SINATRA (Substrate Integrated Novel Antenna Technology for millimetre -wave RAdars)

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ABSTRACT

This project aimed to achieve a method to design and make possible millimetre-wave antennas on PCBs capable of providing breakthrough performance in the Field Of View (FOV), that is a strong front to side gain ratio or, in general, to tailor the shape of the radiation pattern at preference. This is key for short or mid-range RADAR sensors that look in a specific direction, with negligible side interference, overcoming the current false-alarms limitations in automatic vehicle driving. The idea to make them so small and to integrate many of these sensors in a single PCB paves the way to compact and cost-effective applications.

Keywords: Intelligent viewing; SIW; array antenna; radar sensors; false alarms; automatic vehicle drive.

1. INTRODUCTION

Combining and integrating in small space arrays of mm-waves sources, so to shape the desired radar coverage, is a fundamental step to enter in the next generation of sensor fusion.

We have pushed the Substrate Integrated Waveguide (SIW) antenna to a 840 elements array at 77 GHz, developing a method for selecting the desired pattern (synthesis) and the feeding methods requirements. As a benchmarking an equivalent array of slotted waveguide "in air" instead of substrate has been used.

The results have shown that the SIW-antenna has the capability we were searching for, and that 100 GHz is the current technology operating frequency upper limit to manufacture them with acceptable losses. On the other side the slotted waveguides at the same frequencies, have clear mechanical accuracy limitations as produced by machining method.

2. STATE OF THE ART

Obstacle detection techniques used in railway or automotive applications at 77 GHz today are based on phased arrays but have limitations in achieving the goal. New automotive devices promise automatic anti-collision, but false stops are frequent for example due to vehicles on the adjacent lane that are erroneously judged as a potential front obstacle. This is due to the limitations of the sensor to reject objects out of its FOV. Capability to reject a side obstacle depends on phased array cross range resolution, which depends on array's dimension. Despite MIMO radar techniques can increase the number of virtual elements the limitations in the front/side rejection still dominate the achievable performance (Fig 1-2).

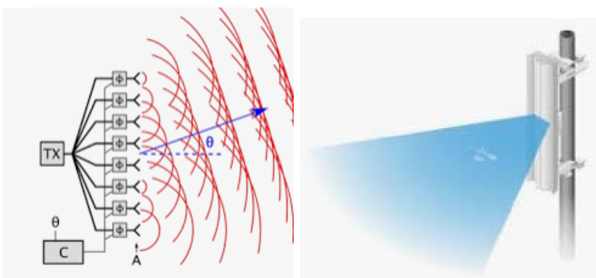

Fig. 1. (right) Radar with Phased Array: Front versus side rejection is depending on cross-range resolution of the phased array, therefore on the number of elements; (left) Sectorial Radar antenna: Front versus side rejection is directly the antenna's roll off (front directivity / side directivity).

Automotive 77 GHz MIMO radars use often 2 or 3 transmitting antennas and 4 receiving antennas, virtually corresponding to one transmitting and 8 or 12 receiving elements. This limited number of elements reduces the maximum potential front/side directivity of the equivalent antenna.

Some Obstacle Detection Systems at level crossing use 77 GHz radars with sectorial antennas, where this characteristic to distinguish in/out of FOV are higher but have still non optimal performance. These devices are big and heavy, preventing large-scale manufacturing for sensor fusion (Fig 2).

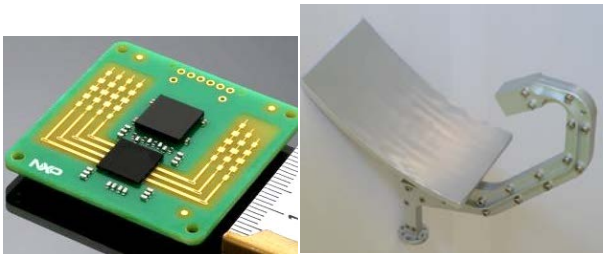

Fig. 2. (left) Commercial automotive 77 GHz radar: the antenna is printed on a PCB and integrated with the electronics. (right) Sectorial reflector radar antenna for level crossing surveillance: the antenna is heavy, bulky and difficult to integrate.

3. BREAKTHROUGH CHARACTER OF THE PROJECT

To overcome the limitations in the antenna performance and to permit a low-cost mass production and easy integrability with the radar front end electronics, we have designed, realized and tested prototypes of SIW array antenna. During the project we have developed a novel ad-hoc design procedure, including appropriate numerical simulation tools allowing for the antenna optimization. We have designed a fixed position radar array, composed by more than 800 radiating elements, creating a sectoral coverage radiation pattern with a formidable roll-off, still maintaining a potential low-cost manufacturing, due to the SIW method which is very cost effective.

Fig. 3. (left) Prototype of the 77 GHz SIW radar antenna. (right) All-metal slotted waveguide array prototype with similar number of radiating slots built for benchmarking the SIW one.

The SIW antenna (Fig. 3, left) challenge design was to include the substrate losses, the modelling of multi-layer behaviour of the waveguides and a complex feeding network inside the design.

The challenging radiation pattern requirements of the application were applied also to a benchmarking similar antenna (Fig. 3, right) composed by slotted waveguide on 4 alloy plates, and manufactured by means of precision mill machining.

4. PROJECT RESULTS

The operating principles of the proposed antenna and the criteria adopted for its design and fabrication are here summarized. The antenna dimensions are A×B = 70×100 mm, and it was designed in standard PCB technology, easily allowing to etch slots on laminates with high-precision (tolerance of 50–70 μm) and to make vias (tolerance on pin radii of 100 μm) as required for SIWs. Three low-loss dielectric laminates (ROGERS 5880, ε_r=2.2, tan $\delta = 9\times 10^{-4}$, thickness h_d=0.79mm) metalized on both the sides (Cu 7 μm) were used to integrate the radiating aperture and the feeding network. In Fig. 4, the stack-up of the adopted technology is sketched where the four metal layers, with coupling and radiating slots, are denoted from M1 to M4, whereas the three stacked dielectric substrates, in which the vias are made are tagged from D1 to D3.

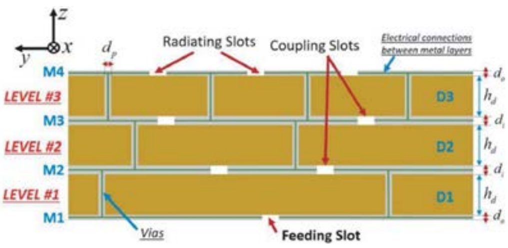

Fig. 4. Schematic stack-up of the multilayer SIW arrangement.

In Fig. 5, the antenna general architecture and the working principle are described. SIW waveguides have walls a_e=3.3 mm apart, made of vias with diameter d_p=0.3 mm and spacing T_p=0.6 mm. The H-shaped SIW network at level #1 was realized in D1, the 4 SIWs at level #2 in D2, and the SIWs associated to radiating rows in D3. At level #1, the feeding wave at the input port is equally split into two waves exciting 4 coupling slots (yellow) at the end of the H-shaped SIW; such (yellow) slots couple level #1 to #2 where 8 waves are launched to feed at their centre 4 linear arrays of additional coupling slots (red), which in turn excite the radiating rows at level #3. Radiating aperture design

The proposed antenna requires to radiate a beam which is narrow in the vertical plane and sectoral in the horizontal plane, hence a suitable aperture distribution must be a truncated sinc along *x* and along *y*.

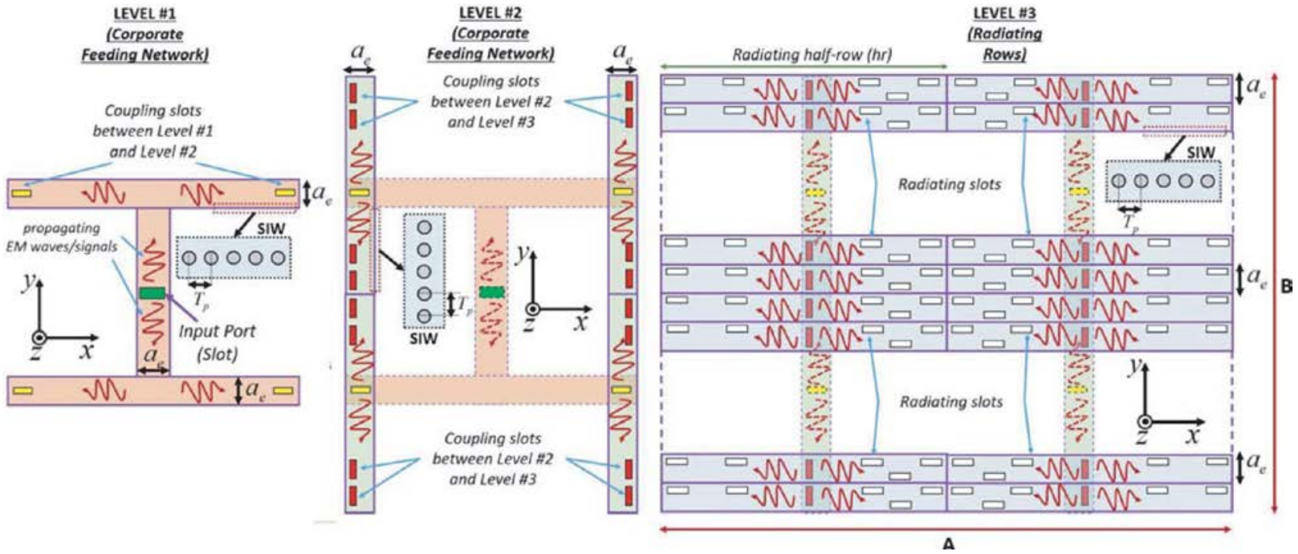

Fig. 5. General architecture of the SIW designed in the dielectric layer D1 (level #1), including an H-shaped corporate feeding network separately feeding 4 sub-arrays. The H-shaped SIW is coupled to those in D2 (level #2) through four yellow slots (etched on M2), whereas the red slots in the broad side of the SIWs at level #2 are etched on M3 and couple level #2 to the SIWs realized in D3 (level #3), which allow the radiating white slots to radiate a sinc-shaped magnetic current distribution.

The truncated sinc aperture distribution has been synthesized by optimizing a standing-wave slotted array [Elliot] in SIW technology in x-direction, whereas the uniform distribution along y-direction has been achieved by simply replicating the radiating rows. Invoking the antenna symmetry with respect to xz-plane only a half-rows was considered by introducing in the electromagnetic model a magnetic wall (H-wall) in the xz-plane at y=0, and periodic boundary conditions (BCs) in the yz-plane at $x=\pm T_r/2$, as shown in Fig. 6.

A numerical optimization loop has been developed in Matlab interfaced with the commercial electromagnetic full-wave solver CST. The overall optimization process is very fast and converges in 15–20 steps involving a moderate size electromagnetic analysis (80.000 tetrahedrons).

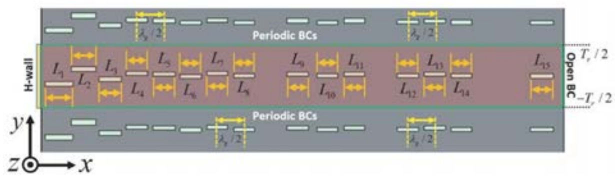

Fig. 6. Radiating half-row arrangement. Slots are etched on the metal layer M4 synthesizing a sinc-shaped aperture distribution, to radiate a sectoral pattern in the horizontal plane.

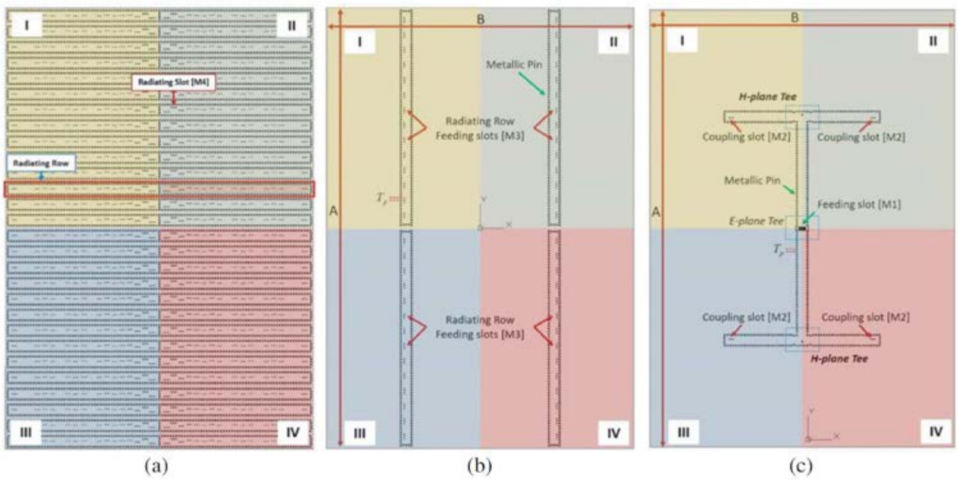

Fig. 7. Antenna final layout: drill and slot maps corresponding to the three different layers: (a) D3, (b) D2, and (c) D1, with reference to the stack-up in Fig. 5. The four subarrays are denoted by I, II, III and IV.

Feeding network design

To enlarge the antenna operating bandwidth, the radiating aperture has been divided into 4 independent subarrays and fed by means of a corporate feeding network. The final antenna layout is shown in Fig. 7. With reference to Figs. 7(a)–(b), radiating half-rows are fed by transverse feeding slots etched on the metal layer M3. In turn, such slots are spaced a waveguide wavelength λ_g and placed on the maxima of the voltage standing-wave generated inside the four feeding SIWs, thus exciting all the slots in-phase and maximizing the power transfer between D2 and D3. The feeding slots in Fig. 7(b) are then coupled to D1 through the 4 coupling slots etched on M2. Finally, the 4 waves are combined in-phase through the H-shaped SIW network depicted in Fig. 7(c) up to the antenna input port, i.e. a feeding slot etched on M1 directly connected to a standard WR12 waveguide, which is the radar interface. In the H-shaped SIW network two Tee junctions in both H-plane and E-plane are present, which were properly designed and matched. The designed feeding network has been simulated together with the radiating aperture by using the full-wave frequency-domain solver of CST Microwave Studio. The computational resources used for entire full-wave simulation are non-negligible, since more than 800.000 tetrahedrons are required. Such a simulation has to run only few times, for geometry final refinements and not for the optimization of the radiating aperture. Hence, the proposed two-step optimization (i.e., radiating aperture and then feeding network) has been successful and allowed to avoid computational issues. The aperture field distribution is shown in Fig. 8.

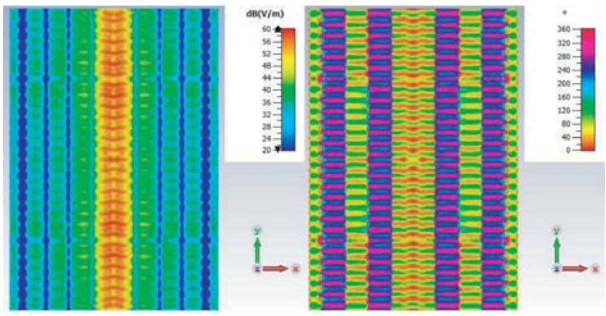

Fig. 8. Magnitude (left) and phase (right) of tangential electric field distribution at λ/2 from antenna aperture, after the optimization process. A sinc-shaped (uniform) profile is present along x-direction (y-direction), as required.

Antenna prototype measurements

Some SIW antenna prototypes where realized and measured at ECM, labs. The input reflection coefficient was tested with a SNA and is reported in Fig. 10 together with the antenna radiation pattern. The latter was acquired by processing the radar signal of a reference target when moving the radar on a turning table. The S_{11} about -15dB in the operating bandwidth and the radiation pattern shows a horizontal plane sector beam with a high roll-off (> 5.5 dB/deg) and a limited ripple (< 1.3 dB). The SIW antenna was compared in terms of performance and producibility against a benchmark antenna in standard metallic waveguide technology (not reported for lack of space). The SIW antenna electrical performance are excellent except for higher losses, compared to the benchmarking antenna (the metallic waveguide) whose producibility is critical requiring top precision machinery which makes it also very expensive.

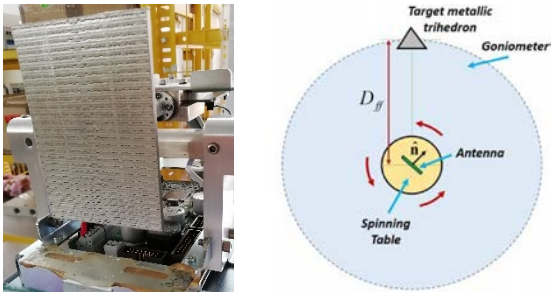

Fig. 9. (left) Antenna prototype integrated with the radar and (right) turning table arrangement for pattern measurements.

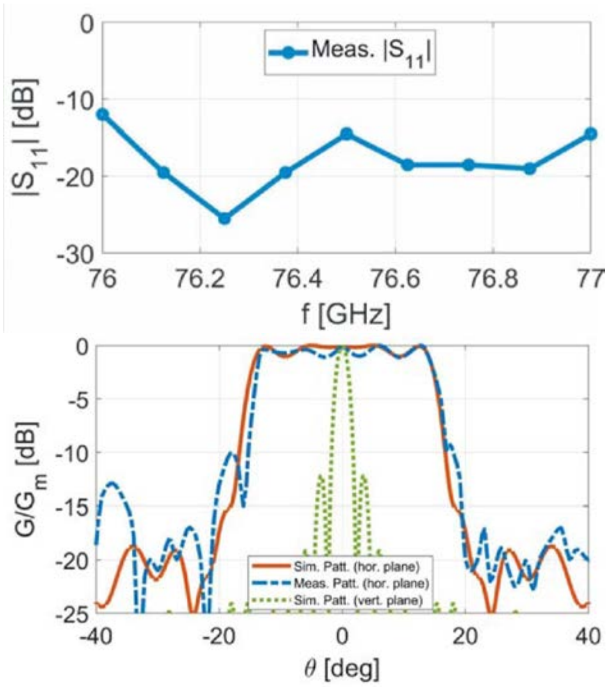

Fig. 10. Input reflection coefficient (above) and radiation pattern (below) of the SIW antenna prototype.

5. FUTURE PROJECT VISION

5.1. Technology Scaling

To further proceed in making this technology usable by large-scale industry the following steps are required:

- Import the developed array synthesis concepts into an antenna CAD (Computer Aided Design) to allow automatic support to design.

- Connect the above CAD to the technology constraints given by materials and processes of the PCB (Printed Circuit Board) manufacturing.

- Integrate the method with current MIMO RADAR technology and electronics.

5.2. Project Synergies and Outreach

For achieving TRL 5-7 other companies need to enter in the consortium, especially to cover some technologies which are not owned by the phase-1 partners.

- We search for a PCB manufacturer wishing to invest in pushing the technology limits.
- We need on board a microwave CAD supplier to support the array design method and fit into a tool for good usability.
- We search for an electronic radar on-chip manufacturer to get the
- Also, a car manufacturer would be welcome in the consortium to provide clear requirements and real application test cases.

5.3. Technology application and demonstration cases

The technology application would be in the field of automatic vehicle driving, which directly influences smart, green and integrated transport. Our demonstration will be a scenario of a narrow lane street road, with the enhanced method, where a vehicle is not influenced by adjacent lanes obstacles, benchmarking it with the current anti-collision radar existing on a commercial car, where false brakes exist.

This improvement will give to the automotive and transportation market an impulse to new standardizations, potentially associating also car industry makers.

5.4. Technology commercialization

Again car and train makers could be attracted by this technology that could be licensed by the consortium to the interested partners.

5.5. Envisioned risks

The difficulty in benchmarking the current versus a new technology often resides in optimizations (experience based) applied in the existing technology that are not present in the new one, thus reducing the evaluation of real different capabilities on a fair base.

To mitigate such a risk we should insert in the consortium a partner that already manages and owns such current technology.

5.6. Liaison with Student Teams and Socio-Economic Study

Already in this first stage, thanks to the leading participation of University of Siena, the project has involved MSc and PhD students.

An eventual second stage, with bigger scope of work, would be the ideal place for involving tens of MSc students, as individuals and in teams.

6. ACKNOWLEDGEMENT

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7. REFERENCES

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