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Through-Wire Microstrip-to-Empty-Substrate-Integrated-Waveguide Transition at Ka-Band

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Abstract: The advantages of the Substrate-Integrated Waveguide (SIW) in terms of low profile, integration with Printed Circuit Board (PCB) and low cost are maintained by the Empty Substrate-Integrated Waveguide (ESIW). Moreover, as the dielectric fill is avoided, other advantages are also added: resonators with higher quality factor and lower insertion losses. Since 2014, when it was proposed, several devices for X-band to Ka-band applications have been accurately designed and manufactured. In this way, transitions are one of the most important components, as they allow the connection between the ESIW and other planar transmision lines such as microstrip. To accomplish this aim, different transitions have been proposed in the literature: based on sharp dielectric tapers combining metallized and non-metallized parts, which increases the manufacture complexity; with a broadened ESIW section, that is less complex at the cost of increasing reflection and radiation losses due to the abrupt discontinuity; based on tapered artificial dielectric slab matrix, more difficult to mechanize; using a tapered microstrip transition, with high radiation losses; and even transitions for multilayer devices. Among all the transitions, the most versatile one is the through-wire transition, as microstrip and ESIW can be implemented in different layers and allows any feeding angle between the microstrip line and the ESIW. In this paper the through-wire transition has been properly validated at Ku- and Ka-bands. Moreover, a back-to-back transition has been accurately manufactured in Ka-band with measured insertion losses lower than 3.7 dB and return losses higher that 11.7 dB, concluding that the transition is not frequency dependent.

Keywords: Empty Substrate-Integrated Waveguide (ESIW); Ka-band; through-wire transition

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1. Introduction

The Empty Substrate-Integrated Waveguide (ESIW), first proposed in 2014 [1], maintains the main features of the Substrate-Integrated Waveguide (SIW) [2], such as small size and integration with other circuits in the same substrate, easy manufacturing, and low cost. Moreover, since the dielectric is removed in ESIW circuits, other advantages are also added: higher quality factors in resonators and better performance (mainly in terms of insertion losses).

To test the good performance of the ESIW, many different devices (filters, antennas, directional couplers, phase-shifters, etc.) have been properly designed and manufactured, and several transitions to connect the ESIW to microstrip lines have also been proposed [3].

The first transition proposed [1] had a sharp dielectric taper. In this transition, the transformation of the microstrip mode into the fundamental mode of the waveguide is carried out through a metallic iris followed by an exponential taper. This transition was improved in [4] for thin substrates. To make it possible, an additional taper in the microstrip feeding line was added. The last version of the transition [5] increased its mechanical accuracy adding two air holes and prevented radiation losses with via holes. Nevertheless, all of them include metallized and non-metallized parts, which increases the manufacturing complexity.

Apart from transitions based on sharp dielectric tapers, some more solutions have been proposed in the literature. In [6], a section of ESIW with increased width is used to avoid the sharp dielectric taper, but the size of the transition and the radiation losses were increased. This transition was then modified in [7] using a tapered artificial dielectric slab matrix, which increased considerably its complexity, and then in [8], where an elliptical dielectric taper was added. Another solution consists of using a through-wire from the microstrip line to excite the ESIW resulting in is a very versatile transition [9]. The last transition proposed use a tapered microstrip transition between the 50 Ω microstrip line and the ESIW for impedance and mode matching [10].

Furthermore, it is possible to find other transitions specifically designed for multilayer devices. The first one was presented in [11] to connect ESIWs in contiguous layers, being necessary the continuous concatenation of several versions of this transition to connect non-contiguous ESIWs. Another one was proposed in [12], allowing the connection of ESIWs separated by more than one layer. The last one is based in a sharp dielectric taper and integrated ESIW devices with a higher number of layers through a transformer at a height adapted to the ESIW [13].

Among all of the proposed transitions, the most versatile one is the through-wire transition [9] because it is possible to choose any angle between the feeding line and the ESIW, and the height of the microstrip and the ESIW can be independently chosen as both are implemented in different layers. Thus, it is possible to increase the quality factor in resonators and reduce losses in the ESIW. Apart from that, the transition is extremely compact and less sensitive to manufacturing errors. This transition was first presented in the X-band, with the aim of this paper being the not-always-direct validation of the design method explained in [9] at higher frequencies, more specifically at Ku- and Ka-bands. After the validation process in simulation, a back-to-back transition was manufactured in the Ka-band, as it is the most difficult one as manufacturing tolerances become more important, obtaining measured insertion losses lower than 3.7 dB and return losses higher that 11.7 dB.

2. Design Method

As is was exposed in [9] for the X-band, the through-wire transition consists of three layers (Figure 1): the upper one is used for the microstrip feeding and the top cover of the ESIW, the central one is used to implement the ESIW, and the bottom one is used as bottom cover for the ESIW. The power transfer between the microstrip and the ESIW is carried out with a metallic filament passed through via holes and tin soldered to the upper and bottom layers. It is also necessary to mechanize a circular gap in the bottom of the top layer to avoid short circuiting the microstrip with the upper conductor of the ESIW (which is also the ground of the microstrip), creating a isolated pad from the microstrip ground. This structure has a great impact on the impedance matching of microstrip and ESIW lines, which makes it necessary to carefully optimize pad and gap dimmensions.

As through-wire transition was first proposed in the X-band, it is necessary to validate the design procedure and the transition at upper frequencies. To accomplish that, the procedure and equations shown in [9] were used to design both transition at the Ku- and Ka-bands. For that, the width and length of the microstrip transformer (w_{trans} and d), the width of the coupling gap (gap), the diameters of the circular pads of the upper layer (pad_T and pad_B), the diameter of the via hole for the filament (d_{hole}), the diameter of the filament (d_{cable}), and the distance between the ESIW initial short circuit and the filament (L) were carefully calculated. After that, a final optimization in CST Studio Suite was carried out for all the design parameters (w_{trans}, d, gap, pad_T, pad_B and L) to obtain the final dimensions for each transition, which are shown in Table 1 jointly with those obtained in the X-band.

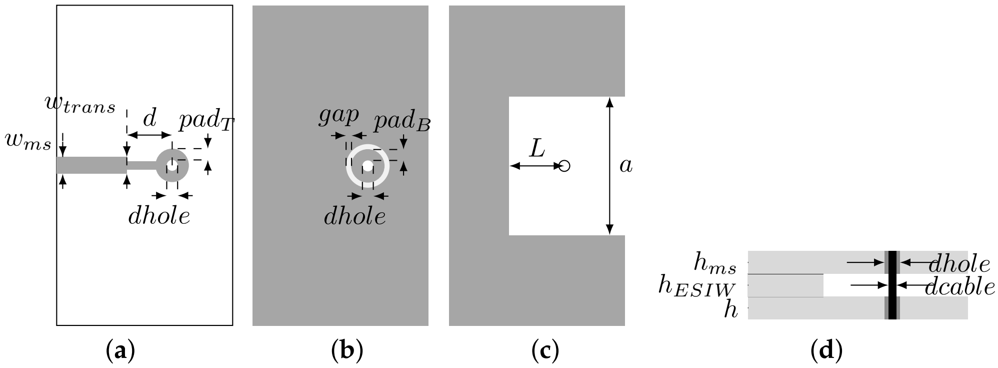

Figure 1. Schematic view of the through-wire microstrip-to-ESIW transition [9]. (**a**) Upper layer top; (**b**) upper layer bottom; (**c**) middle layer; (**d**) transverse section.

Table 1. Dimensions of the Three Designed Transitions in mm.

	X-Band [9] (8.2–12.5 GHz)	**Ku-Band (12–18 GHz)**	**Ka-Band (26.5–40 GHz)**
a	22.86	15.7988	7.112
L	9.259	6.459	3.026
W_{trans}	0.927	0.890	0.360
gap	0.264	0.559	0.184
pad_T	0.453	0.590	0.197
pad_B	0.612	0.740	0.216
d	7.512	2.7863	2.306
d_{cable}	0.51	0.51	0.21
d_{hole}	0.6	0.6	0.3

3. Results and Discussion

To simulate both Ku- and Ka-band transitions in CST Studio Suite, the substrate chosen was Rogers 4003C with 0.813 mm height and copper metallization of 18 µm for the three layers of the transition in Ku-band, whereas in the Ka-band the same substrate was used for the bottom layer, and Rogers 4003C with 0.305 mm height and copper metallization of 18 µm was chosen for the middle and top layers.

Figure 2 and Table 2 show the results obtained in CST Studio Suite for the transitions designed (including the original one in the X-band for comparison) without losses, being port 1 the feeding port connected to the microstrip and port 2 the ESIW port of the transition. Comparing the results at the three frequency bands, it is possible to observe that there is a similar behavior among them with very good results in terms of insertion and return losses, and it is possible to conclude that the design method is independent of the frequency and can be applied to the design of any transition. Moreover, as it is figured out in [9], the design method allows the design for both broadband and narrowband implementations, which reinforces the robustness of the design method.

Table 2. Performance Comparison of the Through-Wire Transition at Different Frequency Bands in Simulation. IL: insertion loss. RL: return loss.

	X-Band [9] (8.2–12.5 GHz)	**Ku-Band (12–18 GHz)**	**Ka-Band (26.5–40 GHz)**
Max. IL (dB)	0.3	0.4	0.2
Min. RL (dB)	16.5	21.2	19.8

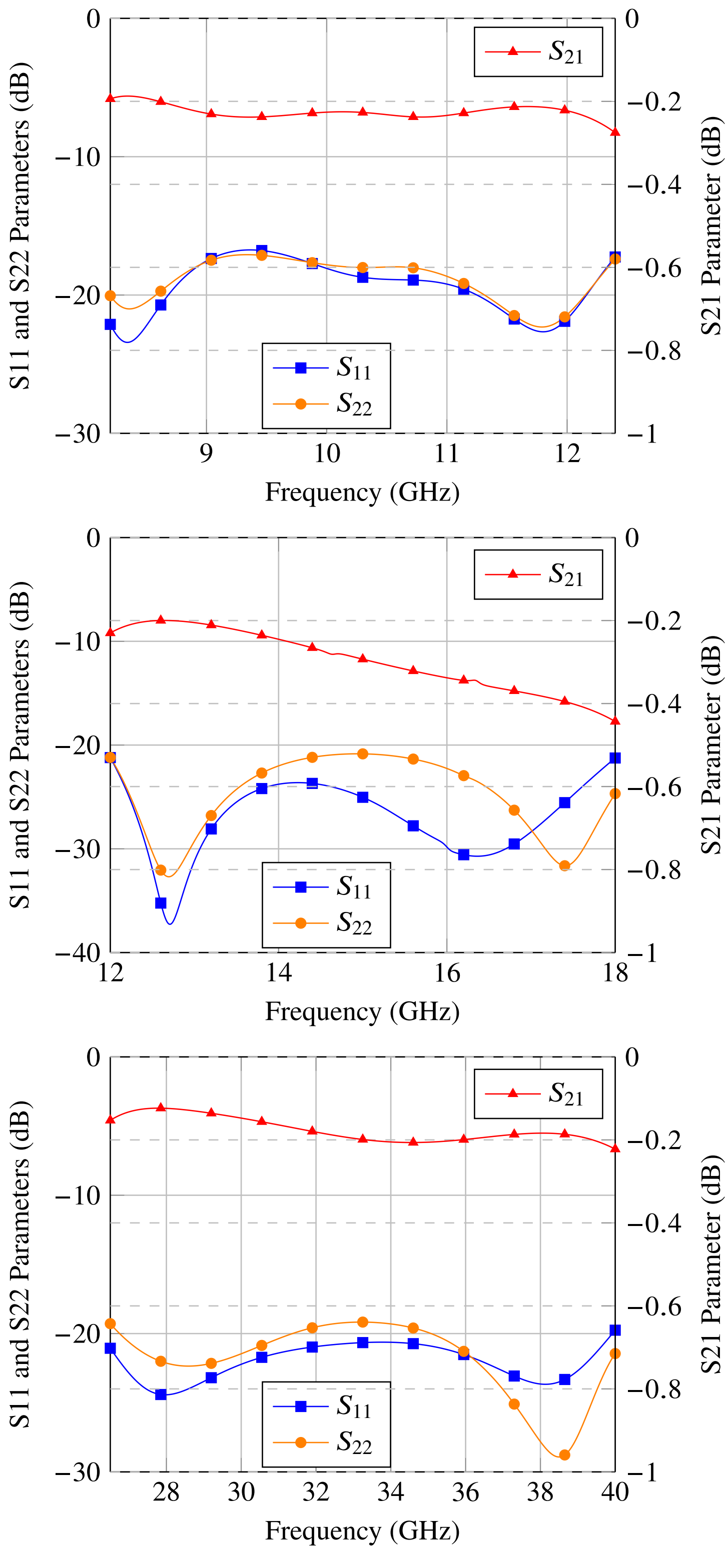

Figure 2. Simulated reflection and transmission of the microstrip to ESIW transition. **Upper**—X-band [9], **middle**—Ku-band, **bottom**—Ka-band.

In order to validate the performance of the manufactured transition, the most difficult one (in the Ka-band, as manufacturing tolerances become more important) was chosen to manufacture a back-to-back structure. The same substrates as in the simulation process have been used, but since all the layers are metallized, additional copper electrodeposition of height 9 µm was added to each one. The three layers have been manufactured using standard printed circuit board manufacturing processes (cutting, drilling, milling, and plating). Then they were soldered using a solder press, where the alignment of the layers is guaranteed by placing tight-fitting pins within the alignment holes. After that, the ends of the wires were manually soldered to the upper and lower layers. Figure 3 shows the layers of the manufactured back-to-back transition before assembling, and Figure 4 shows the final integrated prototype. It should be noted that at high frequency, the diameter of the filament becomes very thin, which implies that it is more difficult to manipulate. Because of this, it is recommended to use rods as straight as possible instead of cables. In this case, Ni-Ag rods were used. Moreover, as the rod has to pass throught the hole in the top and bottom covers, the metallization process should be taken into account as d_{hole} will be reduced due to the electrodeposition process being advisable to carry out some tests before the final manufacturing of the prototype to assure that rods can pass through the hole and the electrical contact is assured. More recommendations about the manufacturing process can be found in [14].

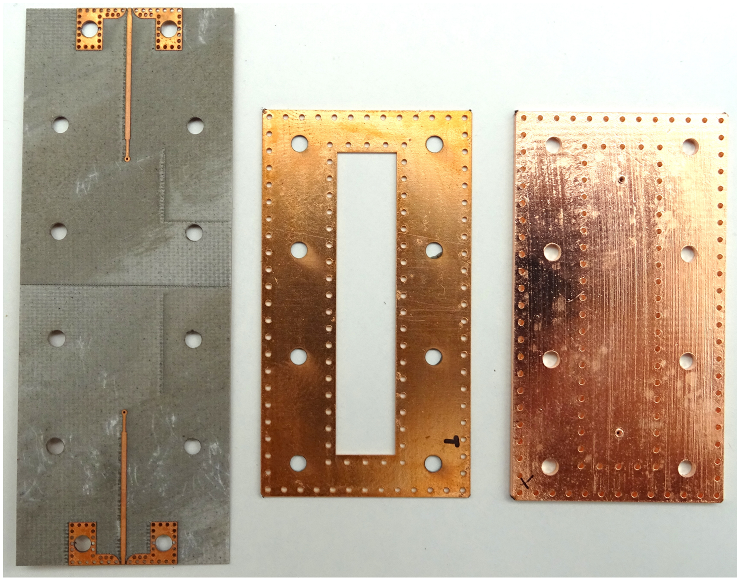

Figure 3. Layers of the back-to-back transition. From left to right: upper layer, middle layer, and lower layer.

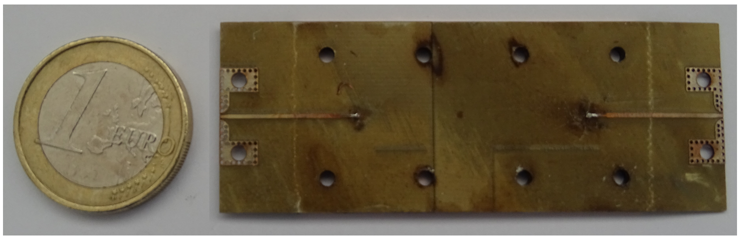

Figure 4. Assembled back-to-back transition.

The back-to-back transition has been measured with a network analyzer Anritsu MS4644A, using a TRL calibration kit to de-embed the coaxial connectors and the microstrip line. Figure 5 shows the results obtained, with it being possible to figure out that the agreement between simulation (considering losses) and measurement results is good. Taking into account that the prototype has been manufactured in the Ka-band, differences in return losses can be due to manufacturing errors that become more important when the frequency is increased. In the whole Ka-band, the measured insertion losses are lower than 3.7 dB and the return losses are higher than 11.7 dB.

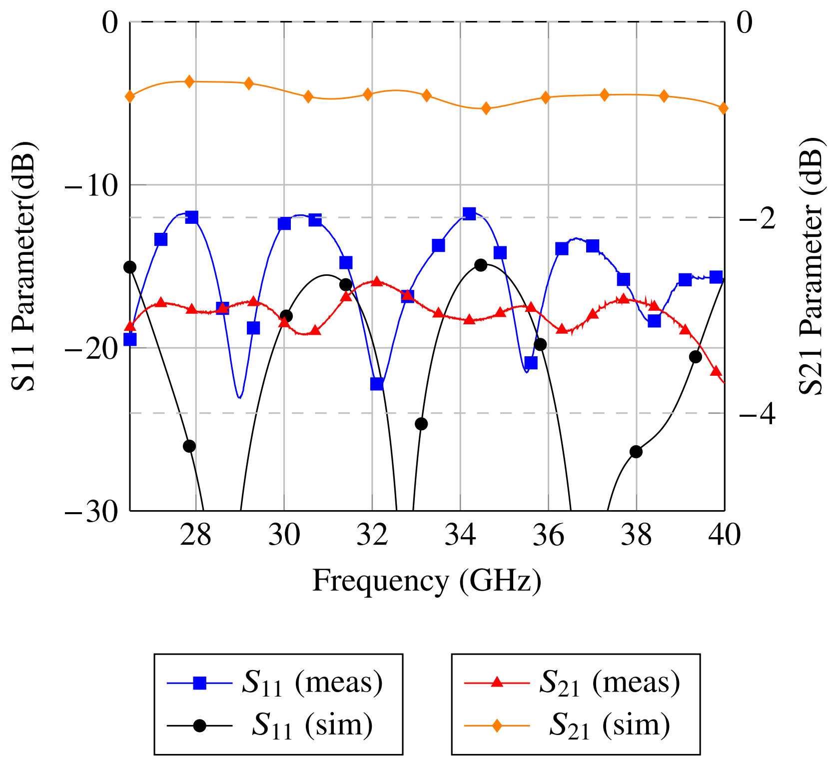

Figure 5. Comparison of simulated and measured transmission and reflection parameters of the Ka-band back-to-back transition.

The back-to-back transition manufactured in this research has also been compared with other transitions in Table 3. In this case, the complexity of the transition, although it continues to be easy, is a little higher due to the increase in frequency that makes it necessary to improve the precision of each one of the manufacturing steps. Moreover, although insertion losses are higher than in other transitions at the same frequency, the advantages of this one (easiness of manufacturing, independence of microstrip and ESIW heights, possibility of implementation of planar circuits in top and bottom layers, feeding of the ESIW from any angle, possibility of designing broadband and narrowband devices and frequency independently) make this transition the most versatile one.

Table 3. Performance comparison of the proposed back-to-back transition with other microstrip-to-ESIW back-to-back transitions.

Transition	Manufacturing Process	Freq. (GHz)	IL Max (dB)	RL (dB)
[4]	medium	12	1.5	13.5
[5]	medium	15	1.2	20
[6]	easy	15	1.08	21
[7]	difficult	33.25	1.26	14.7
[8]	easy	15	0.31	20.8
[8]	easy	33.25	1.36	14.75
[9]	easy	10.25	0.9	12
[10]	easy	10	1.3	15
[15]	medium	12	1.5	13.5
This work	easy	33.25	3.7	11.7

4. Conclusions

In this paper the design method for the through-wire microstrip-to-ESIW transition has been validated at the Ku- and Ka-bands, showing that it is not frequency dependent. The results obtained have shown a very similar behavior of the transition independently of the frequency band, being this proof of its robustness. Moreover, a back-to-back transition has been accurately manufactured in the Ka-band, obtaining measured insertion losses lower than 3.7 dB and return losses higher that 11.7 dB. Taking into account the advantages shown in [9] (easiness of manufacturing, independence of microstrip and ESIW heights, possibility of implementation of planar circuits in top and bottom layers, feeding of the ESIW from any angle, and possibility of designing broadband and narrowband devices) jointly with the advantages shown in this paper (frequency-independent design method and good behavior of the transition at any frequency band), it is possible to conclude that it is the most suitable microstrip-to-ESIW transition independent of the intended application.

Author Contributions: A.B. and J.A.B. designed, simulated, and optimized the device; J.A.B. and M.D.F. manufactured the device and characterized it in the laboratory; J.A.B., H.E. and V.E.B. wrote the manuscript; all the authors revised the manuscript; A.B. supervised the whole work. All authors have read and agreed to the published version of the manuscript.

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