuring ports and in coaxial loads, have many destructive effects in measurement results, and need complex design, fabrication and test procedures to validate the measurements [1–3]. On the other hand, any cable, connector or probe used to contact the ports of the device under test has a non-negligible effect on the measurement results [1].

Sometimes designers need to qualify and develop a multi-port device itself. Reducing the number of discontinuities and connections in a test system reduces measurement error and the possible points of failures. Hence if there is a solution to reduce the destructive effects of the excess matched ports by using an ideal match load, the measurement accuracies are increased.

In this paper, a new technique to match the excess ports and extracting the multi-port circuit results based on the two-port measurements are presented. The best solution to match the other ports in a multi-port circuit is to match the ports to the reference characteristic impedance, which is used in this work by continuing the other ports with the same characteristic impedance by adding an appropriate electrical length and then leave them be opened. Note that design of an open circuits at least in microstrip circuits is desirable up to mm-waves. This ideal matching can be happened if one can separate the each port response in time domain. First, the proposed concept is explained and the procedure is presented. Then validation of the new concept is verified by using simulation and measurement results of a new three-port ultra-wideband (UWB) Wilkinson power divider. Finally, this paper is concluded with good suggestions.

2 Concept and procedure of the proposed technique

The authors designed and fabricated a new Wilkinson power divider in 22–30 GHz [5], which the photo of the fabricated symmetrical UWB Wilkinson is shown in Fig. 1*a* and the simulation and measurement results of the S21 and S11 are depicted in Figs. 3*b*, 4 and 6*b*, respectively. Consider it needs to measure the reflection-S11 and the transmission-S21 of this UWB Wilkinson power divider in 22–30 GHz with a two-ports VNA's with coaxial or ground signal ground (GSG) probes, so the other ports must be matched to the reference load by good match loads.

Suppose that the bandwidth of the proposed circuit is designed to be B, so it can support, for example; a modulated Gaussian pulse with the main lobe width of 2/B-sec in time domain. Now consider the electrical length from ports 1 to 2 (desired measuring port) is, El-sec. The main concept of this new technique is adding a suitable open-ended electrical length, to the other ports, with the same characteristic impedance. In Microstrip technology, the open port is desirable up to millimetre-wave frequencies [3]. The excess electrical length is at least equal to the Max (El, 2/B) in length. The new technique procedure is summarised as the following:

(a) Select the desired ports which must be measured.
(b) Add the appropriate electrical length to the other ports and left them opened (with or without coaxial connectors).
(c) Measure the S-parameters of the desired ports with VNA.
(d) Produce the s1p or s2p from the S-parameters measurement results of the desired ports.
(e) Run a transient analysis by using the prepared s1p or s2p and with suitable circulator or directional coupler in one or two ports, depend on the required S-parameters, in ADS software.
(f) Apply the appropriate modulated signal (Gaussian, Hamming windowed etc.) with bandwidth of B, to the one port.
(g) Gather the full time-domain signals from input forward, input reflection and output ports.
(h) Apply the suitable windows to the gathered time-domain signals and convert the data to the frequency domain.
(i) Extract the desired S-parameters from the frequency domain data, using the S-parameter basic definitions.

Note that the accuracy of the extracted S-parameters in this technique is highly depended on the data separation in time domain, from each part (match ports, open ports, circuit itself etc.), individually. So the minimum length of the excess electrical length is critical and may need some optimisation in it in simulation process.

Fig. 1 *Photo of the fabricated UWB Wilkinson power divider*
a Symmetrical with excess electrical length
b Non-symmetrical with excess electrical length

Also applied signal, or other windowing schemes in simulation process, may need some optimisations, before fabrication process. Besides, the frequency domain data must be measured over a wider frequency range to avoid abrupt amplitude discontinuities and aliasing in time domain or, the measured data can be multiplied by a suitable window function, so the side lobe levels are reduced at the expense of the main lobe width in time domain. Let explain in more detail with a real simulation and experimental example.

3 Simulation results

Considering all facts about choosing suitable low distortion laminate which are explained in [4, 5], the 10 mil laminate of RT/duroid 5880 with the relative permittivity of about 2.2, copper thickness of 17 µm, roughness of 1.8 µm and dielectric loss tangent of about 0.0023 is selected in this paper to design and fabrication.

As it is shown in Fig. 1*b*, the symmetrical Wilkinson power divider of Fig. 1*a* is modified to non-symmetrical Wilkinson power divider by adding an electrical length of about 3.5 cm to the port 3.

Following the proposed technique procedure, the two ports S-parameter simulation results of symmetrical Wilkinson power divider with all matched ports and the non-symmetrical Wilkinson power divider, with leaving the third port opened are used in transient analysis in ADS software. The time-domain signals and the exact S-parameters and the extracted S-parameters with the proposed technique are illustrated in Figs. 2–4.

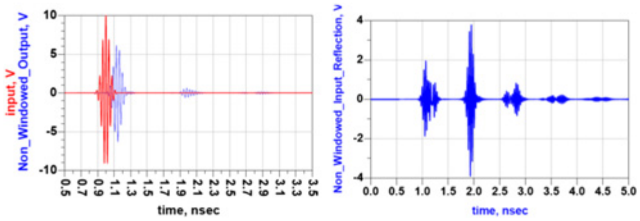

Fig. 2 *Input signal and non-windowed output and reflected signals*

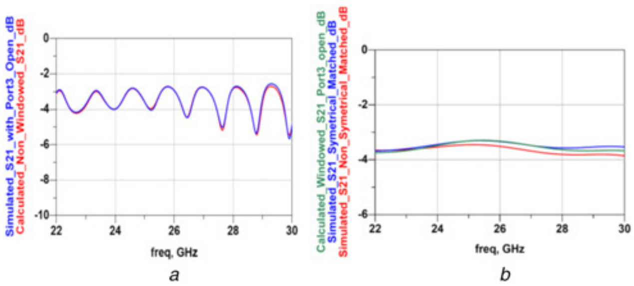

Fig. 3 *Exact simulation results and the extracted results of S21 of non-symmetrical Wilkinson with*
a Port 3 opened and non-windowed time-domain signals
b Port 3 matched and windowed time-domain signals and compared with exact results of S21 of symmetrical Wilkinson with port 3 matched

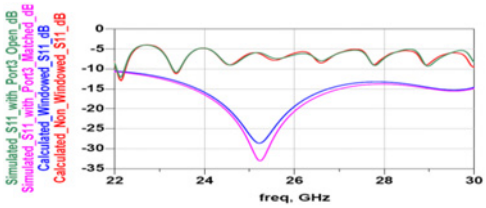

Fig. 4 *Simulation results of S11 of non-symmetrical Wilkinson with port 3 opened or matched, and the extracted S11 from non-windowed and windowed time-domain signals*

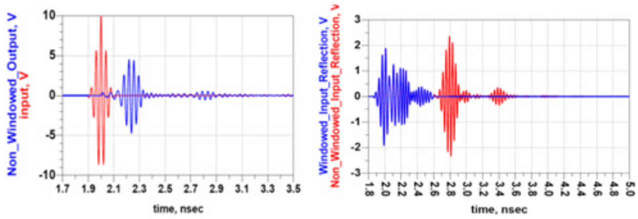

Fig. 5 *Input, windowed and non-windowed output and reflected signals*

The input signal is a Gaussian modulated signal with the bandwidth of about 10 GHz; or about 200 ps in time domain; and a carrier frequency of 26 GHz. Using the non-windowed or full time-domain signals of output and reflected signals, S11 and S21 of the non-symmetrical Wilkinson can be extracted as they are shown in Figs. 3*a* and 4. Notice that these S-parameters are extracted when the port 3 is left opened.

Now let have a look at Fig. 2 again and follow the proposed technique procedure. By making appropriate windowing in output and input reflected signals; which are with considering output signal from 0.8 to 1.4 ns and reflected signal from 0.8 to 1.4 ns; the S-parameters of S21 and S11can be extracted again. In this new extraction, the effects of the opened port 3 are removed and so this port could be considered virtually matched. The new results are shown in Fig. 4 for S11 results and Fig. 3*b* for S21 results.

For better comparison, the simulated S-parameters with the same conditions are depicted with those extracted with proposed technique in the same figures in Figs. 3 and 4. As expected, the results of the frequency domain are very close to the extracted results from the proposed technique. As can be seen from Fig. 3*b*, there are some differences between extracted S21 with new technique and the exact simulation results of S21, which are due to the different effects of the port 3, and will be explained in more detail in measurement results.

4 Measurement results

Photo of the fabricated non-symmetrical UWB Wilkinson is shown in Fig. 1*b*. The measurement results are done using the Network Analyser model *HP* 8510C. Again by applying the proposed technique procedure to the fabricated Wilkinson, as explained in Section 3, the results are obtained. The input signal and the non-windowed and windowed reflected input and transmission output signals are presented in Fig. 5. The all exact measurement and extracted results of S11 and S22 in frequency domain and with new technique are done and the S21 results are shown in Fig. 6.

As it can be seen from Fig. 6*b*, there are some differences between extracted S21 with new technique and the exact results of frequency domain. The differences here are due to different transition effects of the port 3. The transition effects of port 3 are considered in exact results of frequency domain, but in extracted results in time domain, windowing removes the transition effects of port 3. Also the main circuit has a specific electrical length and some discontinuities in itself, so there are multi-reflections in

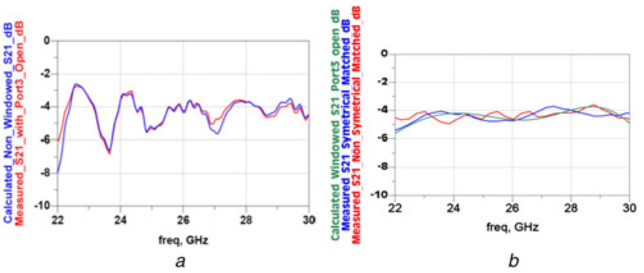

Fig. 6 *Exact measurement results and the extracted results of S21 of non-symmetrical Wilkinson with*
a Port 3 opened and non-windowed time-domain signals
b Port 3 matched and windowed time-domain signals and comparing with exact results of S21 of symmetrical Wilkinson with port 3 matched

multi-ways that must be separated from the matched ports with excess electrical length. So the minimum length of the added electrical length is important to yield better separations in time domain and so more accurate results. For more comparison the measured S21 of the symmetrical Wilkinson is also shown in Fig. 6*b*. As can be seen the extracted S21 from proposed technique are closer to the symmetrical Wilkinson as expected.

5 Conclusion

This paper presented a new concept and technique for measuring S-parameters of multi-port UWB microwave and mm-wave circuits using open-ended added electrical length, as match load. The S11 and S21 simulation and measurement results of the proposed power divider by using this new technique verified the new concept and showed the ability and the accuracy of this technique. The new concept has many advantages like, no discontinuity, no radiation or mutual coupling between matched ports and no unwanted mixed effects caused by matched ports. Also, this new technique is very easy to use in S-parameters measurements of UWB microwave/mm-wave, and the results are accurate enough. For characterising the own circuits (without any probe or connector contact effects), new extracted results are more accurate from those of VNAs exact frequency domain results and other techniques for matched ports. Also a big problem in load pull technique in high power measurements is destroying the active power components in its breakdown voltage, caused by the reflected signal from the load pull tuning procedure. Now suppose that you can separate the forward and reverse signal by adding an appropriate electrical length which is discussed in this paper, between the active component and the load pull, and applying an ultra short pulse modulated signal; depend on the desired bandwidth; to the circuit. With this technique you can sure that the reflected signal cannot destroy the active component, because the reflected signal from the load is returned to the active component in a separated time. Also designing of the directional couplers for measuring forward and reverse power are simpler because they are separated in time and there is no need to have large directivity.

This new technique can be improved by researchers to develop new high precision techniques in UWB mm-wave measurements. Authors are developing this new concept to precise the multi-port measurements via two-port or single port measurements by modifying input signals, processing and optimizing excess length and circuit configuration.

6 References

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