Design of a Substrate Integrated Waveguide Slots Antenna in W Band for Aircraft Radar Application

Lamia Sadaoui [#1], Jerome Lantéri [#2], Jean-Yves Dauvignac [#3], Claire Migliaccio [#4], Fabien Ferrero[#5]
Laurent Brochier[#6], Ronnie Rexhaeuser[*1], Thilo Lenhard[*2], Federico Lolli[¤1], Claudio Palleschi[¤2]

[#] Université Côte d'Azur, CNRS, LEAT, Sophia Antipolis, France
[*] InnoSenT GmbH, Germany
[¤] Inter-consulting, Italy

{ [#1]Lamia.Sadaoui, [#2]Jerome.Lanteri, [#3]Jean-Yves.Dauvignac, [#4]Claire.Migliaccio, [#5]Fabien.Ferrero, [#6]Laurent.Brochier}@univ-cotedazur.fr
{[*1]Ronnie.Rexhaeuser, [*2]Thilo.Lenhard}@innosent.de
{[¤1]f.lolli, [¤2]c.palleschi_ext }@inter-consulting.it

***Abstract*— The paper presents a design of a SIW (Substrate Integrated Waveguide) slot's antenna in W band for a sense-and-avoid radar module to tackle an emerging need of security during landing and take-off for small aircrafts. This work is developed inside the ODESSA project, funded by the European Union. The antenna was formed by 7 slots etched on the top face of a SIW structure designed on a Rogers RO3003G2 substrate. Simulation and experimental results, for both cases with and without radome, are presented inside 76-80 GHz frequency range. Good performances are obtained for efficiency and realized gain which were the main objectives of this work.**

Keywords*— *Substrate Integrated Waveguide, slot antenna, array antenna, MMW radar, sense and avoid.

I. INTRODUCTION

Mid-air, near mid-air, and on-ground collisions are one of the most important cause of accident in general aviation. For this reason, engineering an affordable sensor helping pilots in preventing it could be very important in order to prevent accidents. Present sensors, indeed, are very expensive and cannot be affordable for small aircraft and helicopters. The usage of new generation ADS-B systems, indeed, cover the risk of collisions among aircrafts but not with terrestrial objects as cars, luggage transfer vehicles, people, airport ladders.

The idea of **ODESSA** project (**O**bstruction **DE**tection **S**ensor for **S**urveillance on **A**ircraft) is to provide a small, light, and low-cost sensor (comparing it to the present ones) that could be installed on both airplanes and helicopters piloted on board or remotely. This objective will be achieved by taking advantage of the experience related to Automotive market, where low cost and reliable millimetre radars combined with video cameras are mounted on the motor vehicles for the early detection of obstacles.

By extending the avionic system with this kind of sensors, the collision avoiding capabilities will be dramatically enhanced thus increasing "safety during landing approach and on-ground" handling or taxi phases. Furthermore, ODESSA aims to prevent bird striking during both Take-Off and Landing phases. Modular avionics concepts of on-board system independency, reducing maintenance efforts and granting different platforms will be applied. The main target of ODESSA is to improve, by a quite small investment, the aircraft safety during landing and ground procedures, especially in presence of reduced visibility condition, independently from the airport sensors infrastructures.

Concerning the sensor and more particularly the radar's module, the philosophy is to adapt the solutions developed during the last 20 years for the automotive. First, an existing radar's module (named A-model for clarity) designed for automotive and provided by InnoSenT GmbH (partner in the project) has been used to fabricate the first version of the sensor, and its capabilities have been evaluated during a first fly tests campaign. The A-model radar's module has a detection's range of about 90 m, which is not enough for applications targeted in ODESSA project.

In the project, several tasks are devoted to improve the detection range of A-model from 90m to 150 m, to make it compatible for use during landing and take-off phases.

Many works were done, from A-model, to provide a new PCB (Printed Circuit Board) on which the radar's chip will be mounted. This new PCB and its radar's chip including modulation and radar signal processing improvements will form the new radar's module (named B-model). Antenna system of this new module will consist in 4 RX and 3 TX antennas as presented in Fig. 1.

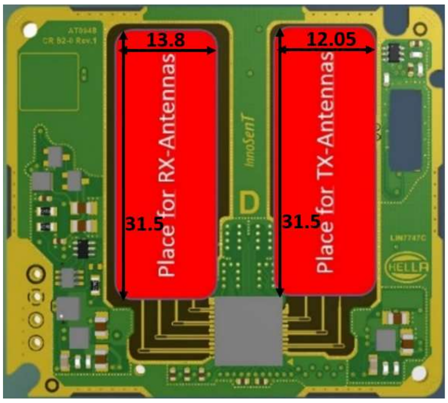

Fig. 1. PCB of B model

In red in Fig. 1, the area where antennas will be implanted. TX antenna and RX antennas must be identical. The targeted specifications of the antenna are summarized below.

- Horizontal polarization
- Bandwidth ($S_{11}<-10dB$ @76…81GHz)
- High efficiency (> 80%)
- Wide beam width in azimuth pattern (>±70°)

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- Realized gain: at least 11.5 dBi including all lines and radome losses
- Thickness of the RF-Substrate: $127\mu m$ to be compliant with A-model PCB
- Robust against manufacturing and material tolerances
- Cheap and simple to manufacture

One way to increase the range detection is to improve the power budget. It can be done by increasing the transmitting power, by increasing the antenna's gain or by combining both. To get a higher range detection with the new model, we carried out our efforts only on the design of the antenna where the main goals are the minimization of the losses and the leakage.

To follow recommendations listed before (distance between adjacent antennas and losses as small as possible) and to fulfil with the specifications as much as possible, the solution proposed here consists in a linear array of slots etched on the top face of a SIW. This antenna carries out some main specifications: i) linear horizontal polarization, ii) PCB and radome are the same as A sensor's model. Linear slots antenna array in SIW technology is widely used in MMW radar sensor for its lower losses in comparison with classical printed patches and its low cost regarding the manufacturing, even if the substrate cannot be considered as a cheap material in W band.

The next section provides a state of the art on SIW slots antenna for MMW radar.

II. STATE OF THE ART

SIWs are high performance broadband devices with excellent immunity to electromagnetic interference and suitable for use in microwave and millimetre-wave electronic system [1]-[2]. They are very low-cost in comparison to the classic metallic waveguides as they may be developed using inexpensive fabrication techniques.

It was discovered how substrate integrated post-wall-waveguide interconnects could be implemented to feed planar PCB antennas in [3]. It has been shown that SIW interconnects, due to their enclosed structure, efficiently confine the electromagnetic fields [4], [5], [6] thus, can be exploited to eliminate crosstalk which is the preventing factor in utilizing closely-spaced PCB transmission lines such as the microstrip interconnects.

In the area of microwave antennas, the waveguide resonant slot array antenna, which has advantages of cross-polarization level and low side-lobe levels, play an important role [7], [8]. Planar resonant slotted-waveguide arrays are used in many applications, especially radar. Therefore, we give an importance to this type of antennas structures.

To give an idea on the performances that this type of antennas can offer, reference [9] shows a simple example of a SIW resonant single-slot antenna with SIW-microstrip transition which is integrated on a single substrate. The SIW antenna shows good performances in terms of return losses. They are lower than -40 dB from 25 to 36 GHz and lower than -18 dB for frequency band [34.6-35.9] GHz.

To reduce dielectric loss and achieve lower transmission loss, a multilayer PCB-based modified SIW with an air-cut in the middle section has been reported for the first time in [10]. However, this paper presents only a computational analysis on the attenuation constant and the cut-off frequency of this structure.

In paper [11]-[12] an Air-filled Substrate Integrated Waveguide (AFSIW) based on multilayer PCB process is proposed for millimeter-wave applications that require low cost, high performances and compactness. This air-filled SIW allows for substantial loss reduction and power handling enhancement. Its fabrication involves three layers. The top and bottom substrates can consist of a low-cost standard substrate such as FR-4 on which baseband or digital circuits can be implemented to obtain a very compact, high performance and low-cost millimeter wave system. Authors report the results of a fabricated back-to-back transition operating in the Ka-band, demonstrating for the first time air-filled SIW. It is shown that a significant improvement in terms of losses and power handling capabilities is achieved by using the proposed air-filled SIW as opposed to the conventional dielectric-filled scheme. At Ka-band, authors show that air-filled SIW compared to dielectric-filled SIW based on Rogers RT/Duroid 5880 and 6002 reduces losses by a mean value of 0.054 dB/cm and 0.11 dB/cm respectively. It achieves a matching of better than -15 dB and an insertion loss of 0.6 ±0.2 dB (0.3 ±0.1 dB for the transition) from 27 to 40 GHz. Later, the same authors developed in [13] an AFSIW slot array antenna based on multilayer PCB process. For comparison and demonstration purposes, they designed a 1×4 slot array antennas based on both AFSIW and conventional dielectric filled SIW (DFSIW) operating at 30.5 GHz.

In paper [14], a novel concept is used to minimize the leakage losses of the SIWs at millimeter wave frequencies. In principle, better antenna performance or higher operation frequencies can be achieved by using lower loss dielectric. Furthermore, by transferring the fabrication process to thicker flexible PCB substrates, the electrical performance of the SIWs and SIW-based components can be improved. Authors demonstrated successfully at 79 GHz SIW-based single slot, longitudinal and four-by-four slot array antennas in a flexible PCB. They fabricated their prototypes in a polyimide flex foil using PCB fabrication processes. It is shown that the proposed antennas achieve sufficient impedance bandwidth, and favorable radiation characteristics around 79 GHz. Results show approximately 4.7%, 5.4% and 10.7% impedance bandwidth (S_{11}=-10 dB) with 2.8 dBi, 6.0 dBi and 11.0 dBi maximum antenna gain around 79 GHz, respectively.

In paper [15] design and comparison of two antennas based on SIW technology are presented, a Yagi-Uda antenna and a linear slot array. The antennas were designed for millimeter wave applications operating in frequency band from 71 to 76 GHz. Authors got a good result with radiation characteristics, the linear slot antenna achieved the gain 13.8 dBi, and the Yagi-Uda antenna 12.4 dBi. They got a main lobe of the width 15° in case of linear slot antenna, and 25° in case of of Yagi-Uda antenna. The side lobe level is lower than -25 dB for linear slot antenna and -13 dB for Yagi-Uda antenna.

In [16] a design of an interesting high gain antenna for 79 GHz automotive short range radar (SRR) applications was developed by using the concept of SIW technology along with superstrate layer. A superstrate dielectric layer of Roger substrate RT-duroid 6010-LM with thickness of t_2=0.254 mm, this thickness is nearly equal to theoretical one $\lambda_g/4 = 0.297\,mm$, and permittivity $\varepsilon_r = 10.2$ with tan (δ) =0.0023 (loss tangent) is added above the base SIW antenna element at a height of h = 1.963 mm (≈ 0.5 λ_0). After the optimization of the size of the superstrate layer, the simulated bandwidth is from 75.9 GHz to 81 GHz (6.46 %). The maximum gain of a single antenna with superstrate layer is 14.6 dBi at 79 GHz, which is higher than the gain of a classical 2×2 array. So, the gain of a single superstrate layer increases nearly 8.78 dB at 79 GHz over its SIW base antenna. The antenna patterns are found to be broadside all over the frequency band of authors interest. Therefore, we think that this idea is very interesting since it allows a significant increase in gain and can be used at similar frequency band of 76-77 GHz and for radar application as the case of Odessa project.

In the next part of this paper, the SIW slot antenna will be designed allowing us to fulfil the specifications required by the application. It will be detailed by giving the simulation results for both cases with and without the radome that protects the PCB in operational conditions. Later, the measurement's result will be presented to validate the simulation ones.

Then, a conclusion will be given detailing the perspective of the work.

III. DESIGNING OF THE 7-SLOTS-SIW ANTENNA

A. *Presentation of the RO3003G2 substrate*

The substrate selected to fabricate the PCB radar's module is the Ro30003G2 from Rogers Corporation. Information and data sheet are available at [17]. This substrate has been developed specially to address the next generation needs for MM-Wave automotive radar applications. We used a thickness of $127\mu m$ as mentioned previously. A preliminary study has been done to determine experimentally the material properties of Ro3003G2 in W Band. Our results give an average dielectric constant ε_r=3.08 (close to the 3.07 value recommended by Rogers) and an average $\tan\delta = 0.0025$ in W band. These values will be used in simulation.

B. *Presentation of the SIW Structure*

The conventional rectangular waveguide resonant longitudinal slots array antenna [9] has one short port and another one for excitation. The spacing of each slot antenna is one-half guide wavelength at the design frequency in order to locate the slots standing wave peaks and all radiators have the same phase. The spacing between the last slot and the short port is one quarter guided wavelength hence the short port is equivalent to open circuit [7]. The array is fed from the waveguide end.

A half wavelength of transmission line has the useful property of repeating impedance, the input and output impedance are the same. As a result, admittances of all the slots appear in parallel. Each parallel resistor represents one slot, so there must be N resistances in parallel. At the resonance, the admittance Y has only a real part, and the calculation is extremely simple [9]: adding N identical admittances together, where N is the number of slots as mentioned in (1):

$$Y_{input} = Y_1 + Y_2 + Y_3 + Y_4 + \cdots .. + Y_N \qquad (1)$$

Depending on the value of Y_{input} that we want and the number of the slots, we can find the value of the admittance to apply to each slot.

Most components of the planar waveguide have been implemented in SIW technology due to the similarity between the SIW structure and conventional rectangular waveguides. This generally allows a reduction in size and weight of components if compared to conventional waveguides. Consequently, the conventional rectangular waveguide (RWG) slot array antenna is transferred to SIW slot array antenna.

The design of the SIW's must be in accordance with the PCB configuration, and the mechanical criteria of our PCB supplier, KSG GmbH. The radar signal processing, which will be used, imposes an interval of 1.9 mm between 2 adjacent antennas, both RX and TX parts. In SIW technology, side walls of the wave guide are realized with vias. Following the mechanical criteria of our PCB supplier, the diameter of a via is 200 µm and the spacing between 2 adjacent vias (center to center) is 350 µm (i.e. 150 µm side to side). The SIW's geometry, considering all these constraints, is given in Fig. 2. The width of 1.6 mm for the SIW is chosen to have a cut-off frequency of the first mode at 57,75 GHz, far enough from 76 GHz which is the lower frequency for this radar application.

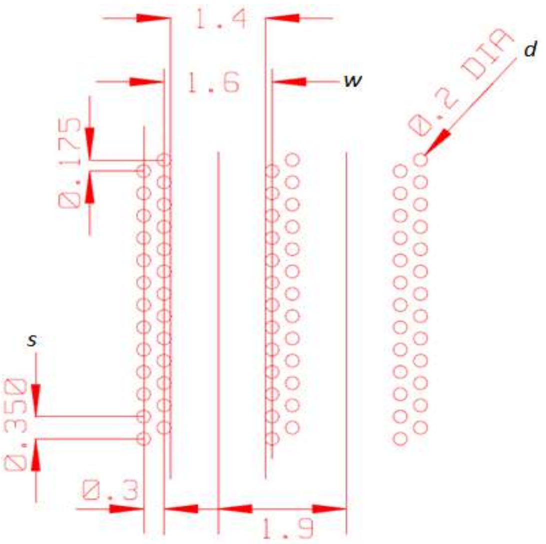
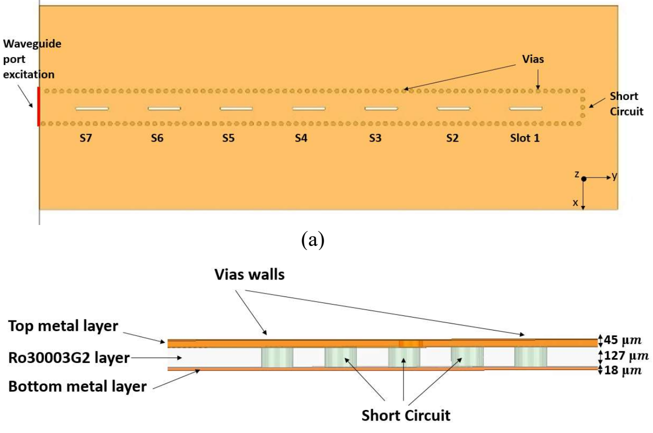


Fig. 2. Geometry of SIW's

C. *Presentation of the antenna's geometry*

This design is composed of 7 slots spaced by λ_g@ 76.5 GHz each other. This spacing and the number of slots were chosen to minimize the mutual coupling effect between slots, to maximize the realized gain and to have a wide beam in the E-plane (or azimuth plane). To fulfill with the gain specification (in simulation > 13,5 dBi at the waveguide port excitation) and the available length on the PCB for the antenna, only a uniform amplitude distribution was possible. This conclusion has been stated after several simulations. The offset for all the slots from their center to the median of the SIW is equal to 58 µm. The dimensions of SIW are given in the Fig. 2. The design of the antenna is shown in Fig. 3. The overall dimensions are 27 mm x 13 mm and are compatible with the area on the PCB allocated to the TX/RX antennas (Fig.1).



(a)

(b)

Fig. 3. Overall view of the 7-slots-SIW antenna design (a) Top view (b) Side view

1) *Results of the strucutre without radome*

The simulations have been conducted with HFSS software. In terms of impedance matching, we obtain a bandwidth of 1.2 GHz with a central frequency close to 76.6 GHz (Fig. 4, red curve). We have also simulated the antenna in a situation closer to reality by adding a microstrip-to-SIW transition because the radar chip will be connected to the antenna by a microstrip line. We can see (Fig. 4 blue curve) that the level of return loss is still good.

Simulated radiation patterns at 76.25 GHz are plotted in Fig. 5. In the H-plane (ϕ=90°) containing the focused beam, we can observe a side lobe level lower than -13 dB which is coherent with a uniform amplitude distribution.

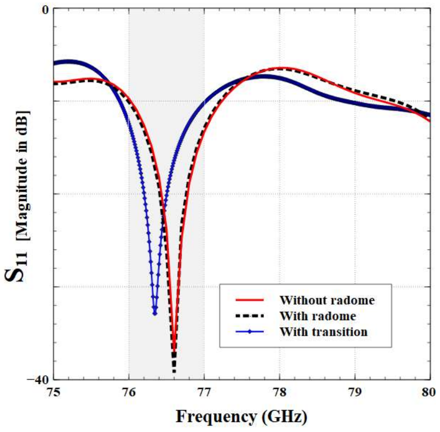


Fig. 4. Simulated return loss

In the plane E-plane (ϕ=0°), the radiation pattern has a large beam as required for the project. We can notice that the maximum gain is observed for large θ angle (~+/-60°) which is due to surface currents on the substrate, and also to the finite dimension of the top ground plane along x axis. The size of the ground plane along this axis is 13 mm. This dimension is imposed by the space available of the PCB for the sets of RX and TX antennas (Fig.1). The peak realized gain is around 12 dBi, but the broadside (direction perpendicular to the PCB) one's is about 10.16 dBi.

The broadside realized gain (ϕ=90°,θ=0°), and the radiated efficiency are shown in Fig. 6 (blue and red solid curves). The gain goes from 8.2 dBi to 11.2 dBi over the bandwidth 76-77.2 GHz, and the radiated efficiency from 48% to 63%.

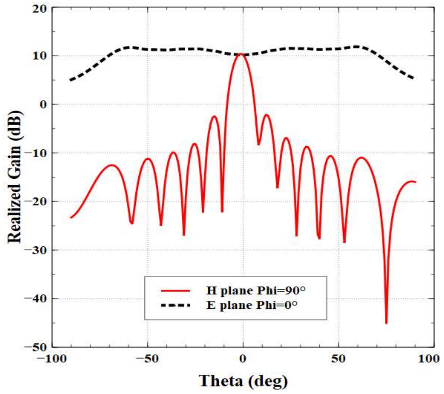


Fig. 5. Simulated radiation pattern @ 76.25 GHz in principal cuts

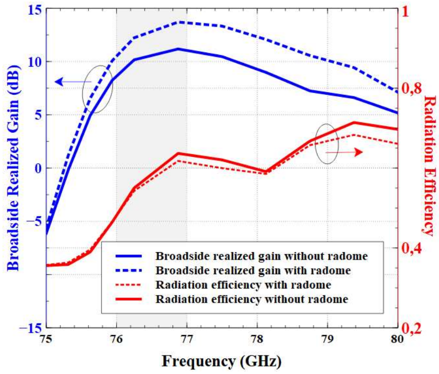


Fig. 6. Broadside realized gain, Radiation efficiency with and without radome

2) *Results of the strucutre with radome*

These previous results have been presented to point out the effects of the radome on the antenna's performances. The radome is used to protect the radar's sensor. Its permittivity is equal to 3.34 and its loss tangent is close to 0.0105. The thickness is equal to 1.2 mm and the distance between the top face of the PCB and the radome is equal to 2.1mm. As shown in Fig. 4, black dotted curve, the radome has no effect on the return loss.

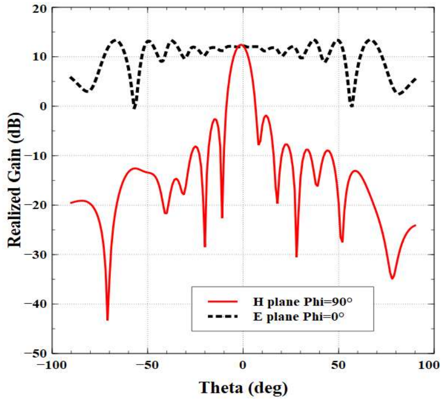


Fig. 7. Simulated radiation pattern @ 76.25 GHz

As expected, the main effects are observed on the radiation patterns. The radome exhibits a "lens effect" providing a more directive pattern. Consequently, the antenna gain is higher, but we can also observe some oscillations in the E-plane as shown in Fig. 7.

With the radome, the realized gain of the 7-slots-SIW antenna increases. In the bandwidth (76-77.2 GHz), the broadside gain with radome goes from 10.5 dBi to 13.7 dBi and the efficiency from 48% to 61% over the bandwidth 76-77.2 GHz. The results are summed up in Fig. 6 (dotted curves). It is important to note that the total efficiency remains quite stable with the radome.

IV. EXPERIMENTAL RESULTS

To evaluate the performance of the 7-slots-SIW antenna, we outsourced the fabrication of five test's vehicles including a TRL calibration kit, 7-slots-SIW antenna and two other antennas with similar specifications for comparison (Fig.8, left picture). To do the radiation measurements, the PCB was mounted on a measuring bench as indicated in Fig. 8 and Fig. 9. On the right picture of Fig.8, we can see the contract of the tips with the PCB.

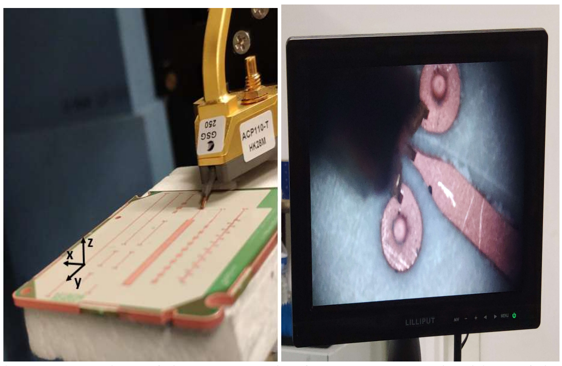


Fig. 8. Mounting of the PCB on the foam support- Checking of the probing

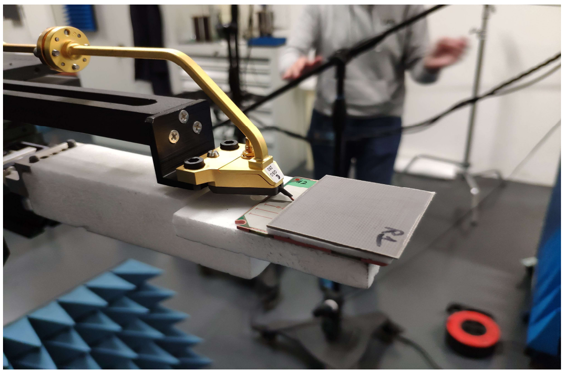


Fig. 9. SIW 7 slots antenna with radome phantom

Fig. 10 shows the measurement results the return loss. We measured the S_{11} parameter of the 7-solts-SIW antenna without radome for the 5 test's vehicles. The two curves are the S_{11} for the best case and the worst case. The operating band of 76-77 GHz is well covered in the two cases, but the resonant frequency is shifted-up to 77 GHz. We reach good levels of adaptation and the minimum value of -10 dB is always respected which validates our previous simulation results of Fig. 4. Radiation patterns are also shifted-up to 77 GHz. These discrepancies between measured and simulated results come certainly from tolerance fabrication. We have observed in simulation that a change of 10 microns for the length or the width of the slot can shift-up or shift-down the antenna's matching.

Fig. 11 *and* Fig. 12 show the simulated and measured radiation pattern normalized to maximum for E plane and H plane @ 77.5 GHz, with and without radome. We must specify here that the 7-Slots-SIW antenna was fabricated with a small ground plane of 2 mm of width on the top face, that's why oscillations arise in the E plane. We simulated the 7-slot-SIW antenna of the test's vehicle and we observe also these oscillations, but with less amplitude. There is a good agreement between simulated and measured radiation patterns. It is important to note that the facility test is installed in a semi-anechoic environment and the system presents a blockage zone on the acquisition sphere where measurements are not possible. The measured cross polarization level is -20 dB below the maximum co-polarization.

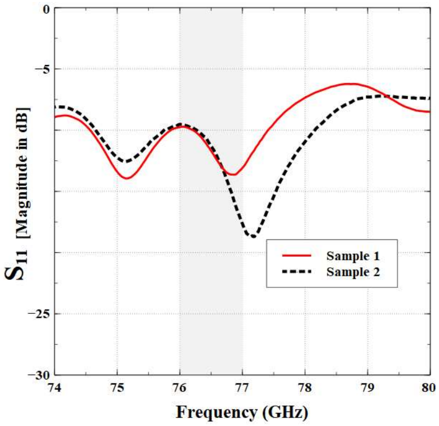


Fig. 10. Measured return loss for two samples without radome

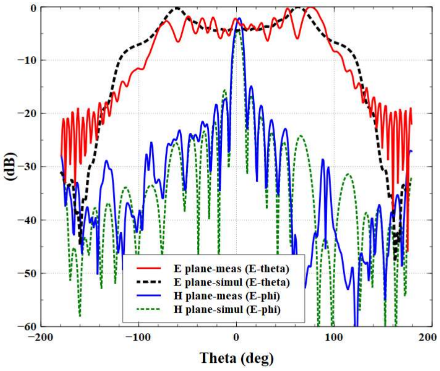


Fig. 11. Measured, Simulated E, H planes @ 77.5 GHz without radome

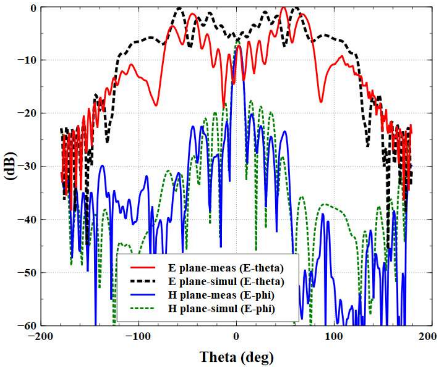


Fig. 12. Measured, Simulated E, H planes @ 77.5 GHz with radome

As showed with the simulation, measurements confirm that the radome produces an increase of the directivity and the gain of the antenna (see Fig. 13). It is estimated between 2 and 2.5 dBi. It was similar in simulation.

The "measured" total efficiency deduced from directivity and gain measurements (Fig. 14) are higher than the simulated ones and shows that the choice of the SIW technology is a right strategy to reduce the losses in comparison with classical linear patches antennas.

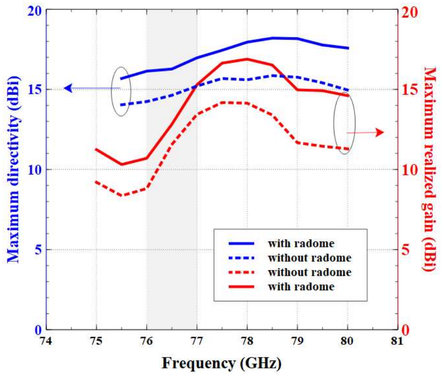


Fig. 13. Measured maximum directivity, and measured realized gain with and without radome

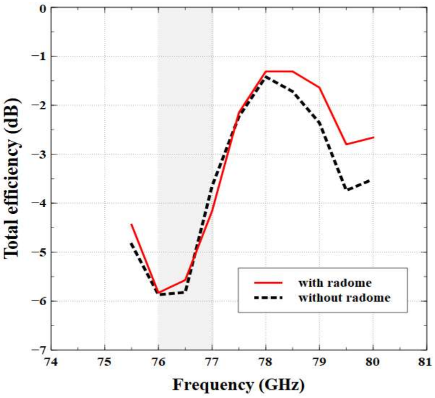


Fig. 14. Measured total efficiency with and without radome

V. CONCLUSION

In this paper, a SIW-slot-array antenna structure is presented. The design is composed by 7 slots spaced by λ_g@ 76.5 GHz each other for an overall dimension of 27mm x 13mm. This spacing was chosen after many studies to minimize the mutual coupling effect between slots and to maximize the realized gain. This antenna allowed us to achieve 10.5 dBi to 13.7 dBi of gain @76.5 GHz, and 48% to 61 % of efficiency. The mutual coupling between Tx and RX is around -23 dB. The PCB of the B-model with 4 RX and 3 TX has been fabricated and the assembling with the radar chip is ongoing.

The proposed SIW structure is a good candidate to be used for radar application in W band. Regarding the measured reflection coefficient, this antenna can be used between 76 GHz to 78 GHz. But it needs to be optimized because the sidelobe level and the mutual coupling between Tx and RX module are quite lower than expected ones. That's why as a perspective of maximizing the radiation efficiency and therefore the gain, a second design of an interesting high gain SIW antenna is under development by modifying the radome and introducing a superstrate layer. The space between slots can be reduced to $\lambda_g/2$, and consequently the length of the antenna. Then, it will be possible to shift one TX antenna with respect to its neighbor ones to decrease the coupling. This design will be developed in a future paper.

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