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Influence Of An Extended Stub At Connector Ports On Signal Launches And TRL De-embedding

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***Abstract*—Characterization of PCBs (Printed Circuit Boards) is usually associated with measurement using a VNA (Vector Network Analyzer) in the frequency-domain or a TDR (Time Domain Reflectometer) in the time-domain. The often used signal launch techniques on PCBs based on the VNA or TDR measurement in the microwave frequency range use SMA or 3.5 mm connectors, in edge-launch or vertical-launch fashions. The signal transition between the launch port and the DUT (Device Under Test) introduces errors in the measurement, which is dominant when compared with a transmission line itself on the PCB as the technologies of PCB manufacturing well developed today. Discontinuities at connector ports depend on the port structures and the dielectric properties of the substrate materials. However, an extended stub at a connector port may significantly influence signal launches, or even corrupt a TRL calibration in a measurement.**

Keywords-VNA measurement; TDR measurement; port launch techniques; TRL de-embedding;

I. INTRODUCTION

With a continued increase of clock frequencies and data-rates in high-performance electronic systems, losses due to dielectric media and finite metal conductivity associated with a signal path must be taken into account for SI (Signal Integrity) analyses and accurate physical model [1]. This requires the characterization of the signal link-path to obtain the substrate material properties. Using either a VNA or a TDR to characterize planar transmission line structures embedded in PCBs (Printed Circuit Board) is widely used in the microwave frequency range, which means that the well-controlled signals have to be launched onto the transmission lines on a PCB, and their propagation parameters need to be measured. Further processing is done by different time-domain or frequency-domain error corrections. Examples are SOLT (Short, Open, Load, and Thru) or TRL calibration for VNAs, or deconvolution of time domain reflectometer data for TDRs [2]. Unfortunately, the frequently used SOLT calibration cannot remove the losses due to the connector ports though the electrical length introduced by the connector ports can be eliminated using a port extension after the SOLT calibration. This implies that to accurately characterize substrate material for a PCB based on planar transmission line structures, de-embedding techniques are critical especially as the frequency of interest goes above 10 GHz. To remove the port effects, TRL calibration de-embedding techniques are widely used. Since TRL calibration is based on three independent measurements to characterize the error box of a TRL test pattern completely [3], errors due to the imperfections of known standard loads, such as Short, Open, and Load used in the SOLT approach will not result in the measurement. More important, TRL calibration sets the measurement reference plane beyond the DUT test launch-ports so that the influences from ports due to high-order modes and scattering can be eliminated.

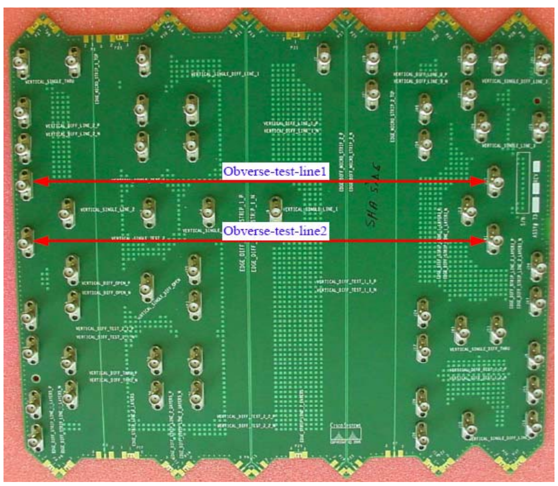
However, error correction using SOLT calibration or TRL calibration is limited. Error correction can also introduce artifacts or additional uncertainties, as the uncertainty of the calibration or the uncertainty of assumptions is "convolved" into the measured data [4], [5]. On the other hand, PCB manufacturing technologies are well developed today. The dimensions and substrate of transmission lines are well controlled, and the significant discontinuities on a propagation path come from the signal launch ports (transition between transmission line and the connector), and not from the transmission line itself. It is therefore worthwhile to study the signal launches at connector ports to minimize the discontinuities for entire signal link-path.

Signal launches for VNA or TDR based characterization include vertical launch (an SMA/3.5 mm connector mounted on PCBs vertically), edge launch (an SMA/3.5 mm connector mounted on the side of PCBs), and mircroprobing (the tip of a microprobe directly contacts to a DUT). As indicated in [2], the discontinuities from edge launch are usually less than from a vertical launch if no specific pattern embedded in a PCB is used for the vertical launch port. In this paper, the microprobing or other launch methods based on slot lines will not be discussed. The extended stubs at launch ports are the only concern, and investigated for vertical launch SMA connectors. Test board, port structures and measured discontinuities for the ports with different stub length configurations are introduced first. A longer stub at connector port corrupting a TRL calibration in a measurement is detailed then, and conclusions are summarized and given at the end of the paper.

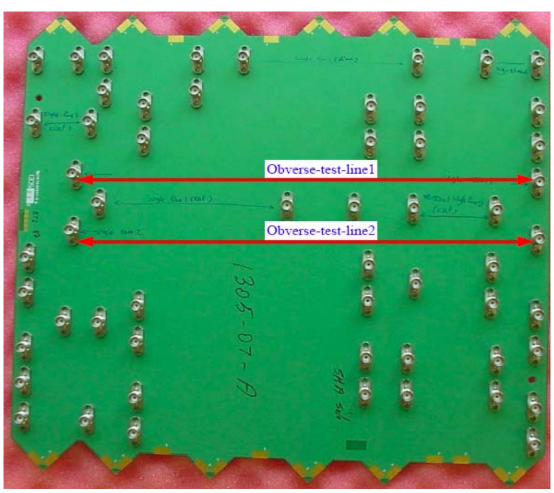
II. TEST BOARDS AND DISCONTINUITY MEASUREMENTS

A. *Test Board and Port Structures*

Two specific 8-layer test boards were designed for investigating the influences of the extended stub at the connector port on signal launches and TRL de-embedding. Dimensions, test patterns, and layer stackup of the two test boards are exactly same. The only difference between the two test boards is that the via stubs with the stub length of 16.7 mils are back-drilled (removed) on one test board, and there is no drilling on the other board. The board dimensions are 264 mm x 248 mm x 2.69 mm as shown in Figure 1 with top and bottom views of one test board.



(a)

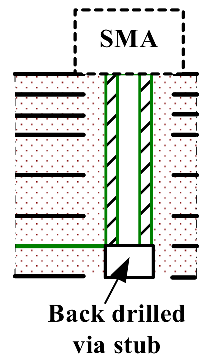


(b)

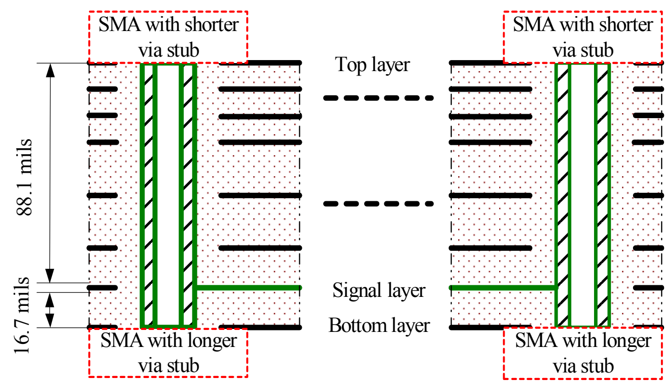
Figure 1. A test board: a) Top view of one test board. b) Bottom view of the test board.

Two types of vertical mounting SMA connectors are widely used for signal transitions between coaxial lines and PCBs. An SMA connector having its center conductor jutting out the mount surface of the SMA with a longer length creates one type of the vertical mounting SMA connector, and the other is the field replaceable jack receptacle SMA connector with a tiny bulge of the center conductor as shown in Figure 2 part (a). The SMA connector shown in Figure 2 (a) was used in the test board. Referring to Figure 2 (a) in the lower right corner, a via with seven surrounded vias comprises a pattern like a coaxial line for signal transition between the SMA connector and a transmission line on the PCB. The center via acted as the center conductor of the SMA, and the seven surround vias formed the reference. This kind of pattern built in PCBs provides better signal launches from SMA connectors to transmission lines on the PCBs. The layer stackup of the test boards is shown in Figure 2 (b) and (c).

(a)



(b)



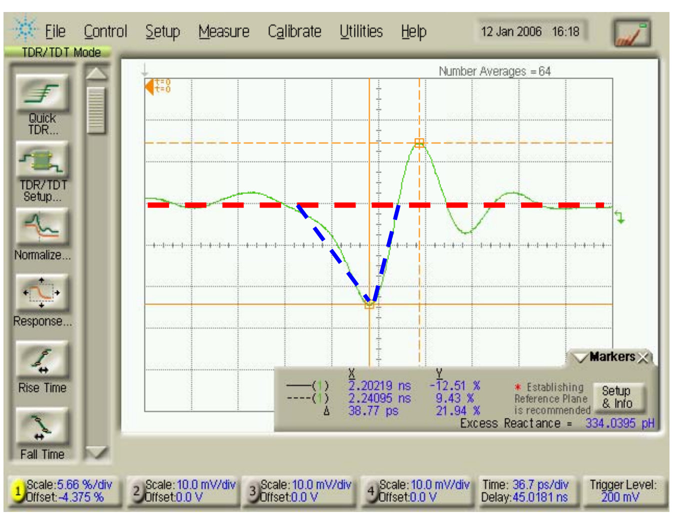
(c)

Figure 2. (a) Field replaceable jack receptacle SMA connector; (b) Layer stackup and port structure with back-drilled stub; (c) Layer stackup and port structures with longer or shorter stub when SMA connectors one mounted on the top or bottom surface of the PCB.

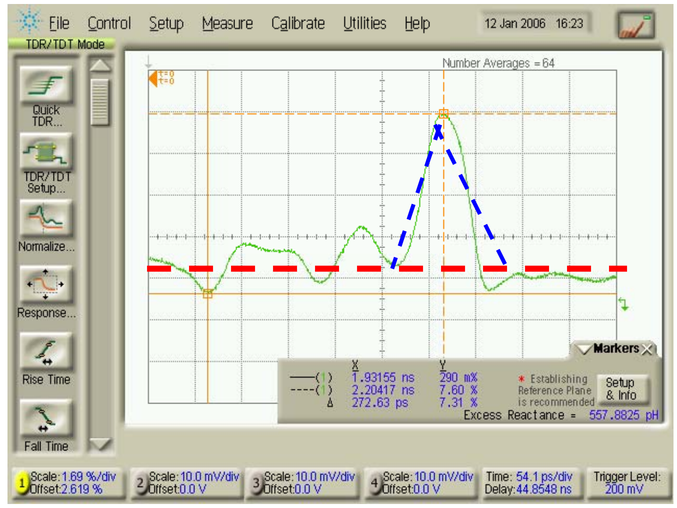
Three single-ended striplines were built on two test boards for examining the discontinuities at the connector ports with different extended stub length. Referring to Figure 2 (b), the first test line was built on one test board when the SMA connectors were mounted on the top surface of the test board. The tiny via stub length of 16.7 mils was drilled (removed) from the bottom side at the two SMA connector ports, which meant that the length of the stub at the SMA connector ports in this board configuration was zero. The test line on the board with zero length stub configuration is denoted a no-stub line. The second test line was constructed as SMA connectors mounted on the top surface of the other test board. Referring to Figure 2 (c), the length of the stub at the SMA connector ports was then 16.7 mils in this board configuration. The test line with the board configuration for the stub length of 16.7 mils is denoted a shorter-stub line. The third test line was created as the SMA connectors on the shorter-stub line configuration were moved to the bottom surface at the same position. The stub length at the SMA connector ports was 88.1 mils in this configuration as shown in Figure 2 (c). The longer-stub line is denoted as the stub length on the board configuration was 88.1 mils. It can be seen that the longer-stub configuration and the shorter stub configuration share the same test board by mounting SMA connectors on different sides of the test board, and the test line is exactly the same line with different port configurations.

B. *Measurements of Reflection Coefficients at Signal Launch Ports*

An Agilent 86100B TDR was used to measure the transitions at the signal launch ports for the three lines with the different port configurations described above. Measured transitions for the three lines are shown in (a), (b) and (c) of Figure 3, and the measured minimum and maximum reflection coefficients for the three lines at one of the two ports for each line are summarized in Table I. It can be seen in Table I that the measured reflection coefficients at the port of the longer-stub line are the worst case where both the parasitic capacitance and inductance exist at the signal launch port with the parasitic capacitance dominant. The signal transitions at the port of the no-stub line are the best, with the reflection coefficients at the port in the line much smaller than in the longer-stub line. The measured reflection coefficients at the signal launch port for the shorter-stub line is not as good as in the no-stub line, but it is still much better than in the longer-stub line case.



(a)



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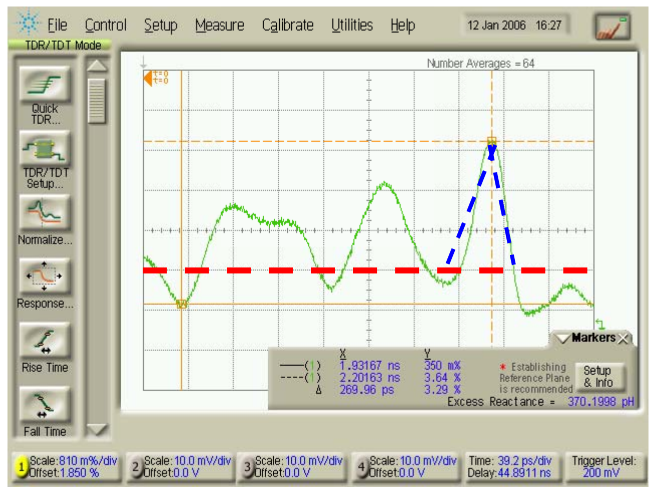


(c)

Figure 3. Transitions at SMA connector ports with different port stub length configurations: (a) Longer-stub line; (b) Shorter-stub line; (c) No-stub line.

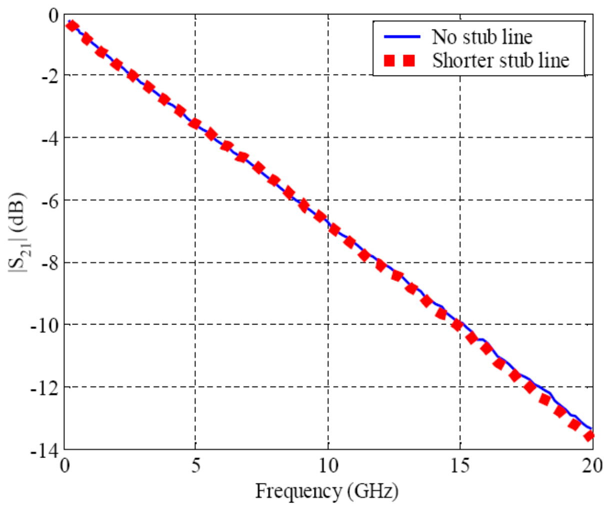
TABLE I. MEASURED REFLECTION COEFFICIENTS

	Longer-stub line	*Shorter-stub line*	*No-stub line*
$\rho_{\max}$	0.0943	0.076	0.0364
$\rho_{\min}$	-0.1251	0.0029	0.0035

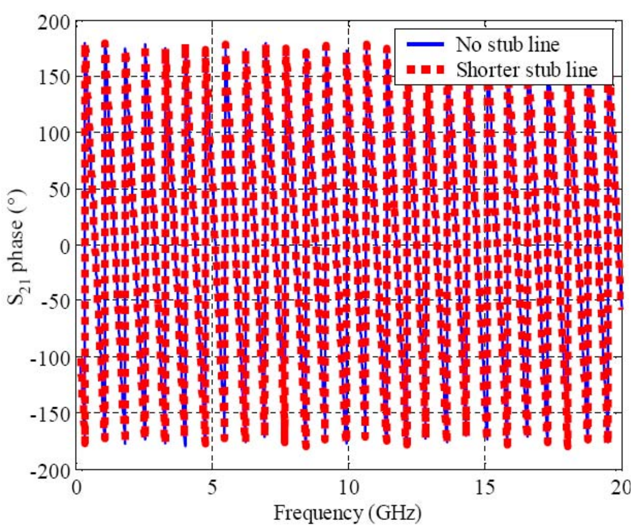
III. TRL DE-EMBEDDING AND ANALYSES OF THE TRL CALIBRATION ARTIFACTS IN THE LONGER-STUB LINE CASE

Each test line on the test boards has its own TRL calibration pattern. These TRL calibration patterns were used to de-embed port effects for the three lines. The stub length at each port in the TRL pattern on the board with a zero length stub configuration for the test line was still zero, which meant that the stub length of 16.7 mils was removed at each SMA port in the TRL pattern as well. The TRL pattern was applied in the measurement of the no-stub test line to eliminate undesired parasitics from the ports. On the other test board, if the SMA connectors were mounted on the top surface of the test board, the TRL pattern had a shorter stub length configuration at each connector, and it was used to calibrate port effects for the shorter stub line. If the SMA connectors were mounted on the bottom surface of the test board, the stub length was 88.2 mils long at each port in the TRL pattern. The TRL pattern was then used in the longer stub line measurement to de-embed port effects.

The S_{21} measurements for the three lines were conducted on a HP 8720ES VNA with an ATN-4112A S-parameter Test Set with TRL calibration. The measurement frequency was from 200 MHz to 20 GHz, which was separated into three frequency spans in the TRL calibration pattern designs (200 MHz to 930 MHz, 930 MHz to 4.3 GHz, and 4.3 GHz to 20 GHz) so that the requirement of insertion phase and useable bandwidth in the pattern could be readily met. The measured S_{21} both in magnitude and phase for the no stub line and the shorter stub line are shown in (a) and (b) of Figure 4 respectively. It is seen that the TRL calibration pattern works well from 200 MHz to 20 GHz in both cases.

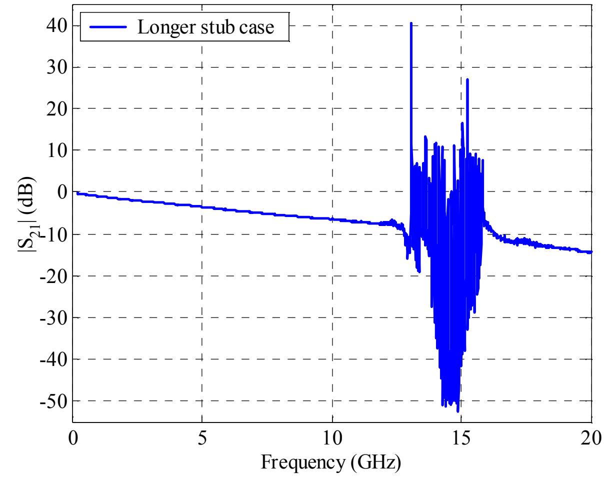


(a)

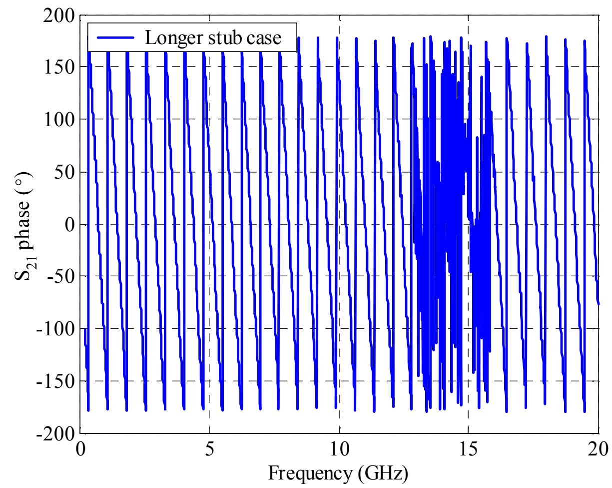


(b)

Figure 4. Measured S_{21} with TRL de-embedding for the no-stub line and the shorter-stub line: (a) Magnitude; (b) Phase.



(a)



(b)

Figure 5. Measured S_{21} with TRL de-embedding for the longer stub line: (a) Magnitude; (b) Phase.

Figure 5 shows the measured S_{21} for the longer stub line with TRL calibration for magnitude and phase. The TRL calibration fails above 10 GHz, especially in the frequency range from 12 GHz to 18 GHz. Since the longer-stub line is exactly the shorter-stub line by moving the SMA connectors from the top surface of the test board to the bottom surface at the same position, the failure of the TRL calibration in the longer-stub line configuration is entirely caused by the length of the longer stub at the SMA ports. This problem arises because the equivalent electrical length of the longer-stubs (open stubs) transfers the open into a short at the port for frequencies around 14 GHz, which causes most of the incident energy at the incident port to be reflected back, with only a small amount of energy transferred to the second port. Furthermore, the small energy at the receive port may be not transmitted from the launch port, but from near field coupling of the launch port, which is more dependent on the local configurations, such as traces, connectors, and their relative positions. This small transmitted or coupled energy causes the magnitude of S_{21} having a large dip around the frequency of 14 GHz, which may even exceed the dynamic range of the VNA. Consequently the phase of the S_{21} is unstable around this frequency range. This situation exists not only in the test lines, but also in the TRL calibration pattern. This implies that the error correction data from the TRL calibration pattern are incorrect around this frequency range, and they can not eliminate systematic errors from the measurement adequately. This unstable phase and extremely small values of $|S_{21}|$ causes the TRL calibration procedure to fail in the frequency range around 14 GHz.

The measured $|S_{21}|$ for the longer-stub line with SOLT calibration are compared to the measurement using TRL calibration with scaling the line length the same as the line length in the SOLT measurement. The comparison of measured $|S_{21}|$ between the shorter-stub line and the longer-stub line are implemented as well. These two comparisons above are shown in Figure 6. Again, the shorter-stub line and the longer-stub line are the same line exactly with the launch connector moved between the top and bottom of the board as seen in Figure 2 (c). If the TRL calibrations work properly in both cases, the difference between the two measured $|S_{21}|$ (shorter stub line and longer stub line) should be very small. This is true only in the frequency range below 12 GHz and above 18 GHz, as seen in Figure 6. The difference is large from 12 GHz to 18 GHz. The measured $|S_{21}|$ shown in Figure 6 with SOLT calibration also reveals that the dynamic range in this measurement requires approximately 70 dB, which is close to, or even exceeds the dynamic range of the VNA for an IF BW (IF Band Width) set at 3k Hz.

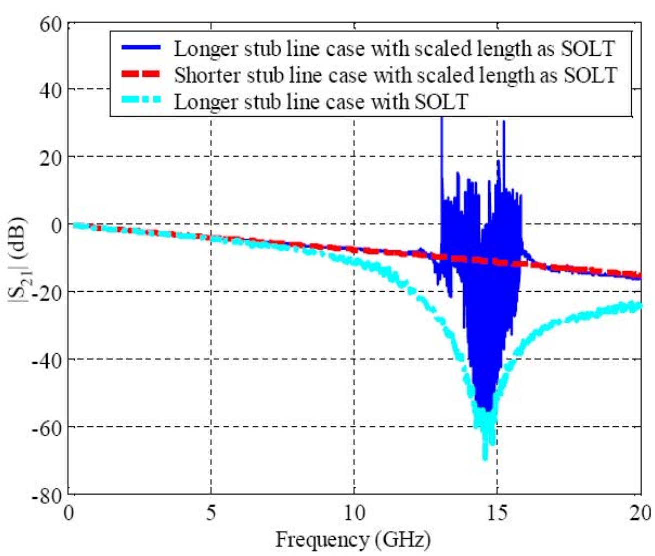


Figure 6. Comparison of measured $|S_{21}|$ for the same line using different calibration methods and port structures with length scaling.

Further measurement with TRL calibration was done by decreasing the IF BW from default 3k Hz to 10 Hz in the VNA setup so that the maximum dynamic range of the VNA could be achieved. Since the change of this setup made the calibration time extremely long, only a limited frequency range from 10 to 18 GHz was examined. The longer stub line was measured. And the measured $|S_{21}|$ is shown in Figure 7. Comparing the Figure 7 to the Figure 5 part (a), it is found that there are no significant changes in the measured $|S_{21}|$, which indicates that a certain amount of dynamic range increase does not help too much for the longer-stub line in the $|S_{21}|$ measurement. This indicates that the extended stub in the longer-stub line case is equivalent to a short circuit at the signal launch port, and the incident energy at the port is almost totally reflected. This causes the $|S_{21}|$ to exceed the dynamic range of the VNA for all the lines on the test board with the same stub length at their ports, and it is therefore not possible for this kind of lines to transfer signals from one port to the other when the stub length is 88.1 mils as shown in Figure 2 (c). Lines on the test board with this stub length at their ports operate like band stop filters at frequencies around 14 GHz. TRL calibration can not complete the error corrections for these lines in measurement. This stub length of 88.1 mils corrupts the TRL calibration thoroughly at the resonant frequency near 14 GHz.

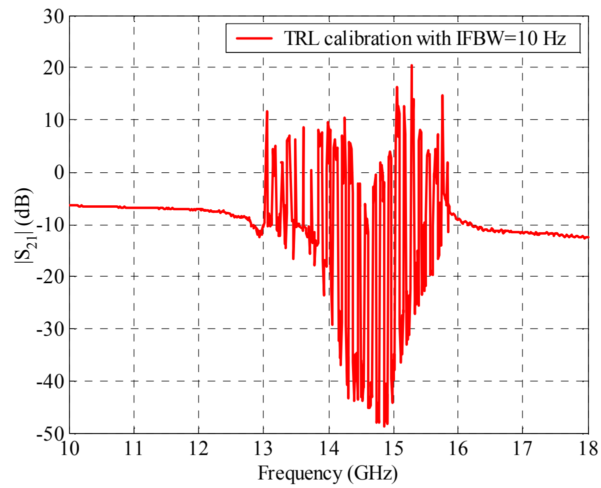


Figure 7. Measured $|S_{21}|$ for the longer stub line using TRL calibration with setup of IFBW equal to 10 Hz in VNA.

IV. Conclusions

Influences from extended stub lengths at connector ports are examined for signal transitions and TRL de-embedding. The discontinuity measurements show that if the extended stub can be back-drilled at the connector ports, this is the best way to decrease the discontinuities caused by the extended stub at the ports. If this is not feasible, to make the stub as short as possible is helpful for minimizing the discontinuities from the extended stub. The influence from the extended stub length in TRL de-embedding is critical. It impacts the signal transmission from one port to the other, and results a TRL calibration procedure failure. Though the conclusions above are from the measurements based on the signal transitions from coaxial line to transmission lines on a PCB through SMA connectors, they are equally applicable in via transitions as well.

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