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Two-Tier Multiline TRL for Calibration of Low-Cost Network Analyzers

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***Abstract*–We compare calibrations for use on three-sampler vector network analyzers (VNAs), which do not allow the direct application of some advanced error-correction schemes such as TRL (thru-reflect-line). Here we compare various alternatives, including an approximate version of TRL that has been introduced commercially and two-tier multiline TRL using external software. We consider both coaxial and coplanar open-short-load -thru (OSLT) calibrations for the first tier, showing that the latter can lead to inaccuracies. Finally, we investigate the stability of the load reflection terms to show that the first tier calibration need not be frequently repeated.**

I. INTRODUCTION

In this paper, we compare calibrations for use on a three-sampler vector network analyzer (VNA). Such inexpensive VNAs typically operate at the high radio frequencies (up to several gigahertz) and are therefore popular in the wireless telecommunications industry.

High-end VNAs often use a four-sampler architecture. This allows flexibility in the calibration and a wide range of choices for the correction of load mismatch error. In particular, the fourth sampler allows the implementation of TRL (thru-reflect-line) [1] or its derivatives, such as multiline TRL [2], LRM (line-reflect-match) [3], LRRM ((line-reflect-match) [4], and modified LRM [5]. In some cases, these TRL-based methods may offer distinct advantages. For instance, the multiline TRL method is well suited for on-wafer measurements and offers high accuracy and bandwidth, full transmission line characterization, and arbitrary reference plane and reference impedance.

The three-sampler architecture precludes straightforward TRL because it provides no direct mechanism for assessing the load reflection errors due to nonideal terminations on the port opposite the one to which the incident signal is applied. Since error occurs only if the switchable source and load have nonidentical reflection coefficients, the effect is generally known as "switching error." Users of three-sampler VNA find themselves forced to use lumped-element methods such as OSLT (open-short-load-thru).

Recently, an approximate version of TRL intended for use on a three-sampler VNA has been introduced commercially [6]. However, it simply neglects the load reflection errors and therefore may be unsuitably inaccurate [7,8].

Another way to overcome the limitations of a three-sampler system is to apply a two-tier calibration. In this case, the first tier may be an OSLT calibration in which only the load reflection terms will affect the measurements, since the second tier calibration will effectively overwrite all of the other calibration coefficients. Since the switch terms are determined in the first tier, the second tier can use TRL or a derivative. Two-tier calibrations in which the second tier is a TRL-based method have been used for many years [9]. More recently, this approach has been applied specifically to three-sampler VNAs [8,10]. The former documents that the accuracy of this method may be superior to TRL without load reflection correction.

Previous publications have neglected the major issues regarding the first calibration tier. The first question is how much freedom we have in selecting the OSLT calibration standards. Must we use nearly ideal coaxial standards, or can we use wafer-probed planar standards, which, though less well known, are far more convenient if the second tier standards and test devices are also probed? Here show that probed OSLT standards in the first tier can lead to grave errors.

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Since the first tier will thus typically require a laborious coaxial calibration, another question arises: how often must it be repeated? In the typical error model, *all* of the error coefficients drift with time and are sensitive to cable and connectors. However, we show here how to use the computed error coefficients to compute the load reflection terms and demonstrate that they may drift very little during nearly a week. Correspondingly, we see no apparent physical explanations that would cause such a drift. Thus, the first tier need not be frequently repeated. This makes the two-tier TRL approach a practical, accurate, and attractive solution to the calibration of three-sampler network analyzers.

II. NETWORK ANALYZER ARCHITECTURES & MODELS

Figure 1 is a simple operational schematic of a four-sampler VNA; this model neglects crosstalk, which can be included in the conventional way. Directional samplers behind each test port can sample the incident and reflected waves with the source switched to either port and the other port terminated by a nominally ideal load. Due to imperfections in the samplers (and the effects of cables and connectors, which can be modeled as sampler imperfections), the measured scattering parameters which can be extracted using all four sampler outputs are related to the actual scattering parameters at the test ports by the error model of Fig. 2. In this model, all of the errors are accounted for by a pair of "error box" matrices on either side of the device under test (DUT). Reflections from the source or load do not lead to errors since they are explicitly measured.

In typical use, four-sampler VNAs do *not* make use of all four data channels. Instead, only the transmitted signal, not the reflected signal, is sampled on the terminated side; this limits the cost of the electronics and increases sweep speed. Neglecting the reflected signal introduces additional error into the estimate of the DUT scattering parameters. However, this error can be corrected provided that the load reflection coefficients Γ_{load}^1 and Γ_{load}^2 are repeatable and that they can be measured at least once. The terms are expected to be repeatable and stable in electronically switched instruments. Conventionally, the resulting error model is expressed not as in Fig. 2 but instead in the form of Fig. 3.

If ideal OSLT standards are available, Γ_{load}^1 and Γ_{load}^2 are indirectly measured as part of the OSLT calibration. No similar possibility exists for TRL-based methods. However, most four-sampler VNAs allow for sampling of the fourth channel under special conditions. This allows for the direct measurement of the load reflection coefficients, which can in principle be obtained with any transmitting device at the test ports.

In three-sampler VNAs, as illustrated in Fig. 4, there is no option for the direct measurement of Γ_{load}^1 and Γ_{load}^2. Therefore, one-tier TRL-based calibrations are unavailable. Commercial implementations which attempt one-tier TRL by neglecting the load reflection may be inaccurate [7,8]. An alternative is to perform a first-tier OSLT, which implicitly determines Γ_{load}^1 and Γ_{load}^2. To perform a subsequent second-tier TRL calibration, the "uncorrected" data used as input to the second tier must be corrected using the first-tier error coefficients. After the completion of the second calibration, a new set of error coefficients is stored in the VNA. While all of these coefficients are new, the terms

$$\Gamma^1_{\text{load}} = \frac{E_{LR} - E_{SF}}{E_{RF} + E_{DF}\left(E_{LR} - E_{SF}\right)} \tag{1}$$

and

$$\Gamma^2_{\text{load}} = \frac{E_{LF} - E_{SR}}{E_{RR} + E_{DR}\left(E_{LF} - E_{SR}\right)} \tag{2}$$

are preserved.

As (1) and (2) point out, the load reflection terms depend on eight of the usual error correction terms E_{ij}. While one-tier TRL determines Γ_{load}^1 and Γ_{load}^2 directly, the first-tier OSLT determines them indirectly through the E_{ij}. Thus, errors in the OSLT standards will result in erroneous values of Γ_{load}^1 and Γ_{load}^2 that will invalidate the second-tier calibration. Obviously, some elements, such as the load standards, need not be ideal. However, erroneously defined opens and shorts will be problematic.

III. MEASUREMENTS

We compared the accuracy of several calibrations using a three-sampler VNA. We performed second-tier multiline TRL calibrations with respect three first tiers: on-wafer OSLT, coaxial OSLT, and an "empty" calibration; the last ignored the load reflection terms altogether, as in [6]. We also investigated the long-term drift of the load reflection terms. We used a multiline TRL calibration on a four-sampler VNA for comparison. All multiline TRL calibrations used the NIST software MultiCal.

A set of commercial APC-7 standards was used for the first-tier coaxial OSLT calibrations. The artifacts consisted of a short circuit, an open circuit, and two nominally 50 Ω loads. We used a direct connection between the ports to serve as a through line. The electrical behavior of the coaxial standards was defined in accordance with the manufacturer's recommendations [11]. The multiline TRL standards were constructed of coplanar waveguide on GaAs [12]; the gold center conductor was 73 μm wide and separated from the grounded plane by 49 μm gaps. The five line standards included a 0.55 mm through line and four additional lines that were 2.135, 3.2, 6.565, and 19.695 mm longer. These standards were measured using on-wafer probes. The OSLT open circuit was defined by lifting the probe heads off of the wafer. For each standard, whether coaxial or on-wafer, we measured scattering parameters at frequencies between 50 MHz and 6 GHz with an averaging factor of 256.

In order to assess drift of the load reflection terms, a one-tier coaxial OSLT calibration was repeated after a period of five days. These terms showed virtually undetectable drift, as Fig. 5 partially illustrates, even though drift in the conventional error correction terms (from which the load reflection terms were extracted as in (1) and (2)) was large.

For comparison, an on-wafer OSLT was also performed as a first tier. Figure 5 demonstrates its inadequacy, showing that it ineffectively determines the load reflection terms. This is due to the on-wafer OSLT standards, which are far from ideal.

Next, on-wafer second-tier multiline TRL calibrations were performed with respect to the various first tiers. An on-wafer second tier calibration was also performed with an empty first tier in order to show the effect of completely ignoring the switching terms.

In Figs. 6-7, we plot the real and imaginary parts of the load impedance of a resistor. Most of the calibrations compare well. However, with the on-wafer OSLT as the first tier, the impedance is apparently in error by around $(2-j)$ Ω at the lower frequencies and around $2j$ Ω at the higher frequencies. The two-tier calibration without load reflection correction compares well except at the lower frequencies.

Figures 8-9 plot the magnitude and phase of S_{11} of a short circuit. Here, the calibrations compare moderately well except when neglecting load reflection correction. The calibration using the one-tier on-wafer OSLT show a drift in phase with increasing frequency.

Figures 10-11 compare the real and imaginary parts of the characteristic impedance Z_0 of the lines as determined by the four-sampler VNA using one-tier multiline TRL and the three-sampler VNA using two-tier multiline TRL with coaxial OSLT as the first tier.

IV. CONCLUSIONS

Multiline TRL can be easily implemented on a three-sampler VNA using external software. The accuracy can be nearly as good as a four-sampler VNA. Although an additional first-tier calibration using coaxial standards is required, this first tier need not be repeated frequently as long as the calibration factors are retained in the VNA. Alternatively, the load reflection coefficients could be extracted from the first-tier calibration and stored externally for later use.

Obviously, this method allows for various TRL derivatives, including LRM, modified LRM, and LRRM.

V. ACKNOWLEDGEMENTS

Donald C. DeGroot of the National Institute of Standards and Technology (NIST) modified the NIST calibration software MultiCal (formerly entitled DEEMBED) so as to interface with a series of three-sampler VNAs.

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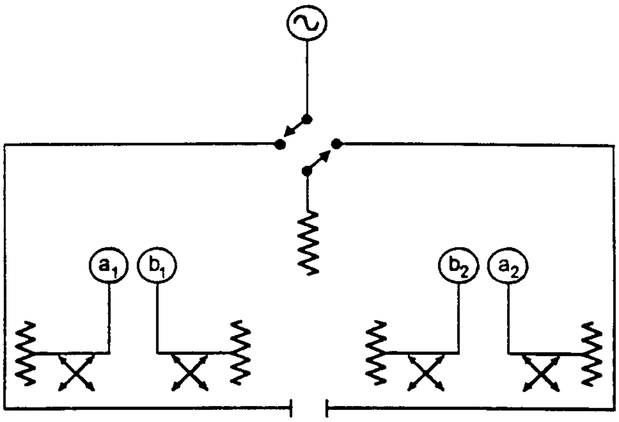

Figure 1: Four-Sampler Vector Network Analyzer

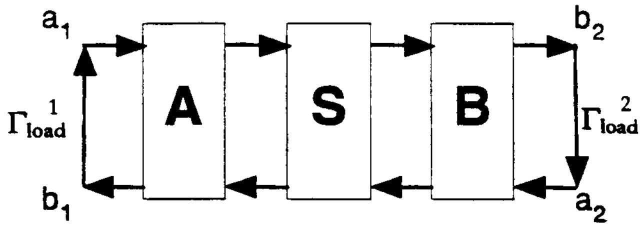

Figure 2: Network Analyzer Error Model. **S** is device under test; **A** and **B** are error two-ports associated with Ports 1 and 2 respectively.

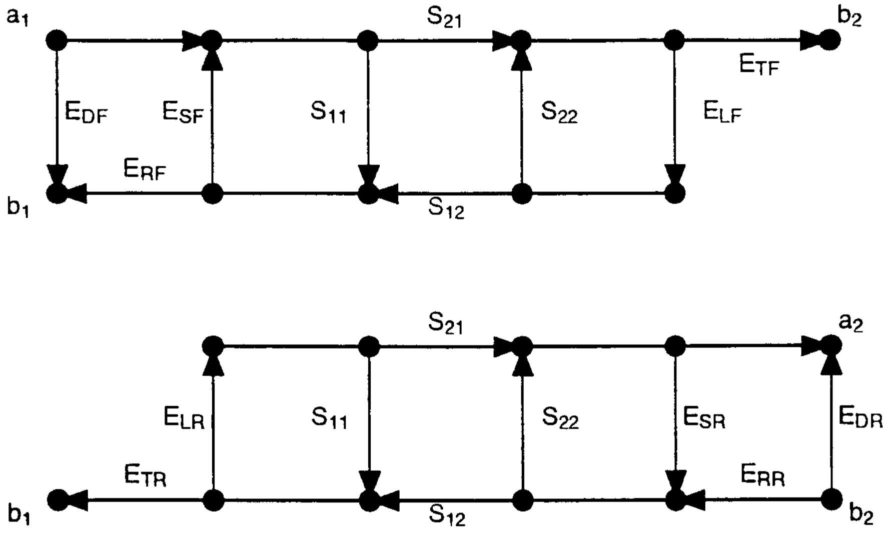

Figure 3: Conventional Network Analyzer Error Model. S is device under test. The top diagram applies when power is applied to Port 1, the bottom for power on port 2.

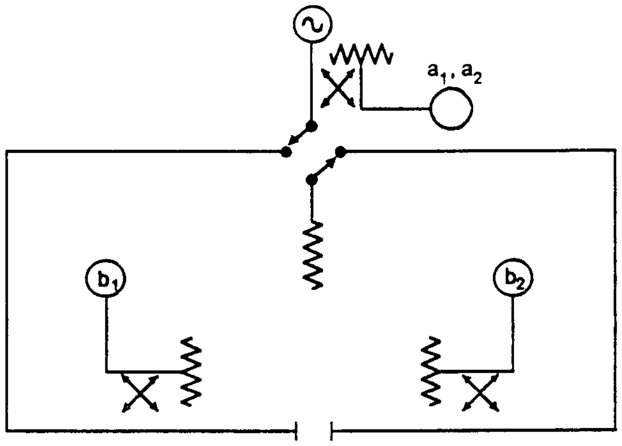

Figure 4: Three-Sampler Vector Network Analyzer

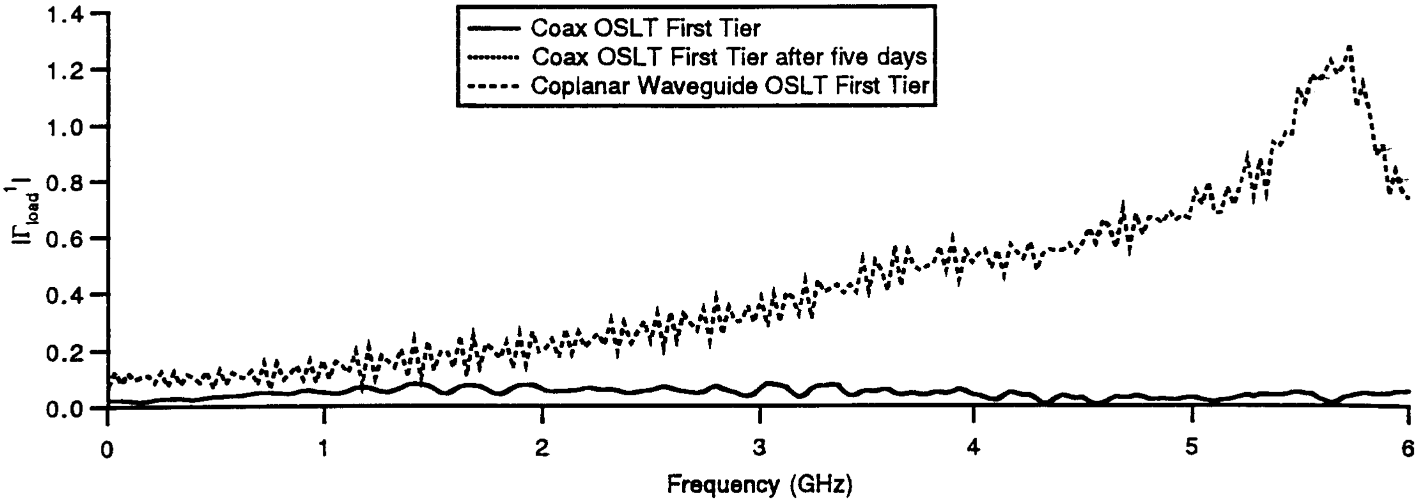

Figure 5. Magnitude of Port 1 Load Reflection Coefficient

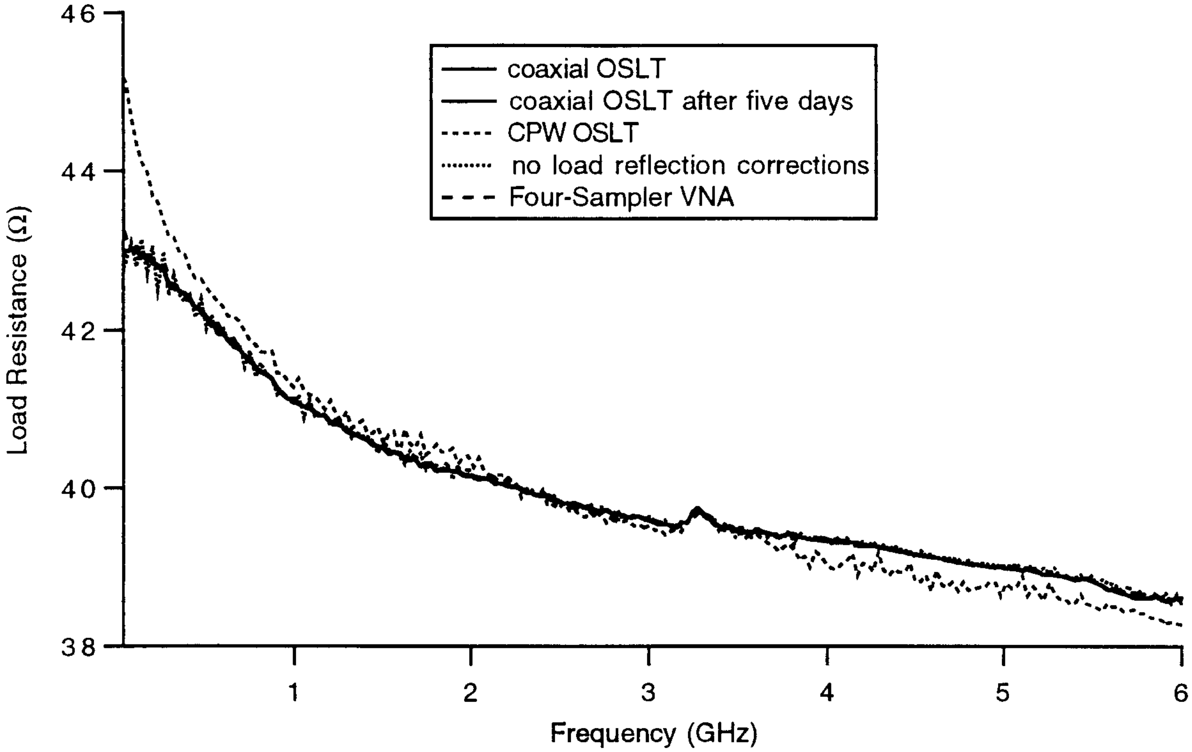

Figure 6. Measured resistance of resistor embedded in coplanar waveguide.

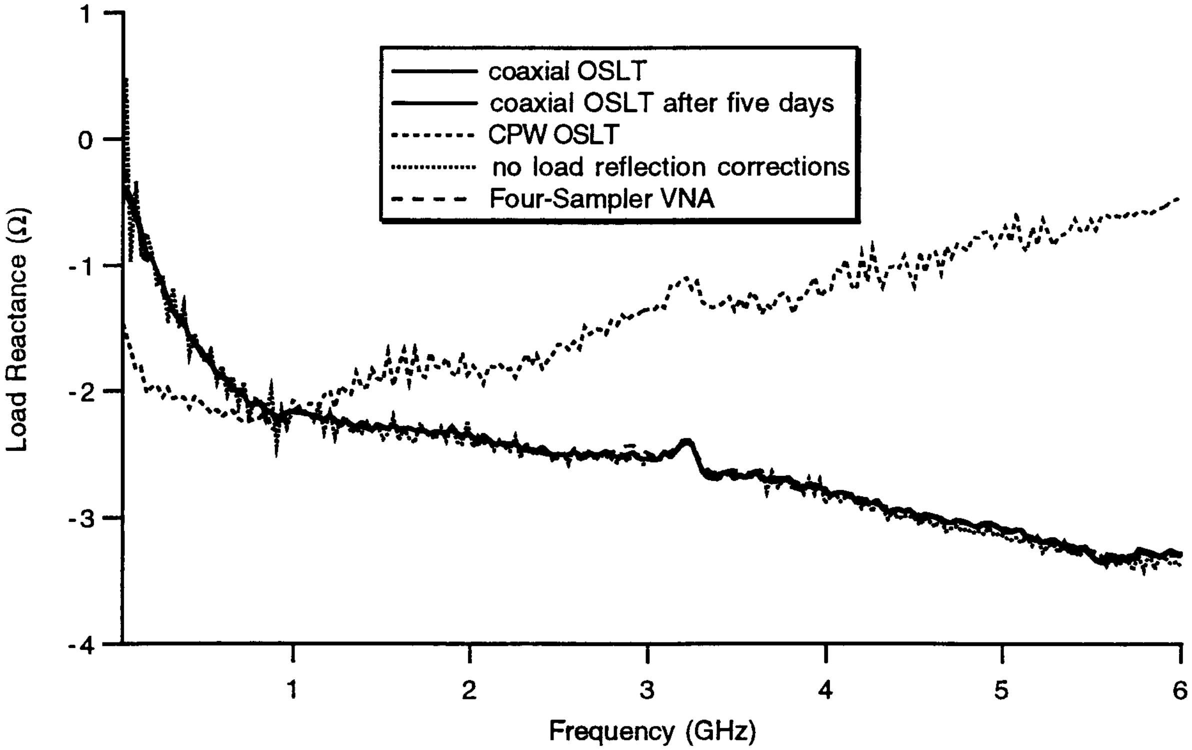

Figure 7. Measured load reactance of resistor embedded in coplanar waveguide.

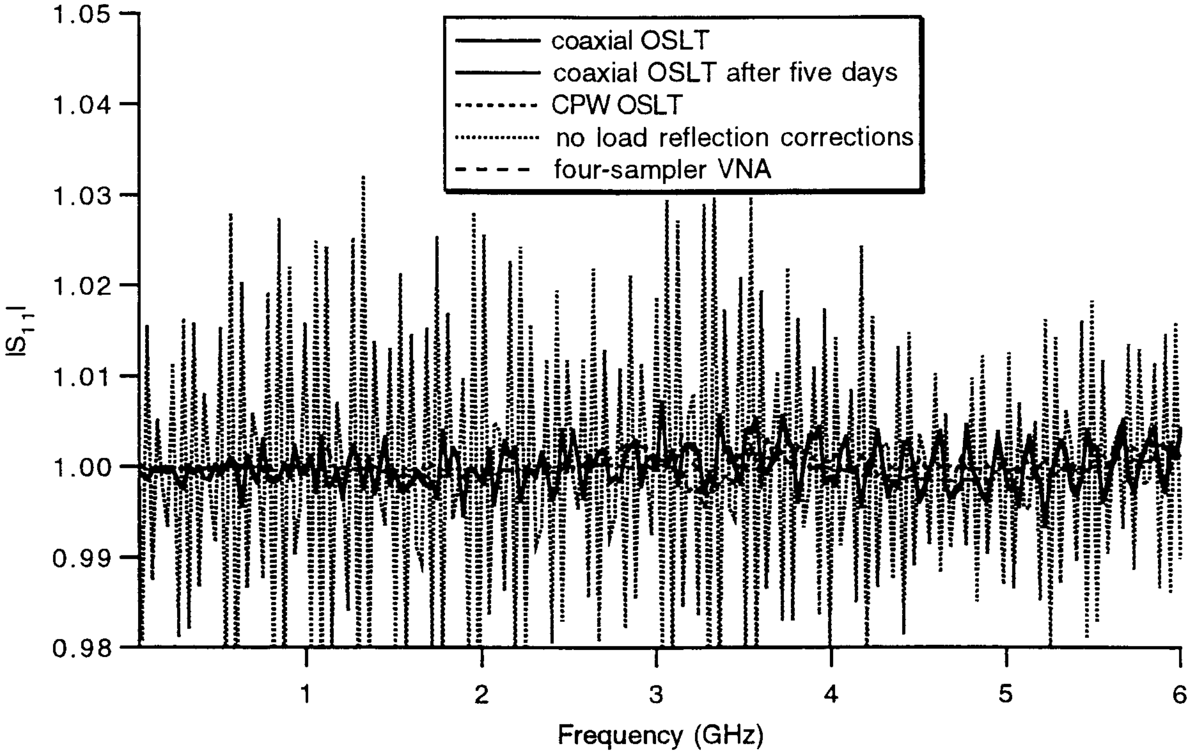

Figure 8. Magnitude of reflection coefficient of a coplanar waveguide short circuit.

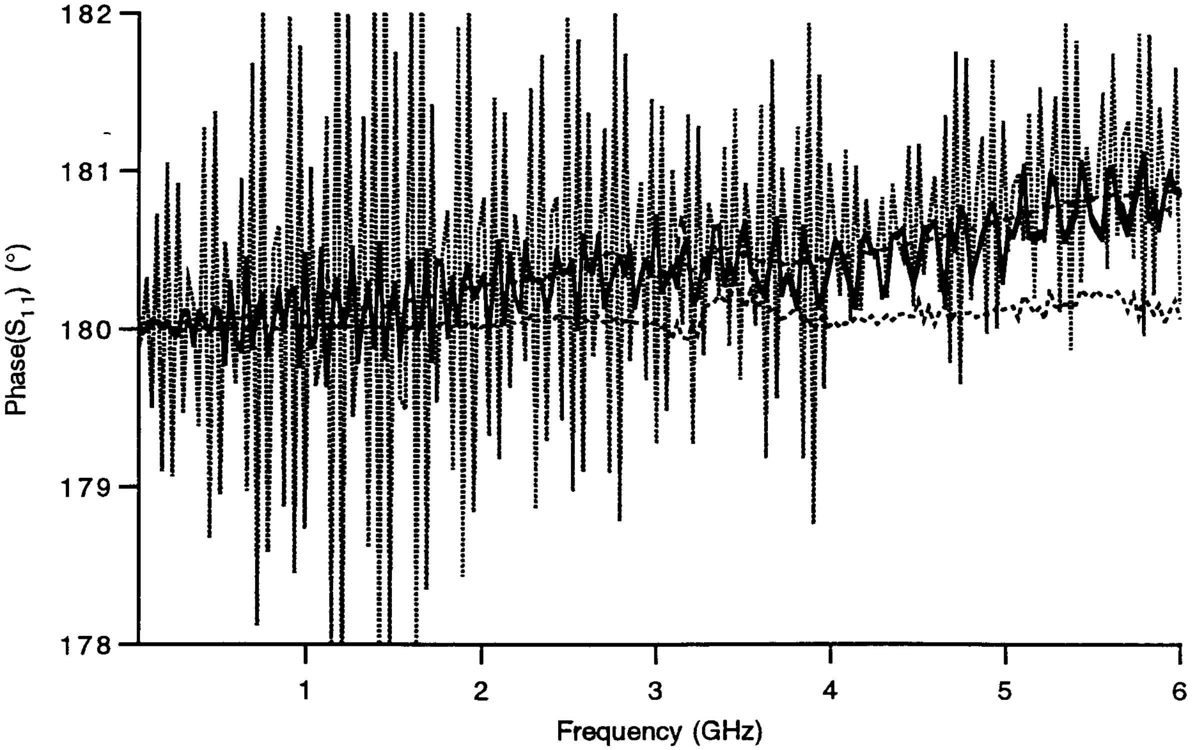

Figure 9. Phase of reflection coefficient of a coplanar waveguide short circuit.

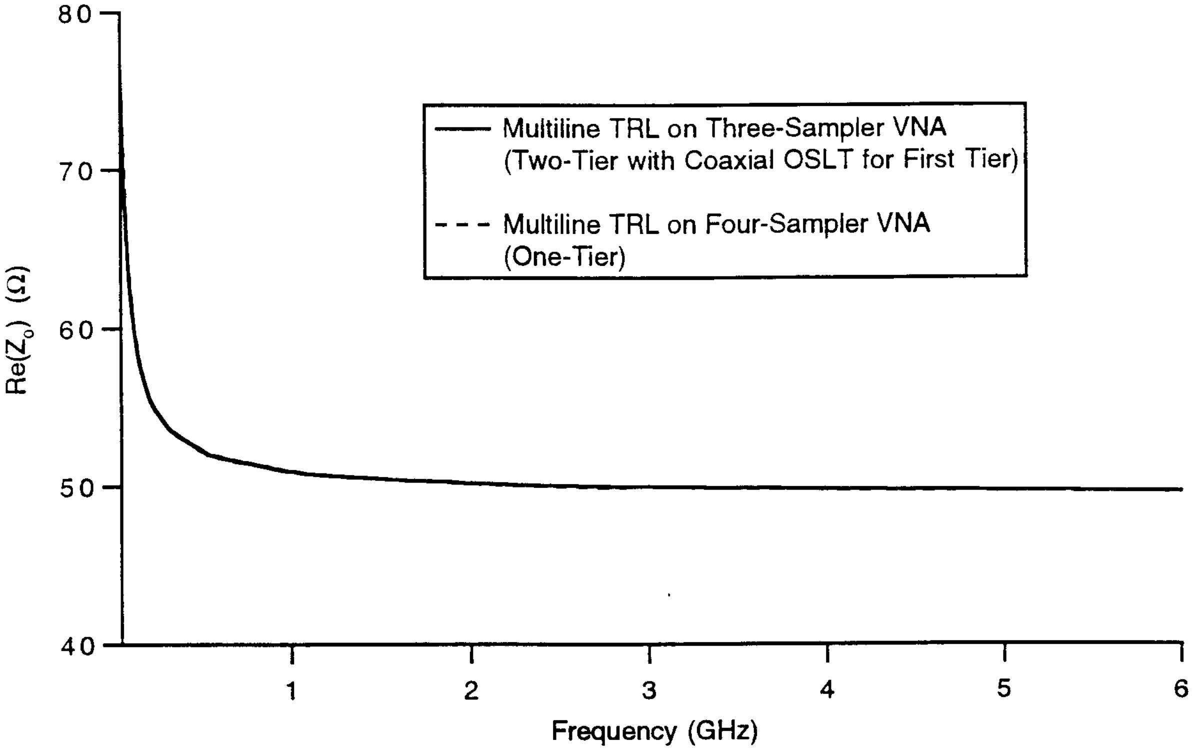

Figure 10. Real part of characteristic impedance.

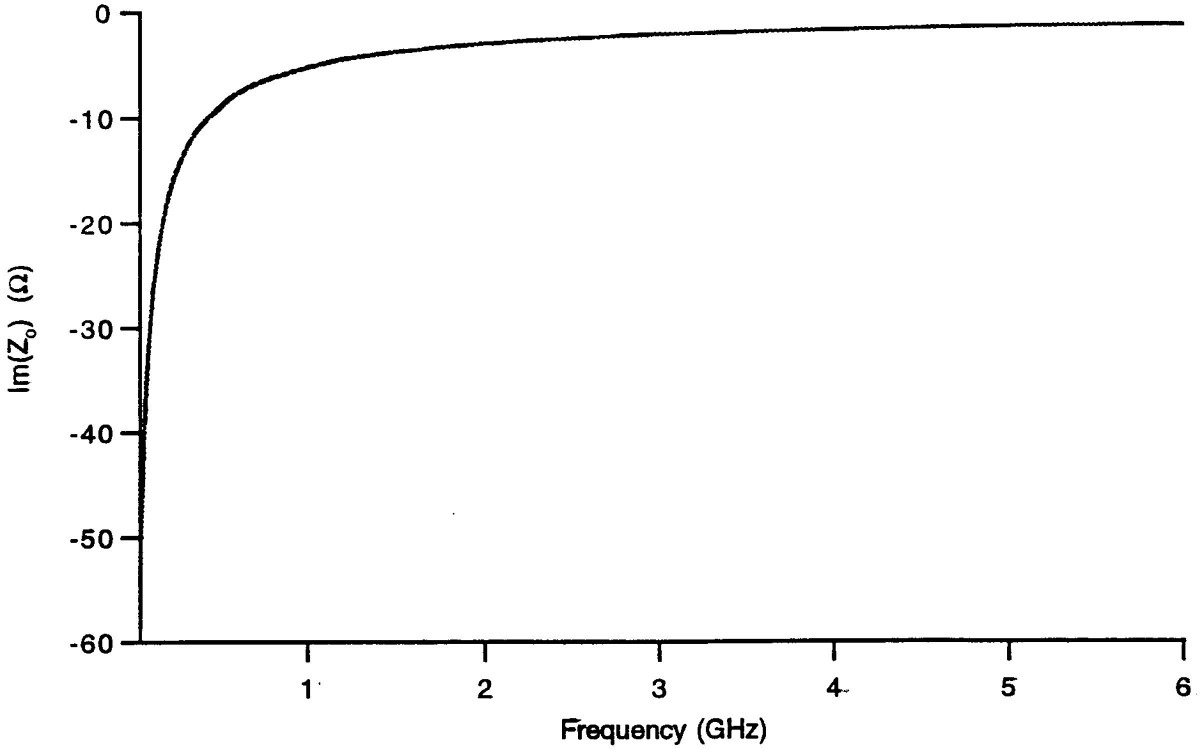

Figure 11. Imaginary part of characteristic impedance.