Thru-Reflect-Line calibration for empty substrate integrated waveguide with microstrip transitions

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In the last years a great number of substrate integrated circuits have been developed. These new circuits are a compromise between the advantages of classical waveguide technologies, such as high quality factor and low losses, and the advantages of planar circuits, such as low cost and easy compact integration. Among all these new transmission lines, the substrate integrated waveguide (SIW) has received special attention. Although the quality factor and losses of these new integrated lines are better than for planar circuits, these characteristics are worse than in the case of waveguides, mainly due to the presence of the dielectric substrate. In order to improve the performance of the integrated circuits, a new methodology for manufacturing empty waveguides, without dielectric substrate, but at the same time completely integrated in a planar substrate, has been recently proposed, resulting in the novel empty substrate integrated waveguide (ESIW).

In this work a low-cost and easy to manufacture TRL calibration kit for de-embedding the effect of connectors and transitions when measuring ESIW devices is presented. Results prove the high quality of this calibration kit.

Introduction: Much effort has been devoted to the integration of waveguides inside printed circuit substrates. These new type of substrate integrated transmission lines are generically known as Substrate Integrated Circuits (SIC). Their performance (losses and quality factor) is midway between the performance of classical waveguides and planar circuits. Among them there is a great variety, but the most popular one is the *Substrate Integrated Waveguide* (SIW).

SIW devices improve the performance of planar circuits because they present lower losses and greater quality factors, although the losses and quality factor are still better in rectangular waveguide devices. SIW devices are easy to manufacture, are integrated in printed circuits, and are much less bulky. This length reduction, however, makes SIW devices more sensitive to manufacturing tolerances, which can be a very limiting factor at high frequency.

In an attempt to go one step further, in [1] a new type of transmission line was presented. It was called *Empty Substrate Integrated Waveguide* (ESIW). This line is an empty rectangular waveguide that can be manufactured with low-cost techniques, using the same machines that are present in any standard laboratory for manufacturing planar circuits. The ESIW is build emptying a substrate sheet, so it can be embedded with planar circuits, thanks to a new wideband transition that tapers from microstrip to the rectangular waveguide emptied in the substrate. The results presented in [1] and [2] for coupled cavities filters proved that the quality factor of the ESIW filters was around 4.5 times greater than for the equivalent filter in SIW. And all this maintaining the advantages of SIW: low-cost, easy manufacturing and integration with planar circuits, and less sensitivity to manufacturing tolerances.

However, both SIW and ESIW components must be interconnected with planar structures in order to be measured or connected to active circuits or to other planar circuits implemented for example in microstrip technology. For that purpose, transitions from SIW to microstrip line [3], [4] or to coplanar waveguide [5] to SIW or from microstrip to ESIW [1] have already been developed.

When a SIW or ESIW device is measured, most of the mismatch loss is due to the transition, together with the SMA connectors and their solders. If a microstrip test fixture is used to perform the measurements, the SMA connectors can be de-embedded with a standard thu-reflect-line (TRL) calibration procedure, so that the reference planes for the measurements are now placed at the input and output microstrip lines. However, there is still a great amount of losses that are due to the microstrip to SIW or ESIW transition. And these losses may greatly mask the real response of the SIW or ESIW device alone.

For that purpose, a thru-reflect-line (TRL) [6] calibration kit for SIW was presented in [7], which successfully removed the effect of the transitions from microstrip to SIW and from SMA to microstrip from the measurements.

This calibration kit, however, is specific for SIW devices, and cannot be used for measuring the novel ESIW devices.

TRL calibration for ESIW: The aim of this work is to present a new TRL calibration kit for ESIW devices, and to prove its validity for de-embedding the effect of the SMA to microstrip and microstrip to ESIW transitions. An additional advantage of this calibration kit is that any designer or researcher can fabricate its own calibration kit with standard machinery for manufacturing planar circuits, so it is much cheaper than any standard commercial calibration kit, which, besides, would not be so accurate, as they can, at best, correct the deviations due to the measurement circuit between the network analyser itself and the SMA connectors, but not those due to the microstrip line and the microstrip-to-SIW tapered transition.

We are going to develop a calibration kit for the measurement of the ESIW filter shown in Figure 1. It is a pass band coupled cavity filter with Chebyshev response and four cavities (and therefore, with four reflection zeros). The filter is centered at $15,15$ GHz, with 500 MHz of bandwidth. The ESIW filter has been manufactured using a ROGERS 4003C substrate. The permittivity of this substrate is ε_r=3,55, and the height is $h = 1,524$ mm. The rectangular waveguide that is cut in the substrate to mechanize the ESIW has a width of $a = 15,7988$ mm, so that the transversal dimensions of ESIW empty rectangular waveguide are $a = 15,7988$ mm and $b = h = 1,524$ mm. The width a has been chosen to be the same as the width of the standard WR-62 classical rectangular waveguide. Therefore, the ESIW is the same as a classical rectangular waveguide in WR-62, except that its height is lower (the height of the substrate, so it is low-profile and integrated in the substrate), and that it has been manufactured using standard low-cost planar circuit machinery and materials.

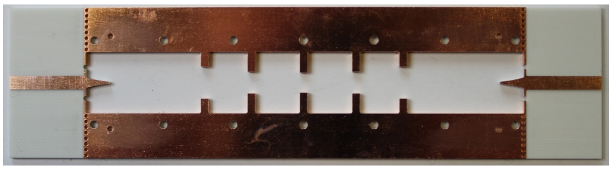
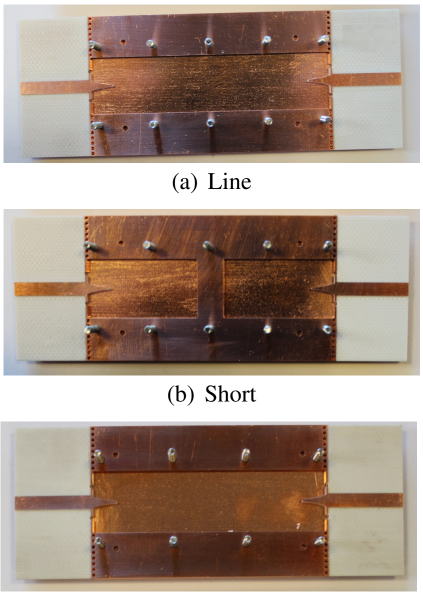


Fig. 1. Filter

In order to perform a TRL calibration, three standards have to be manufactured (a thru, a reflect and a line). These standards must include the microstrip to ESIW transitions so that they are de-embedded from the measurements and the reference planes are positioned at the beginning and at the end of the ESIW device. The width of the ESIW lines has to be the same as for the device we want to measure. In this case, $a = 15,7988$ mm.



(a) Line

(b) Short

(c) Thru

Fig. 2. The three standards of the TRL ESIW calibration kit

The calibration kit that has been manufactured in order to measure the filter of Figure 1, is shown in Figure 2. As it can be observed, three standards are needed for the calibration (line, reflect and thru). The three standards incorporate a section of microstrip line, the microstrip to ESIW transition, and a section of 30 mm of ESIW empty line. This is also included at the input and output of the device under test (in this case the filter of Figure 1), and this is what will be de-embedded from the measurements. The reflect has to be ended with a load with high reflectivity. In this case the reflect has been implemented with a short-circuit. The thru is obtained connecting the input and output directly (so it is an empty ESIW line of 60 mm), and the line is obtained adding a section of ESIW empty line between both ports of and appropriate electrical length (7, 0698 mm, which gives a total length of 67, 0698 mm).

This calibration kit can be used to calibrate the measurements of any ESIW device whose width is the width of the standard WR-62. So, in order to measure any ESIW device for any working frequency, one could manufacture with this low-cost procedure a similar calibration kit for each type of standard rectangular waveguide width, in the same fashion as it is done at present with the classical rectangular waveguide where there are commercially available calibration kits for each one of the standard sizes of rectangular waveguides. In this case, however, it is quite straightforward and low-cost to manufacture each calibration kit with standard planar circuit manufacturing facilities.

The calibration kit of Figure 2 has the same operating frequency as the standard WR-62 calibration kit for classical rectangular waveguides.

This calibration kit will de-embed the microstrip to ESIW transitions, as well as the microstrip line and SMA connectors. However, other type of transitions and exiting planar lines (i.e. coplanar line) could have been equally used.

Once the standards have been manufactured, the procedure that has to be followed is the usual in a TRL calibration. First we define the calibration kit in the network analyser [8]. Then we measure the three standards of the calibration kit of Figure 2 so that the analyser corrects all the systematic errors and deviations in the measure with its built-in full two-port TRL calibration function. Finally, once we have calibrated, we measure the ESIW device. Alternatively, one can store all the measurements and perform the TRL calibration with your own software (for example, in MATLAB).

Results: The calibrated measurements of the 4-pole ESIW filter of Figure 1 are shown in Figure 3. These are the measurements of only the ESIW device, since all transitions and connectors have been de-embedded.

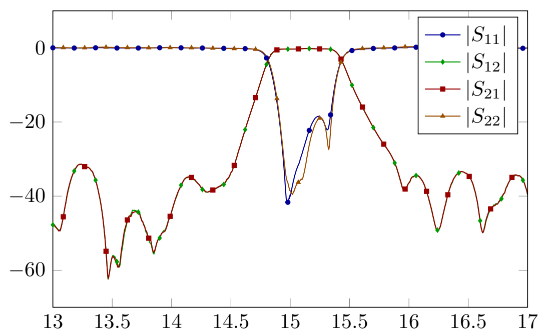


Fig. 3. Measurements of the filter with the ESIW calibration

In Figure 3 the high quality of the measurements can be appreciated, but for further validation we present in Figure 4 the calibrated measurement of the ESIW line of Figure 2.(a). As it can be observed, the return losses are greater than 40 dB in all the bandwidth of the ESIW line, thus proving the quality of the calibration technique.

Figure 5 compares the measurements of the filter of Figure 1 with the ESIW calibration with the same measurements but with a microstrip calibration kit. As it can be observed, with the ESIW calibration the losses due to the microstrip to ESIW transition have been eliminated.

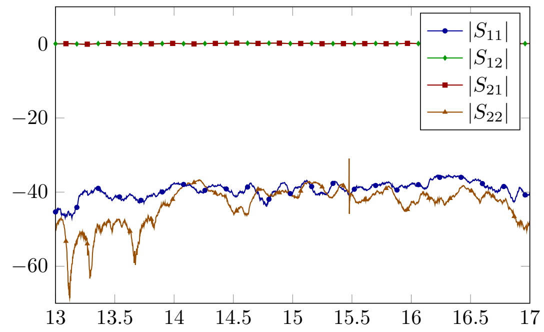


Fig. 4. Measurements of the line

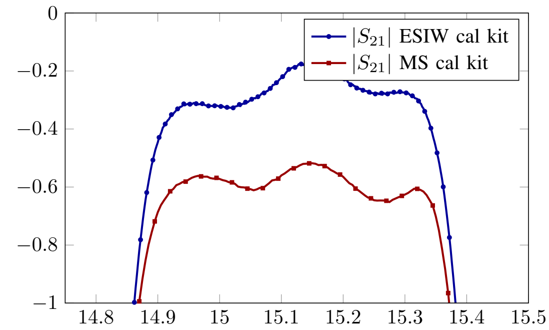


Fig. 5. Comparison between ESIW and microstrip calibration kits

Conclusion: A novel TRL calibration for ESIW devices has been presented in this work. ESIW devices are completely new, and no calibration technique has still been developed for this promising transmission line. This TRL calibration is similar to the one already developed for SIW devices. It has the advantage of being low-cost, and that you can manufacture it yourself with standard machinery and materials for planar circuits. Results have been presented for the calibrated measurement of a 4-pole ESIW filter and an empty ESIW line that prove the high quality of the calibration kit here presented.

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References

1 A. Belenguer, H. Esteban, and V. E. Boria, "Novel empty substrate integrated waveguide for high-performance microwave integrated circuits," *IEEE Trans. on Microwave Theory and Techniques*, vol. To be published, pp. 1–8, April 2014.

2 A. Belenguer, H. Esteban, V. E. Boria, and J. V. Morro, "Evaluación de las prestaciones de filtros de orden elevado implementados con la nueva guía vacía integrada en sustrato," in *XIX Simposium nacional de la Unión de Radio Científica Internacional (URSI 2014)*, Valencia, Spain, September 2014, pp. 1–4.

3 D. Deslandes and K. Wu, "Integrated microstrip and rectangular waveguide in planar form," *IEEE Microwave and Wireless Components Letters*, vol. 11, no. 2, pp. 68–70, February 2001.

4 M. Abdolhamidi, A. Enayati, M. Shahabadi, and R. Faraji-Dana, "Wideband single-layer DC-decoupled substrate integrated waveguide (SIW)-to-microstrip transition using an interdigital configuration," in *Proc. Asia-Pacific Microwave Conf., (APMC 2007)*, 2007, pp. 1–4.

5 D. Deslandes and K. Wu, "Analysis and design of current probe transition from grounded coplanar to substrate integrated rectangular waveguides," *IEEE Transactions on Microwave Theory and Techniques*, vol. 53, no. 8, pp. 2487–2494, August 2005.

6 G. Engen and C. Hoer, "Thru-reflect-line: an improved technique for calibrating the dual six-port automatic network analyzer," *IEEE Trans. Microw. Theory Tech.*, vol. 27, no. 12, p. 987âĂŞ993, 1979.

7 E. Díaz, A. Belenguer, H. Esteban, and V. Boria, "Thru-reflect-line calibration for substrate integrated waveguide devices with tapered microstrip transitions," *Electronic Letters*, vol. 49, no. 2, pp. 132–133, Jan 2013.

8 Agilent, "Specifying calibration standards for the agilent 8510 network analyzer," Agilent Product Note 8510-5B, Tech. Rep., 2006.