Thru–reflect–line calibration for empty substrate integrated waveguide with microstrip transitions

M.D. Fernández Berlanga, J.A. Ballesteros Garrido, L. Martínez Cano, H. Esteban González✉ and Á. Belenguer Martínez

In past years, a great number of substrate integrated circuits have been developed. Among 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 the planar circuits, these characteristics are worst than in the case of waveguides, mainly due to the presence of dielectric substrate. To improve the performance of the integrated circuits, a new methodology for manufacturing the 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 SIW (ESIW). A low-cost and easy to manufacture thru–reflect–line 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 the printed circuit substrates. This new type of substrate integrated transmission lines are generically known as substrate integrated 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 the 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.

In an attempt to go one step further, in [1] a new type of transmission line was presented. It was called the empty SIW (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 built 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] for coupled cavities filters proved that the quality factor of the ESIW filters was about 4.5 times greater than for the equivalent filter in the SIW. Moreover, all this is by maintaining the advantages of the 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, the transitions from the SIW to the microstrip line [2] or from the coplanar waveguide [3] to the SIW or from the microstrip to the 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 thru–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. Moreover, these losses may greatly mask the real response of the SIW or ESIW device alone.

For that purpose, a TRL [4] calibration kit for a SIW was presented in [5], which successfully removed the effect of the transitions from the microstrip to SIW and from the SMA to the 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 Letter 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 their own calibration kit with standard machinery for manufacturing planar circuits, so it is much cheaper than any other standard commercial calibration kits, 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.

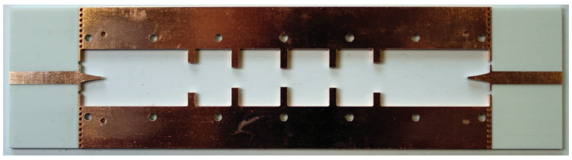

Fig. 1 *Filter*

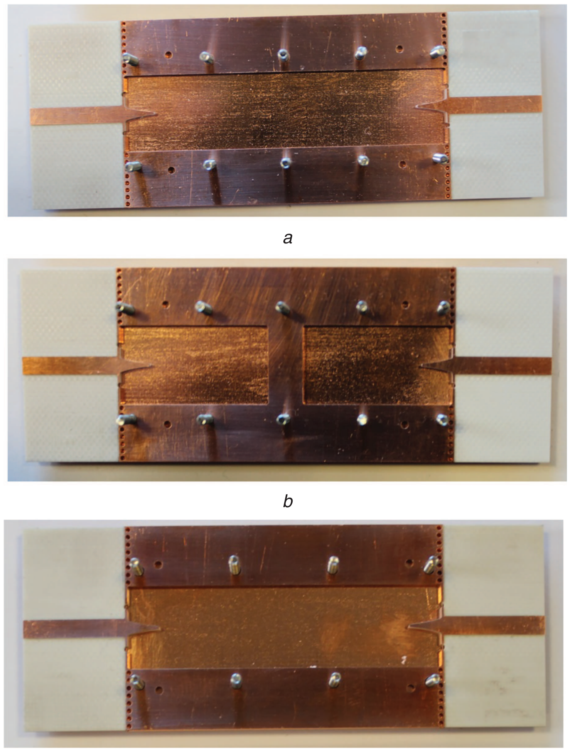

Fig. 2 *Three standards of TRL ESIW calibration kit: line (Fig. 2a), short (Fig. 2b), thru (Fig. 2c)*

We have developed a calibration kit for the measurement of the ESIW filter shown in Fig. 1. It is a passband coupled cavity filter with Chebyshev response and four cavities (and therefore, with four reflection zeros). The filter is centred 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 $\varepsilon_r = 3.55$, and the height is $h = 1.524$ mm. The rectangular waveguide that is cut in the substrate to mechanise the ESIW has a width of $a = 15.7988$ mm, so that the transversal dimensions of the ESIW empty rectangular waveguide are $a = 15.7988$ mm and $b = h = 1.524$ mm. The width a was 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.

To perform a TRL calibration, three standards have to be manufactured (TRL). 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.

The calibration kit that has been manufactured to measure the filter of Fig. 1 is shown in Fig. 2. As can be observed, three standards are needed for the calibration (TRL). 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 Fig. 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, this reflect has been implemented with a short circuit. The thru consists of an empty ESIW line of 60 mm, and the line is obtained by adding a section of ESIW empty line between both ports of and an 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. Therefore, 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 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 Fig. 2 has the same operating frequency as the standard WR-62 calibration kit for the 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 types 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 that usual in TRL calibration. First, we define the calibration kit in the network analyser [6]. Then we measure the three standards of the calibration kit of Fig. 2 so that the analyser corrects all 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 one's own software (for example, in MATLAB).

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

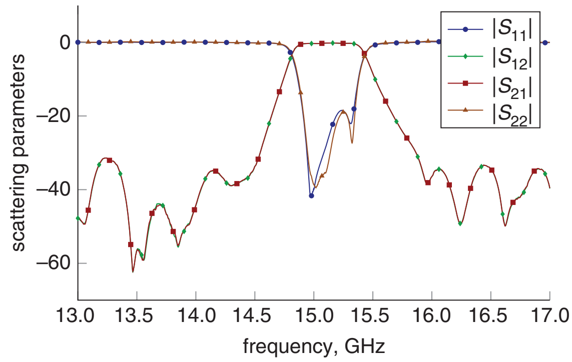

Fig. 3 *Measurements of filter with ESIW calibration*

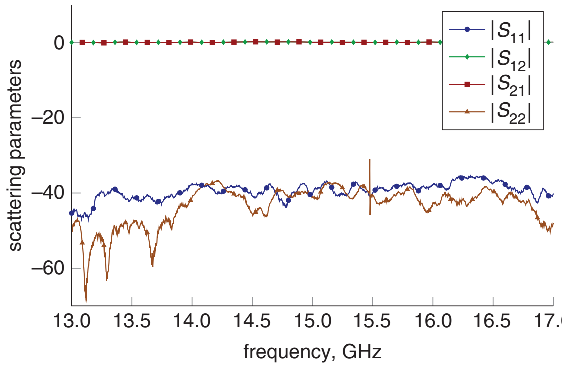

Fig. 4 *Measurements of line*

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

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

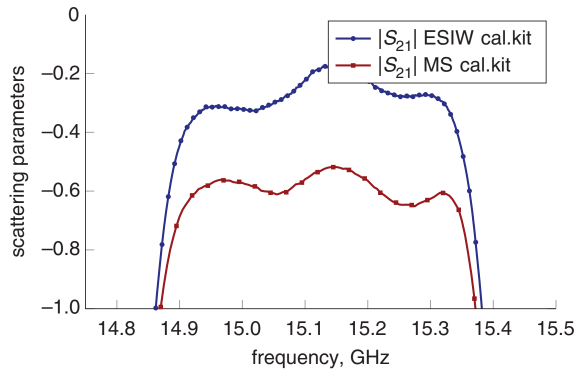

Fig. 5 *Comparison between ESIW and microstrip calibration kit*

Conclusion: A novel TRL calibration for ESIW devices has been presented in this Letter. ESIW devices are completely new, and no calibration technique has still to be developed for this promising transmission line. This TRL calibration is similar to that already developed for SIW devices. It has the advantage of being low cost, and can be manufactured by individuals 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 presented calibration kit.

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One or more of the Figures in this Letter are available in colour online.

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