AGU PUBLICATIONS

Radio Science

RESEARCH ARTICLE

10.1002/2017RS006244

Key Points:

- First time that a cross-guide Moreno coupler is implemented in empty substrate integrated waveguide
- The coupler has been manufactured; the prototype has excellent performance, with isolation above 15 dB in the whole band of the ESIW
- Prototype is integrated in a printed circuit

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Citation:
Miralles, E., A. Belenguer, H. Esteban, and V. Boria (2017), Cross-guide, Moreno directional coupler in empty substrate integrated waveguide, *Radio Sci.*, *52*, 597–603, doi:10.1002/2017RS006244.

Received 13 JAN 2017
Accepted 28 MAR 2017
Accepted article online 4 APR 2017
Published online 3 MAY 2017

Cross-guide Moreno directional coupler in empty substrate integrated waveguide

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Abstract Substrate integrated waveguides (SIWs) combine the advantages of rectangular waveguides (low losses) and planar circuits (low cost and low profile). Empty substrate integrated waveguide (ESIW) has been proposed as a novel configuration in SIWs recently. This technology significantly reduces the losses of conventional SIW by removing its inner dielectric. The cross-guide directional coupler is a well-known low-profile design for having a broadband waveguide coupler. In this paper a cross-guide coupler with ESIW technique is proposed. In such a manner, the device can be integrated with microwave circuits and other printed circuit board components. It is the first time that a cross-guide coupler is implemented in ESIW technology. The designed, fabricated, and measured device presents good results as a matter of insertion loss of 1 dB (including transitions), reflection under 20 dB, coupling between 19.5 and 21.5 dB, and directivity higher than 15 dB over targeted frequency range from 12.4 GHz to 18 GHz. The coupler implemented in ESIW improves the directivity when compared to similar solutions in other empty substrate integrated waveguide solutions.

1. Introduction

Nowadays, private companies already play a huge role in the space industry. Therefore, the economic exploitation of space is becoming more and more important. Cost reduction without decreasing the quality has become crucial, especially because most parts of the costs, as for instance the regulation, qualification, and test of the space payload, may become unavoidable. On the other hand, size and specially weight reduction are still possible and profitable. Proof of that is the growing interest of companies and space agencies in nanosatellites and picosatellites [*Heidt et al.*, 2000].

Waveguide solutions are typically used for satellite payload, fundamentally due to its high quality factor, robustness against space hazard conditions, and power-handling capabilities. One of its main drawbacks is its bulkiness. A new spectrum of planar technologies has arisen in recent years, such as substrate integrated waveguide (SIW) [*Farzami and Noroozíarab*, 2013; *Cheng and Fan*, 2012; *Farzami et al.*, 2011; *Dong and Itoh*, 2011], which greatly increases the quality factor of traditional planar resonators. SIW circuits have been proposed for some space applications [*Rautschke et al.*, 2016; *Chen et al.*, 2009]. In the last years a new substrate integrated technology was introduced. Empty substrate integrated waveguide (ESIW) [*Belenguer et al.*, 2014] improves the performance of SIW in terms of quality factor and losses while maintaining the advantages of low cost and low profile. It also slightly increases the fabrication complexity, considering that more layers and more fabrication steps are required [*Belenguer et al.*, 2014]. ESIW technology can compete with classical waveguide components such as filters or multiplexers providing an easier to integrate, smaller, and lighter solution. An ESIW filter [*Belenguer et al.*, 2014] and a hybrid 90° coupler [*Fernandez et al.*, 2015] have already been measured and designed. Directional couplers are typically used in the space industry for sampling of signal for monitoring or calibration purposes. One of the most popular directional couplers is the cross-guide [*Moreno*, 1946] (also known as Moreno) coupler due to its compactness, broadband performance [*Meyer and Kruger*, 1998], and high directivity. The cross-guide coupler includes two piled waveguides through cross-shaped slots. Theoretical models of the coupler were presented in *Chen* [1998], *Ball and Sulda* [2000], *Rambabu et al.* [2005], *Zhang et al.* [2013], *Labay et al.* [2009], and *Parment et al.* [2016].

This paper presents a fabricated cross-guide coupler in planar form. The coupler consists of two crossed waveguides, which are connected through two coupling cross slots placed on its common wall. The presented device can be integrated in a complete ESIW RF system with more components, such as filters, circulators,

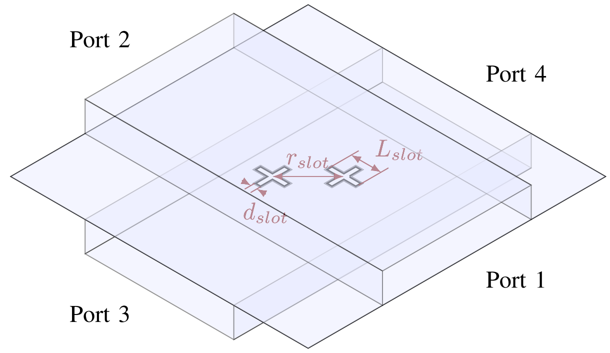

Figure 1. Representation of a waveguide cross-guide coupler. Perspective view.

antennas, or even Integrated Circuits in the same printed circuit board (PCB) reducing significantly the whole size of the system.

2. Cross-Guide Coupler

Figures 1 and 2 show a cross-guide coupler in a rectangular waveguide. The four ports have been numbered. A small fraction of the signal traveling from port 1 to port 2 (main waveguide) passes through the cross-shaped coupling slots to the secondary waveguide and is directed to port number 3. Port 2 is the direct port, port 3 is the coupled port, and port 4 is the isolated port. Thus, $| S_{31} |$ is the coupling, which should be small so that it does not distort the main flow and is relatively constant over the desired frequency range, and $| S_{32} |=| S_{41} |$ is the isolation, which should be smaller than the coupling. The difference between $| S_{32} |$ and $| S_{31} |$ is the directivity. If the directivity is small, then undesired reflections coming from port 2 could pass to port 3 and mask the fraction of signal coming from port 1 and coupled to port 3.

3. Implementation in ESIW

Figure 3 depicts the five different substrate layers needed to manufacture a cross-guide coupler in ESIW. All layers are manufactured with standard planar circuit manufacturing techniques as described in *Belenguer et al.* [2014]. Figure 4 introduces the fabricated substrate layers; the layers are numbered corresponding to the substrate layers of Figure 3. Layers 2 and 4 (main and secondary ESIW lines) have been manufactured in this work using a RO4003C substrate (height $h = 0.813$ mm, relative electric permittivity $\epsilon_r = 3.55$, and metal thickness $m_1 = 0.0525$ mm), so the height of the ESIW is $b = h + 2m_1 = 0.918$ mm. The width of the ESIW has been chosen to fit the WR62 ($a = 15.7988$ mm). The transitions from microstrip line to ESIW are presented in *Belenguer et al.* [2014].

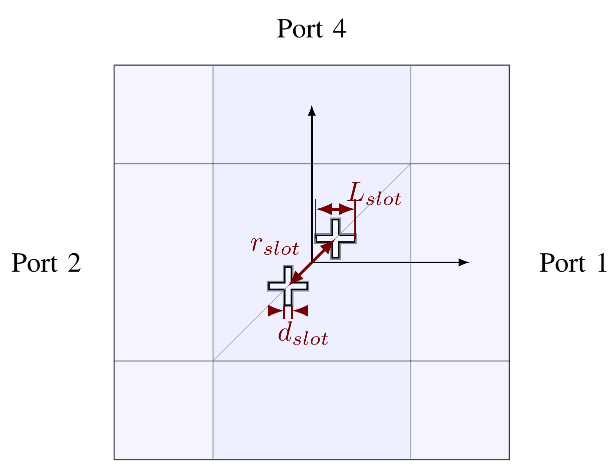

Figure 2. Representation of a waveguide cross-guide coupler. Top view.

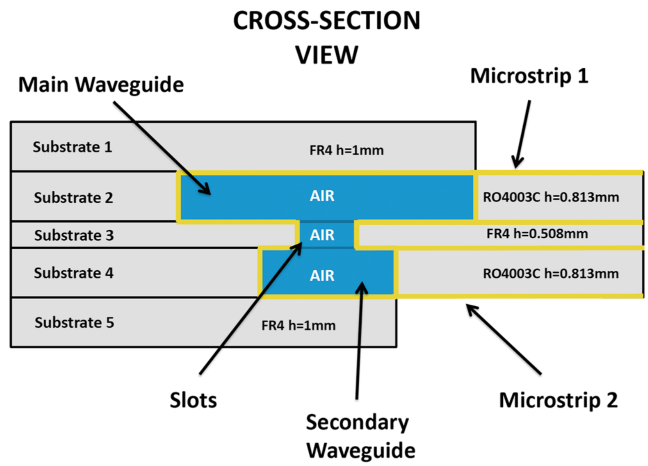

Figure 3. Layer stackup of the designed PCB.

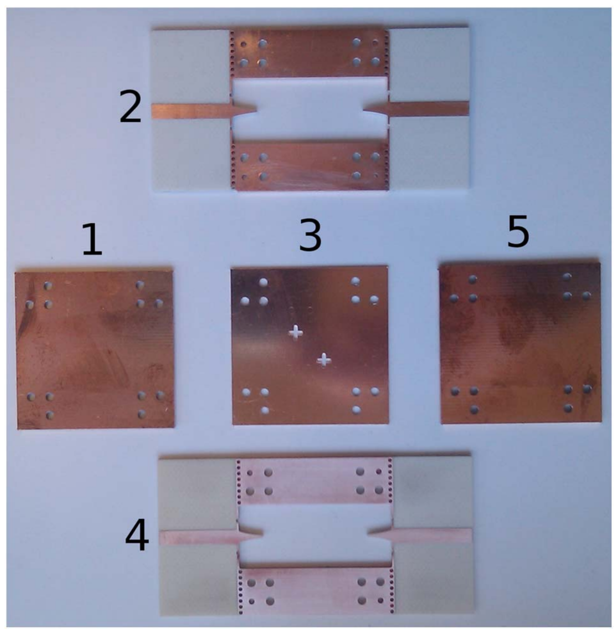

Figure 4. Photograph of the separated substrate layers. The layers are numbered corresponding to the substrate layers of Figure 3. Layer 1 is the bottom cover. Layer 2 is the bottom ESIW line. Layer 3 is the intermediate layer with the star-shaped coupling slots. Layer 4 is the top ESIW line. Layer 5 is the top cover.

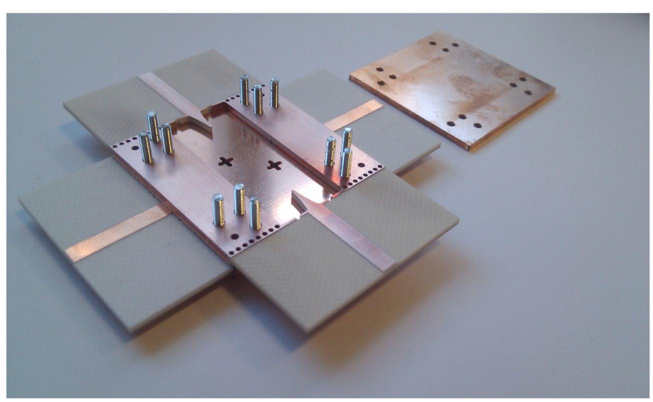

Figure 5. Photograph of the mounted device.

Table 1. Specifications of the Designed Coupler

Frequency	Coupling	Directivity	Return Loss
12.4 GHz to 18 GHz	20.5 dB ± 1	15 dB	20 dB

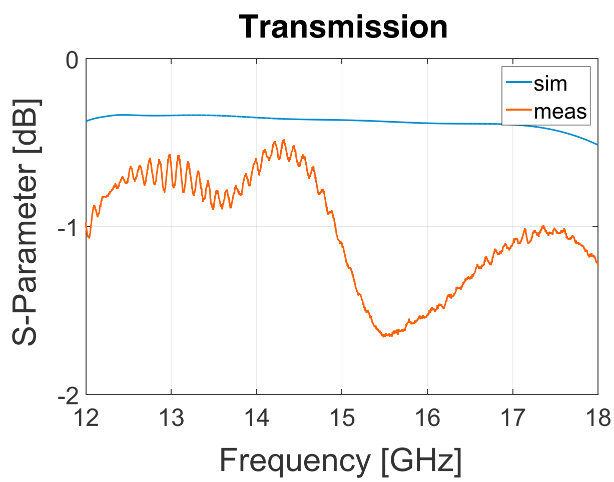

Figure 6. Comparison between measured and simulated transmission (| S_{21} |).

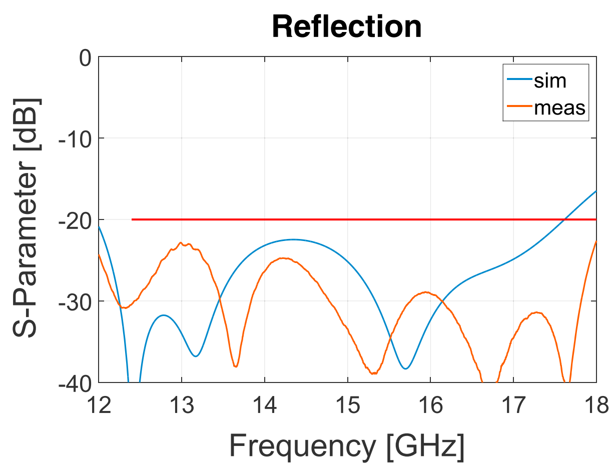

Figure 7. Comparison between measured and simulated return loss(| S_{11} |).

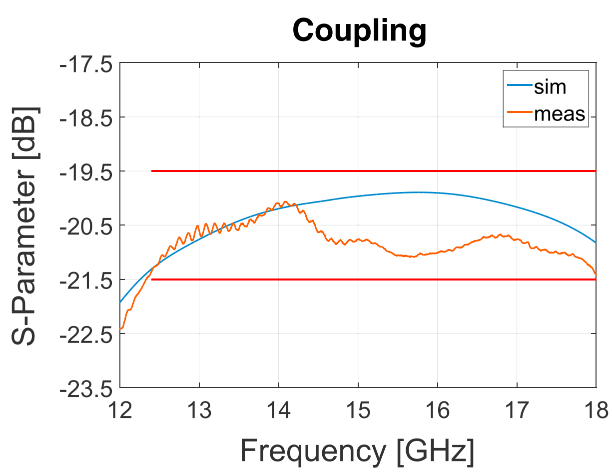

Figure 8. Comparison between measured and simulated coupling (| S_{31} |).

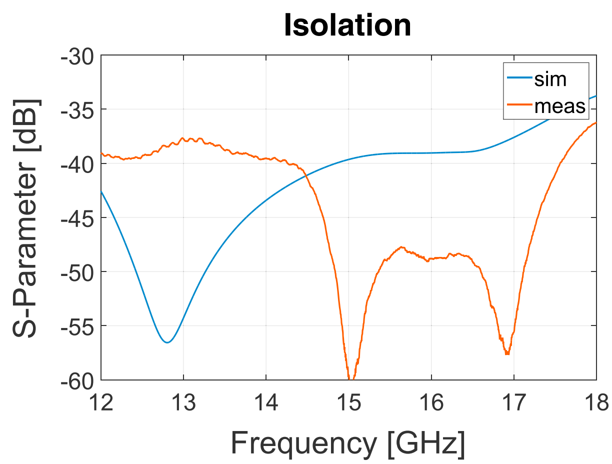

Figure 9. Comparison between measured and simulated isolation ($|S_{41}|$).

Layer 3 contains the coupling slots. The thickness of this substrate has been chosen to be the thinnest available in our laboratory (0.5080 mm). The total thickness of the coupling layer is $t = 0.508 + 2m_1 = 0.613$ mm. From *Ball and Sulda* [2000] we know that the smaller the d_{slot}, the greater the directivity. As a consequence, the smallest drill of our laboratory has been used ($d_{drill} = 1$ mm). Therefore, after its metalization $d_{slot} = d_{drill} - 2m_2 = 0.965$ mm (the metalization on the wall is $m_2 = 0.0175$ mm). Finally, all substrates are integrated together, as Figure 5 illustrates.

All the layers have been drilled with alignment holes, so that the different layers are piled using alignment screws, as can be seen in Figure 5. All the layers are soldered together with soldering paste, and the screws are then removed.

4. Specifications and Design

Table 1 lists the desired specifications for our design. These specifications are based on typical specifications of similar couplers for space applications in waveguide technology. The design parameters of the cross-guide coupler are the dimensions of the cross-shaped coupling slots shown in Figure 1 (d_{slot}, r_{slot}, and L_{slot}). The d_{slot} has already been fixed by using the smallest available drill of our laboratory.

A similar procedure as the one described in the previous article [*Miralles et al.*, 2015] was used. This time, a two-iteration process was followed in order to find out the best values for $r_{slot} = 3.45$ mm and $L_{slot} = 4.93$ mm. In the first iteration a simplified model in a commercial full wave simulator, which is based on an ordinary lossless waveguide structure, was simulated. After that a fine tune adding loses and the microstrip to ESIW

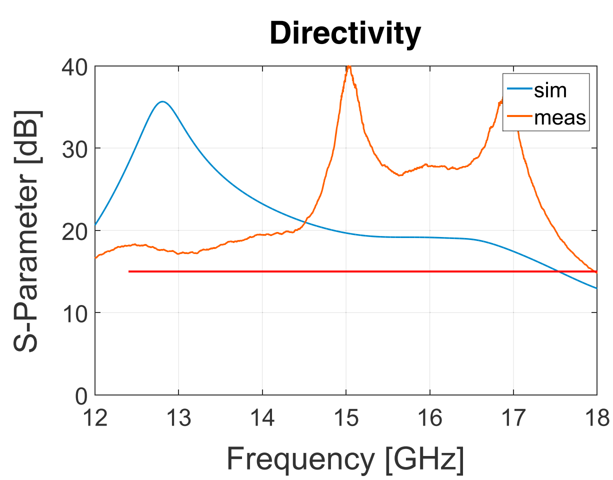

Figure 10. Calculated directivity ($D = |S_{31}| - |S_{41}|$).

Table 2. Comparison of Broadband Cross-Guide Couplers in Planar Form

	Reference		
	Zhang et al. [2013]	*Parment et al.* [2016]	This work
Frequency	28–38 GHz	26–40 GHz	12.4–18 GHz
Coupling	15 dB	20 dB	20 dB
Directivity	15 dB	10 dB	15 dB
Data	Simulated	Measured	Measured including transitions
Technology	SIW	AFSIW	ESIW

transitions was performed. The commercial simulator for all the simulations has been Computer Simulation Technology (CST), and the general purpose frequency domain solver has been used, with tetrahedral mesh and interpolative frequency sweep.

5. Results

A two-port network analyzer and two matched loads have been used to measure the S parameter of the device under test (DUT). In order to subtract the effect of the coaxial to microstrip transitions from the measurements, a Thru-Reflect-Line (TRL) calibration procedure has been used, so that these measurements only include the ESIW coupler plus the transitions from ESIW to microstrip.

As Figure 6 depicts, the insertion loss is around 1 dB (including microstrip to ESIW transitions) and the reflection (see Figure 7) is lower than −20 dB over the whole bandwidth. Moreover, Figure 8 illustrates the coupling, which is between 19.5 dB and 21.5 dB over the targeted frequency range. The isolation (see Figure 9) is lower than −37 dB from 12 to 18 GHz. Furthermore, the directivity is presented in Figure 10; it is greater than the targeted 15 dB. In general terms the simulation and the measurements fit rather well. As a conclusion, the measured results meet the specifications from Table 1 over the whole frequency range of a WR62 waveguide.

Table 2 shows a comparison of broadband cross-guide couplers in planar form. The presented device improves the performance in terms of the directivity of *Parment et al.* [2016]. *Zhang et al.* [2013] presents a very interesting device at simulation level; unfortunately, fabrication and measurements were not performed. Transitions to a well-known transmission line, as coplanar or microstrip, are needed in order to integrate the device with standard PCB circuits. These transitions, which worsen the directivity and the insertion loss, are only included in the measurements of this work.

6. Conclusion

A planar cross-guide directional coupler has been proposed by using the ESIW technology in this work. It is the first time that a cross-guide coupler is implemented in ESIW technology. The measured results fulfill the proposed specifications (Table 1), which are typical specifications for space applications in rectangular waveguide technology. High directivity and low return loss have been measured. The ESIW device implemented in this work has been proven to outperform other similar couplers in other empty substrate integrated waveguide technology in terms of directivity. ESIW is a promising technology in those applications where a traditional waveguide is utilized and smaller size would be beneficial. A performance comparable to conventional waveguide (even more bandwidth of operation if transitions from waveguide to coaxial connector are mounted) is achieved with ESIW in a planar substrate, allowing a straightforward and easy integration with IC and substantially reducing its size.

Acknowledgments
This work was supported by the Ministerio de Economía y Competitividad, Spanish Goverment, under research projects TEC2013-47037-C5-3-R and TEC2013-47037-C5-1- R. All the data related with this work can be requested from H. Esteban (hesteban@dcom.upv.es).

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