Wide-Bandwidth Thru-Reflect-Line Calibration for Empty Substrate Integrated Coaxial Line with GCPW Transitions

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Abstract: Empty coaxial structures built with printed circuit boards have low radiation, low losses, high quality factor and non-dispersive features. The fully integration of empty substrate-integrated coaxial line (ESICL) in a planar substrate is nowadays a fact thanks to a grounded coplanar transition. To properly characterize and measure this new ESICL family of devices, a low cost and easy to manufacture thru-reflect-line calibration kit is proposed to de-embed not only the connectors and feeding lines, but also the ESICL transitions.

1. INTRODUCTION

Substrate Integrated Circuits (SIC) are becoming most important every day due to their good performance characteristics (losses and quality factor)¹. One of the technologies that take profit of this achievements is the *Substrate Integrated Coaxial Line* (SICL); these lines have single mode propagation, non-dispersion and low radiation, and therefore are suitable for wide bandwidth applications with low losses². Recently, a new advance has been developed regarding this kind of lines with the *Empty Substrate Integrated Coaxial Line* (ESICL) presented in³ in 2015, which is a novel structure that can be entirely fabricated with standard dielectric substrate layers by using exclusively *Printed Circuit Board* (PCB) standard manufacturing procedures; ESICL shows low cost, low losses, non-dispersion, immunity to interferences and cross-talk, etc.

Recently, some devices have been developed using ESICL: transition to grounded coplanar lines (GCPW)³, a wideband bandpass filter³ and a high-Q narrow bandwidth bandpass filter⁴. At the same time, specific analysis techniques (BI-RME, FEM) for ESICL have also been carried out, which allow the full-wave analysis and design of ESICL devices¹.

ESICL is built up by piling conventional substrate layers³. The general topology can be observed in Figure 1; it is composed of five separated PCB layers accordingly aligned and metalized to generate a suspended rectangular conductor within an empty guide. With the available transition GCPW-ESICL, it has been possible to integrate a dielectricless TEM line in a planar substrate. Devices implemented in ESICL can be manufactured quite easily and would achieve very high quality responses and low losses, with performance only comparable to *Empty Substrate Integrated Waveguide* (ESIW) devices and much better than the rest of conventional planar lines or SICs¹.

2. DESIGN AND MANUFACTURING OF THE TRL CALIBRATION KIT FOR ESICL

When an ESICL device is measured, most of the mismatch loss is due to the transition, together with the connectors and their solders. If the measurements are taken using a test fixture, a standard thru-reflect-line (TRL) calibration procedure⁵ can be applied to de-embed the connectors, so that the reference planes for the measurements are then transferred to the input and output coplanar lines. Nevertheless, there still remains losses due to the coplanar to ESICL transition, which can even mask the real response of the ESICL device alone.

In other planar technologies, like ESIW, *Air-Filled Substrate Integrated Waveguide* (AFSIW) or *Substrate Integrated Waveguides* (SIW) with similar questions regarding the accuracy of the measurements, calibration kits were designed and implemented to de-embed not only the connectors and the input line, but also the transition, so that the measurements only show the response of the real device^{6,7,8}. Then, accordingly to that procedure, in this paper a specific thru-reflect-line (TRL) calibration kit for GCPW-ESICL is presented that allows the de-embedding of the connectors, the coplanar line and the transition to the ESICL device. Additional advantages of this kit are its low cost, as it can be manufactured with standard machinery for planar circuits, its accuracy in correcting all deviations due to the elements between the network analyzer and the real ESICL device, as well as its wide frequency margin of operation, given that it is intended for bands among 2 GHz and 18 GHz (bands S, C, X, Ku).

The designed TRL calibration kit for ESICL consists of four standards (thru, short, line, long-line), whose central layers are shown in Figure 2; their aim is to place the measurement reference planes at the beginning and at the end of the ESICL device. The standards have been manufactured with a Rogers 4003C substrate ($\epsilon_r = 3.55$, 0.813 mm thickness, loss tangent $\tan \delta = 0.0027$, 17.5 μm of copper metalization) to generate a coaxial line, which presents a width of $w_{coax} = 6$ mm with an inner conductor of width $w_{in} = 1.817$ mm. All the manufactured standards incorporate, before the ESICL specific circuit, a socket for a K connector, a section of GCPW

line and the GCPW to ESICL transition. All these elements are included both at the input and output of the devices to be measured, and consequently, they constitute the elements to be de-embedded from the measurements.

Specifically, the standards operate at the margin of frequencies of S-band, between 2-GHz and 4 GHz, C-band, between 4 GHz and 8 GHz, X-band, between 8 GHz and 12 GHz, and Ku-band, between 12 GHz and 18 GHz, and are characterized as follows:

- The reflect is ended, in this case, with a short-circuit to achieve a load of high reflectivity after a length of 25 mm of ESICL line.
- The thru is made up of an empty ESICL line of 50 mm.
- The line adds an appropriate electrical length of 5.6942 mm between input and output ports, so the total length is 55.6942 mm; this covers X-band and Ku-band.
- The long-line adds an appropriate electrical length of 18.0065 mm between input and output ports, so the total length is 68.0065 mm; this, combined with the former thru, covers S-band and C-band.

The procedure to use the kit is the common in TRL calibration. Initially, the calibration kit has to be defined in the network analyzer⁹; then the three basic standards and the long-line are measured, so that the analyzer could correct all the systematic errors and deviations using its built-in full two-port TRL calibration function. The three basic standards correct the measurements among 8 GHz and 18 GHz and the extended procedure, including the long-line, makes possible also the correction of the measurements among 2 GHz and 8 GHz. After storing the corrections, the ESICL devices can be effectively measured with high accuracy within the operation margin.

3. RESULTS

To check the validity of the calibration kit, first the measurement and validation of the long-line is carried out. Figure 3 shows the calibrated measurement of the ESICL long-line device carried out after the calibration of the network analyzer with the three basic standards, which provides the expected results: almost complete transmission and low reflection.

Then, to prove the utility of the calibration kit using the long-line as a fourth standard to extend the measurement margin, a real useful device has been designed, manufactured and measured. It is a 5th-order Chebyshev filter centered at 13 GHz with bandwidth of 300 MHz, 0.01 dB of ripple and simulated quality factor of 1643 (calculated according to equations given in¹⁰); its layer-composition is shown in Figure 4. This filter exhibits the same topology that was presented in⁴.

Figure 5 shows the measured response of the ESICL filter in the margin from 2 GHz to 18 GHz by applying the extended calibration procedure; this plot reveals a measurement of high quality and accuracy in a wide frequency bandwidth (from bands S to Ku), what reasserts the validity of the measurement procedure. A zoomed version of the plot can be seen at Figure 6 in the narrow designed margin from 12 GHz to 14 GHz; it leads to a measured insertion loss of 0.98 dB, which is very low, and provides a measured quality factor¹⁰ of 1509, which is very high and close to the simulated one. The response of this standalone ESICL filter has been simulated using CST Studio Suite. The results of this simulation are also included in Figure 6, where it can be noticed a good agreement between measurements and simulation. This also proves the high quality of the de-embedding process that the calibration kit is able to provide.

As it has been already stated, the main advantage of using this calibration kit is the high quality and accuracy of the measurements that can be achieved. To reaffirm this fact, the real effect of the calibration kit can be seen in Figure 7, where the comparison of the measurement of the long-line is done by using the standard coaxial calibration of the network analyzer and by using the new ESICL calibration kit; a difference of more than 1.4 dB can be observed between both measurements due to the K connectors, the sections of GCPW lines and the GCPW to ESICL transitions. A similar

comparison can be seen in Figure 8 for the filter in the narrow-margin of the bandpass; a difference of 1.4 dB in the measurement at the central frequency is stated.

4. CONCLUSION

The novelty and high quality of the recent ESICL technology points to a promising development of devices designed according to their principles. So that these devices could be properly characterized, a calibration procedure is required so that connectors, input and output lines and transitions to, and from, ESICL could be de-embedded to achieve measurements of high quality and accuracy.

This paper has presented the design, manufacture and validation of a wide-bandwidth calibration kit for ESICL, which presents also the advantages of being low cost and quite easy to design and manufacture by means of standard machinery and common substrates.

As it may be expected, both basic and extended ESICL calibration procedures are much better than the standard coaxial calibration procedure of the network analyzer; losses due to connectors, coplanar lines and GCPW to ESICL transitions can be removed with the calibration kit.

Consequently, it gives measurements closer to reality, as the characterization of real devices can be achieved with higher accuracy. This is due to the fact that the effects of all the intermediate elements to insert the signal into the device and extract it from the device can be de-embedded.

The basic calibration kit presented has been used to extend the corrections of the measurements to a wider frequency margin, from 2 GHz to 18 GHz, using for that a long-line as a fourth standard; with the extended procedure, it has been possible to successfully measure a practical ESICL device -a bandpass filter-.

The improvement regarding the simple standard coaxial calibration of the network analyzer has also been revealed to reinforce the high quality of the described wide-bandwidth calibration kit.

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FIGURES AND CAPTIONS

FIGURE 1 Construction of a typical ESICL structure³: (left) separated layers; (right) cross-section.

FIGURE 2 Central layer of the manufactured circuits, from top to bottom: short, line, thru, long-line.

FIGURE 3 Measurement of long line with the basic 3-standards ESICL calibration.

FIGURE 4 ESICL filter to be measured.

FIGURE 5 Measurement of filter with the extended 4-standards ESICL calibration in the full-margin (2-18 GHz).

FIGURE 6 Comparison of simulated and measured filter with ESICL calibration in the range from 12 GHz to 14 GHz.

FIGURE 7 Comparison between ESICL calibration kit and standard network analyzer calibration procedure: correction of the de-embedding in the long-line.

FIGURE 8 Comparison between ESICL extended calibration kit and standard network analyzer calibration procedure: correction of the de-embedding in the filter.