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Key Points:
- A slotted atenna array in empty substrate integrated waveguide (ESIW) technology is designed
- High radiation efficiency and very low profile is achieved
- Benefits are obtained in terms of integration with low-cost and conventional printed circuit boards (PCB) and integrated circuits (IC)

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Slotted ESIW Antenna With High Efficiency for a MIMO Radar Sensor

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Abstract This paper introduces a slotted empty substrate integrated waveguide (ESIW) antenna for a multiple-input multiple-output (MIMO) radar sensor. The proposed system is based on the MIMO radar architecture. Orthogonal signals are sent from the transmitters, in such a manner that a MIMO image reconstruction is possible. The presented system application targets the surveillance of strategic areas in gas pipelines and nuclear plants. ESIW technology enables a high-efficiency, low-profile, and compact antenna for these MIMO systems. The fabricated device includes a transition to microstrip line, and, in consequence, the antenna can be integrated with the rest of the system in a standard integrated circuit. The slotted ESIW antenna design and measured results for the targeted application are presented in this paper. The measured results present a gain greater than 15 dBi and return loss below −13 dB over the targeted frequency band of operation (16 – 16.5 GHz). To the best of the authors' knowledge, this is the first slotted ESIW antenna reported in the scientific literature up to now.

1. Introduction

In the recent years terrorist threats have dramatically increased in the whole world. In fact, they have become the number one of the top society concerns (Online, 2003, 2016). In this scenario, the reinforcement of security strategies for hazardous infrastructures like chemical and nuclear plants, fuel transmission, and energy and gas pipelines is of vital importance in order to safeguard our welfare.

Multiple-input multiple-output (MIMO) radar (Li & Stoica, 2008) has demonstrated to be an interesting solution to the presented problem due mainly to two factors: the reduction of the number of antennas and its correspondent radio frequency channels (if compared with a traditional fully populated array-based radars) and the increase of angular resolution thanks to the virtual array concept. The reduction in size and increment in angular resolution are characteristics of MIMO radars that make them suitable for the targeted security applications. The savings in hardware in a MIMO radar lead to higher costs in software; thus, more computational power from the signal processing side is demanded. Moreover, an orthogonal frequency division multiplexing scheme enables to send simultaneously orthogonal signal from the transmitters, in such a manner that a real-time reconstruction is possible (Ganis et al., 2016).

In this scenario a low-cost, low-size, and high-performance system is needed. Traditionally, waveguide technology has been used for high-performance applications despite its bulkiness. Moreover, planar microwave circuits, which can be integrated on well-known printed circuit boards as microstrip lines, are very compact but not that efficient. Recently, a new technology called empty substrate integrated waveguide (ESIW) (Belenguer et al., 2014), which can be integrated in printed circuit boards and joins advantages of planar circuits (low cost and integration with integrated circuits) and waveguides (low losses), was developed. By removing the inner dielectric and replacing the posts with metallic walls, this technology increases the performance of SIW circuits in terms of losses. Some key radio frequency components have been fabricated in this technology (Fernandez et al., 2015)-(Morro et al., 1998). In this paper, a very highly efficient ESIW slotted waveguide antenna, which is suitable for a MIMO radar application (Miralles et al., 2016), is presented.

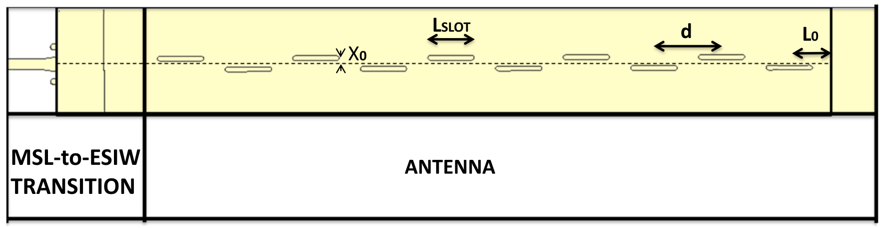

Figure 1. Layout of the designed antenna with its main parameters. MSL = microstrip line; ESIW = empty substrate integrated waveguide.

2. Antenna Element Design

In this section, a design strategy for a slotted ESIW antenna (see Figure 1) with operational frequency from 16 to 16.5 GHz is presented. ESIW technology offers low losses (if compared to SIW) and low cost in terms of design time. ESIW structures replace the characteristic via rows of SIW devices with a conductive wall. This fact enables the possibility to utilize a full-wave simulator with very low computational cost.

The position and orientation of the slots will determine how they radiate. If the slots are parallel to the current flow ($x_0 = 0$), they do not radiate. If the slots are 90° tilted, they represent barriers to the current flow and they do not radiate neither. In order to solve this issue, there are two well-known strategies. The first one is to tilt the slots by a different angle, and the second one is to have an offset (x_0) different from 0. Numerous examples of the last strategy can be found in the scientific literature, for instance, in Kenji and Bender (2013), Misilmani et al. (2015), and Theron and Cloete (1998). This is the solution adopted in this work.

2.1. Waveguide Selection

First of all, a proper rectangular waveguide in which the operational frequency band (from 16 to 16.5 GHz) is within its monomode range must be selected. The cutoff frequency for the TE_{10} mode is

$$f_{1\text{cut-off}} = \frac{c}{2a} \tag{1}$$

where c is the speed of light and a the longer side of the aperture of a waveguide. The first higher-order mode limits the monomode range. Considering $b < a/2$(due to its low profile), this mode is the TE_{20} and its cutoff frequency is

$$f_{2\text{cut-off}} = \frac{c}{a} \tag{2}$$

Considering the commented constraints, the design parameters a and b are set to be 15.8 mm and 1.033 mm, respectively. In such a manner, $f_{1\text{cut-off}} \approx 9.5$ GHz and $f_{2\text{cut-off}} \approx 19$ GHz.

2.2. Layer Stack-Up Selection

Figure 2 illustrates the cross section of the proposed device. It consists of three substrates. Substrate 1 is an FR4 substrate and has a height (h_1) of 1 mm. Substrate 2 is a RO4003C substrate, has a height (h_2) of 0.813 mm, and serves as microstrip line substrate. It provides the desired height b to the waveguide, considering $b = h_2 + 2t$ (the thickness of the metallization is $t = 0.11$ mm). Substrate 3 is an FR4 and has a height (h_3) of 0.613 mm. The slots are drilled through the substrate 3.

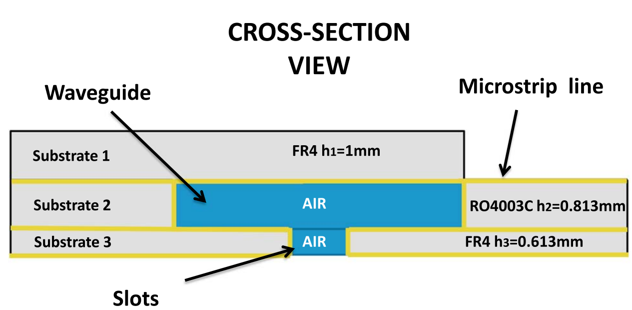

Figure 2. Cross-section view of the selected layer stack-up.

Table 1
Design Parameters of the Fabricated Device

Parameter	L_0	d	L_{SLOT}	x_0
Value	5.68	11.36	7.80	0.91

2.3. Three-Dimensional Full-Wave Simulation

The commercial finite element simulator Computer Simulation Technology has been used in all the simulations. The presented antenna is designed by following a two-step process.

First of all, a simulation of the antenna without the transition is performed. This simulation is based on ideal lossless waveguide, since the dielectric substrate included in the transition is not considered, and the metallic parts are modeled as perfect electric conductors. This leads to a simulation with a very low computational cost. Figure 1 illustrates the main parameters of the device. The distance between the short circuit and the first slot (L_0) must be set in such a manner that the first slot is illuminated with a maximum E field. This is achieved with the following value:

$$L_0 = \frac{\lambda_g}{4} \quad (3)$$

The slots must be fed with maxima of E field and with the same phase. As a consequence, the distance between slots is fixed to

$$d = \frac{\lambda_g}{2} \quad (4)$$

The rest of the design parameters (length of the slots L_{SLOT} and offset x_0) are optimized using a simplex algorithm until the desired return loss at the operational frequency is achieved. Table 1 presents the value of the design parameters of the fabricated antenna.

In the last step of the design process, the model includes the transition from microstrip to ESIW (Belenguer et al., 2014) and considers the losses due to the conductor ($\sigma = 5.8{\cdot}10^7$ S/m) and due to the dielectric substrate ($\epsilon_r = 3.55$ and $\tan(\delta) = 0.0027$).

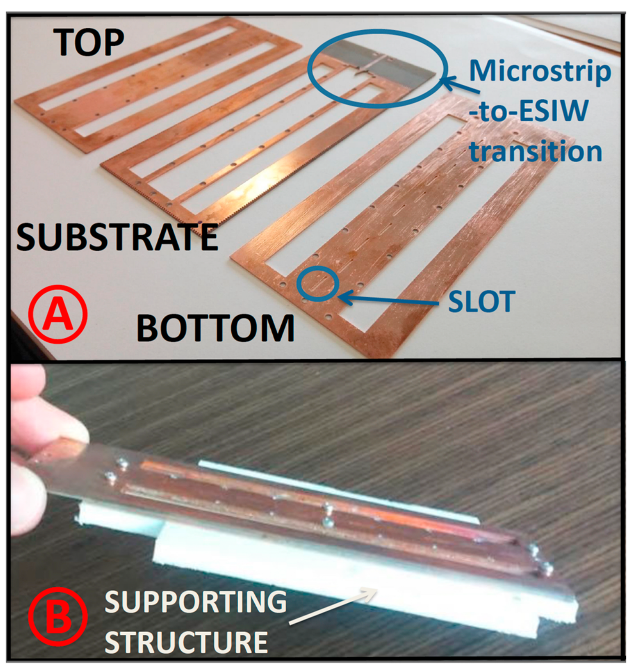

Figure 3. (a) Separated layers of the fabricated device. (b) Stacked layers of the fabricated device.

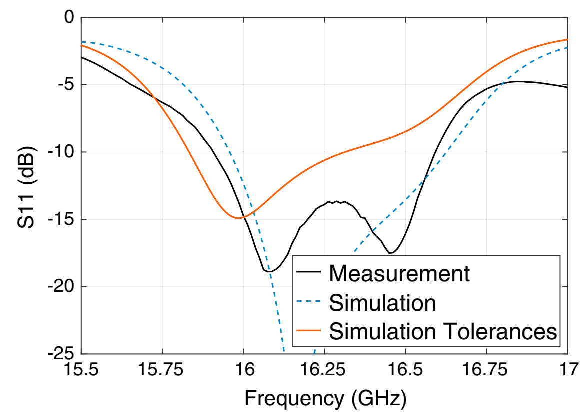

Figure 4. Measured S_{11} in black, simulated S_{11} in blue with nominal values of all dimensions, and simulated S_{11} with all physical dimensions with a random increase/decrease with the standard deviation according to the manufacturing tolerances in red.

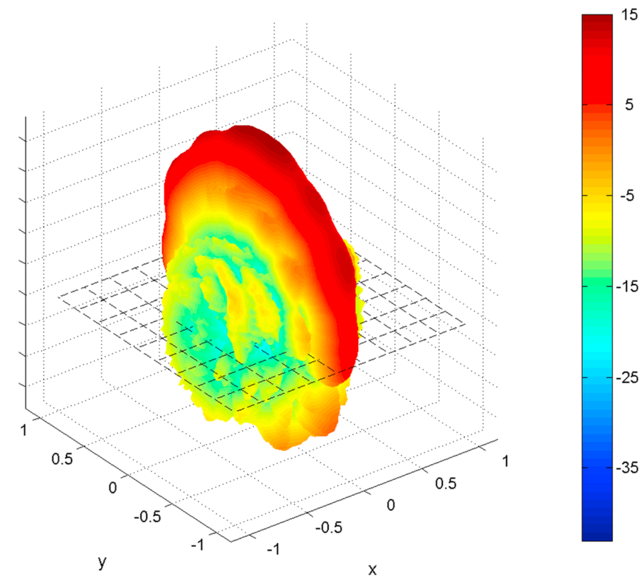

Figure 5. Measured 3-D gain.

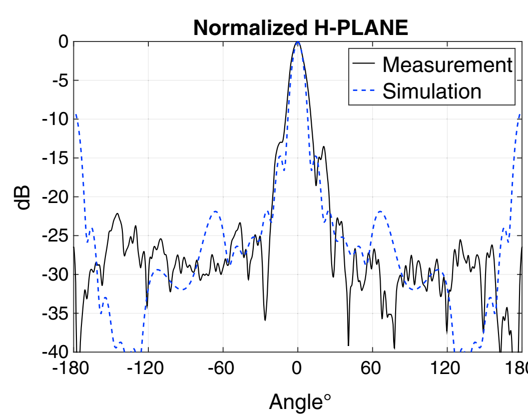

Figure 6. Comparison between simulation and measurement of the H plane radiation pattern of the fabricated antenna.

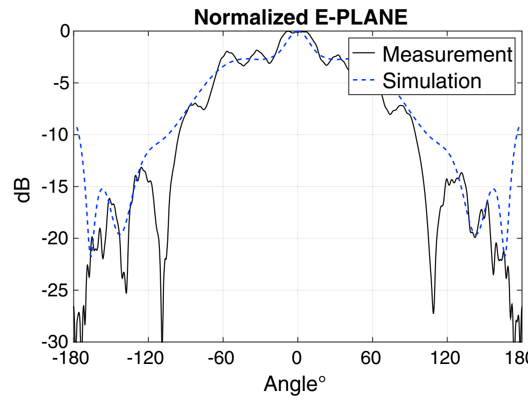

Figure 7. Comparison between simulation and measurement of the E plane radiation pattern of the fabricated antenna.

3. Measured Results

A prototype of the designed structure has been manufactured and measured in order to validate the simulation. The device is fabricated by emptying a hole in a substrate. After that, this substrate is metallized, in such a manner that the lateral walls of the slotted waveguide are created. Later, the microstrip-to-ESIW taper and the bottom slots are cut. Then, the bottom layer is metallized. Figure 3a illustrates these three layers. Finally, top and bottom layers are soldered to the substrate, in such a way that the final result can be observed in Figure 3b. In order to manufacture the proposed device, a LPKF Protomat S103 circuit board plotter was used. This machine manufactures with an accuracy of 0.15 mm and repeatability of ±0.001 mm. The LPKF Mini Contac RS system was used for the electroplating.

Figure 4 presents a comparison between the simulated and measured reflection coefficient. Both measured and simulated S_{11} are below −13.5 dB in the operational frequency band (16 to 16.5 GHz). The small differences between simulation and measurement are due to manufacturing process effects related to substrate permittivity variations, imperfections of the metallization and soldering processes, and milling errors. A tolerance analysis (red curve in Figure 4) has been made that confirms this.

The measured 3-D gain at the central frequency of the operational frequency band (16.25 GHz) is illustrated in Figure 5. The maximum radiation is obtained along the z axis. The measured radiation pattern looks like a classical slotted waveguide antenna. The measurement is in good agreement with the simulation, considering that the simulated gain is 15.8 dBi and that the measured gain is 15 dBi.

Figures 6 and 7 illustrate a comparison between the simulation and measurement of the H plane and the E plane radiation patterns, respectively. The measurement fits very well the simulation. Nevertheless, there are some small discrepancies due to fabrication inaccuracies, which lead to an increment of the ripple in the radiation pattern and a worsening of the side lobe level. Besides, the supporting structure that was necessary for performing the measurements also affects the radiation pattern, especially the front-to-back ratio.

Table 2 introduces a summary of radiation efficiencies. This table shows that the simulated radiation efficiency of a slotted ESIW antenna including its transition to a 50 Ω the microstrip line is 96.83%, while the simulated radiation efficiency for the same antenna, designed in SIW technology, is 72.61%. The measured radiation efficiency of the fabricated ESIW antenna is 90.78%. The measured ESIW radiation efficiency is superior to the simulated SIW radiation efficiency.

The absolute gain, taking only into account dissipative losses (not impedance mismatch), has been used for the calculations of the measured efficiency.

Table 2
Summary of Radiation Efficiencies

Antenna configuration	Efficiency
Simulated ESIW	96.83%
Simulated SIW	72.61%
Measured ESIW	90.78%

Note. ESIW = empty substrate integrated waveguide.

4. Conclusion

In this paper an antenna in ESIW technology has been designed, fabricated, and measured for a MIMO Radar application. The measurement results fit the simulated data very well. The radiation efficiency improves the present state of the art (SIW slotted antenna) by removing the dielectric losses inside the substrate integrated waveguide. The antenna is suitable for the targeted application and ready to be integrated into a MIMO radar system.

Acknowledgments
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