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Integrated Slotted Serpentine Waveguide to Enhance Radiation Properties and Efficiency

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ABSTRACT Slotted waveguides are often used when high-power and high-efficiency antennas must be designed and particularly for millimeter waves applications (automotive radar for example). But it is not easy to choose any distance between radiation slots because of the guided wavelength, to obtain a wide beam in E plane and so to cover a wide angular sector in beam scanning antennas. Moreover, the main beam depends of frequency because it is a progressive wave antenna. In this article, the authors propose an original solution based on a slotted serpentine waveguide with slots on the narrow wall of the waveguide allowing to obtain a very wide radiation pattern in E plane, and this antenna is manufactured, thanks a PCB (printed circuit board) process with empty waveguides to enhance the efficiency for the global structure. Simulations and measurements are given to validate the idea and the technological process in W band, and some different prototypes demonstrate that it could be possible to obtain a wide angular sector in a beam scanning antenna configuration.

INDEX TERMS Slotted waveguides, serpentine, millimeter wave, PCB technology.

I. INTRODUCTION

The slotted waveguide antennas are very well-known structures and are commonly used in microwave transmitter and receiver devices. Such antennas radiate energy from feeding waveguide to a free space through several slots cut in broad or narrow wall of a rectangular waveguide. A special interest in such antennas is caused by their planar and compact structure, high-power handling, and electrical parameters such as high efficiency and good return loss [1], [2]. The waveguide is defined, respectively, by the width of the broad and narrow walls (a and b), and to remember the electric, magnetic fields, distributions and also current lines are given in Figure 1 for the fundamental TE10 mode. The radiating slots must cut the current lines in the waveguide to be excited, and so many solutions of particular slots exist on the broad or the narrow wall as represented in Figure 2. Depending on cases (a) to (e), some constraints exist to design slotted array because of the current line orientation. In case (a), for an array configuration, the slots must be put alternatively in regard to the longitudinal axis of the waveguide and with a distance between them of $\lambda_g/2$ to excite the different slots in phase. Thus, the distance between slots is unchanged, and the beam in E plane (vertically to the slots length) cannot be wide because an array of two slots is realized in this plane. For case (b), the distance between slots cannot be arbitrarily

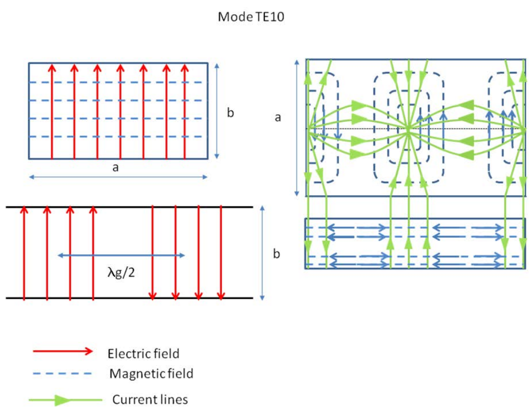

FIGURE 1. Electric/magnetic field distributions and current lines for the fundamental TE10 mode in a rectangular waveguide (a and b are, respectively, the width of the broad and narrow walls).

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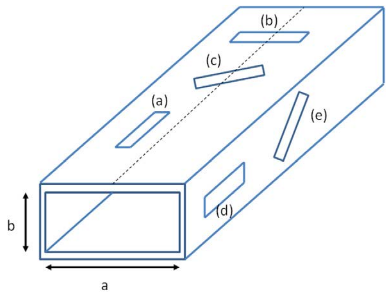

FIGURE 2. Radiating slots in the broad wall (a, b, and c cases) or in the narrow wall (d and e cases).

chosen because of the periodicity of the wavelength in the waveguide. In case (c), a problem of cross-polarization can appear for the radiation outside the broadside direction. When the slots are placed in the narrow wall of the waveguide as for case (d), the distance between slots must be important (more than λ0) to be excited in phase and because of the orientation of current lines on this wall, and so grating lobes appear in the context of slotted array designs. Case (e) gives one solution to overcome this problem by inclining and changing the orientation of slots, but the cross-polarization level can be good only in the broadside direction of the radiation pattern. Other problems can appear with slotted waveguide as side lobe level or difficulty to obtain a wide scanning angle or to optimize the scanning angle with frequency. To fight these difficulties, Radwan *et al.* [3] have investigated the possibility to reduce the side lobe level by using a bended slotted rectangular waveguide, or in the study by Maritz [4] by designing slotted waveguides with Z-shape slots engraved in the broad wall of the waveguide. In Traille *et al.* [5], a novel faceted conformal slotted waveguide is studied for a full 360° azimuth tracking application. Moreover, in this reference, the authors developed a center-fed narrow-wall slotted waveguide array with an H-shape T junction to extend bandwidth and to obtain a broadside radiation (without any scanning of beam vs. frequency). But the level of cross-polarization is not better than −10 dB as they used inclined radiating slots in the narrow wall of the waveguide. In patents [6], [7], the authors propose to design serpentine or helicoidal slotted waveguide to increase the capability of their antenna to scan the beam with frequency. The serpentine of helicoidal shape allows increasing the length of the waveguide between radiating slots and so the phase shift between them. In Coetzee *et al.* [8], the authors propose a technique using a meandering waveguide to design a two-dimensional array and to ensure the excitation of different linear arrays with the same phase. Concerning the technology of realization to manufacture slotted waveguides, they can be classically made by drilling metallic support, by metallizing foam material [9], or by diffusion bonding [10], [11], especially for millimeter wave antenna designs when the size of the waveguides is small. The slotted waveguides can also be manufactured with classical PCB etching process, and in this case, we talk about the substrate integrated waveguide as mentioned in the studies by Yan [12] and Bakhtafrooz and Borji [13] or in the study by Tekkouk *et al.* [14] to design a very compact multibeam antenna based on a Rotman lens design. If this last technology seems very simple, the manufactured waveguides are filled with dielectric substrate that induces loss especially in millimeter wave range. Thus, one solution with waveguides filled with air is better for the efficiency of antennas as far as possible with gap concept waveguide [15] even if this technology is not so easy to implement. In this context of slotted waveguide antennas, the authors in this article propose a serpentine waveguide antenna to enhance radiation properties in order to have a very wide radiation pattern in E plane (vertically to the length of slots), to choose any distance between slots to manage the beam width in H plane and to avoid any grating lobes, to improve cross-polarization level, and finally to have a good efficiency for antenna design in W band (automotive application). The shape of serpentine for the waveguide allows exciting the slots of an array with the same phase by controlling the length of straight and curved waveguides. Moreover, a multilayer PCB etching process is used to manufacture such integrated slotted waveguide to facilitate the integration of active devices and with empty substrate waveguides to cancel dielectric loss and improve efficiency. In the first section, the authors detail the concept of the serpentine waveguide with slots in the narrow wall by giving details about the technological process, before giving simulated and experimental results of a basic linear array in the second section. In the third section, different configurations of two-dimensional planar arrays to synthetize multiple receivers' antenna for a beam scanning application are presented.

II. SERPENTINE SLOTTED WAVEGUIDE CONFIGURATION

The details of the concept of the serpentine slotted waveguide concerning the positioning of slots, the physical characteristics of the meander waveguide, and also important points about PCB etching technological process are given in this section.

A. CONCEPT OF THE SERPENTINE SLOTTED WAVEGUIDE

We propose a new design of serpentine slotted waveguide with slots in the narrow wall based on case (d) of Figure 2. To reduce the distance between slots and choose it as we want for a particular beam width specification in H plane, we implement a serpentine waveguide to achieve the good phases between slots. Moreover, this configuration (d) allows having a very wide beam in E plane that is unavoidable if we want to finally design a beam scanning antenna with a wide scan angle in this plane. Finally, to have a broadside radiation (without beam tilt) in H plane whatever the working frequency, we propose exciting the waveguide in its center. One example of this innovative concept is presented in Figure 3, where a and b are, respectively, the width of broad and narrow walls of the waveguide. The E and H planes are, respectively, defined by the YZ and XZ planes.

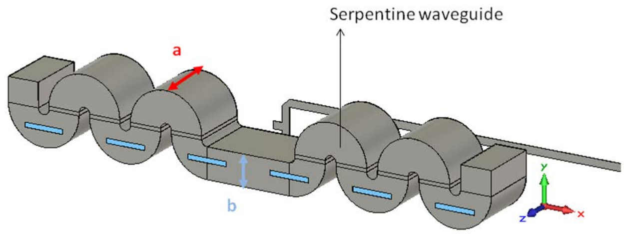

FIGURE 3. Concept of serpentine slotted waveguide with radiating slots in the narrow wall of the waveguide. In this case, the waveguide is fed by a microstrip to waveguide transition.

In Figure 3, only metallic parts of the antenna are shown, and the waveguide is fed in its center by a microstrip to waveguide transition. However, the waveguide could be also fed by other solutions as represented in Figure 4. The curves and straight parts of the serpentine waveguide are optimized to excite the different slots with the same phase. This serpentine allows to excite the radiating slots with the same phase whatever the chosen spacing between them and so to obtain a directive beam with the desired beam width. Moreover as only one slot is present in the E plane, it gives the opportunity to achieve a very wide beam in this plane.

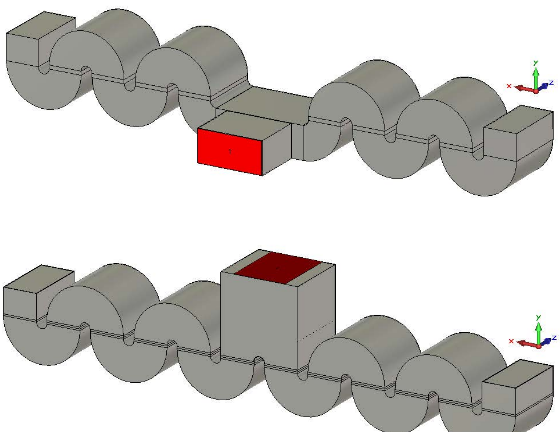

FIGURE 4. Concept of serpentine slotted waveguide with radiating slots in the narrow wall of the waveguide. Different solutions to feed the radiating waveguide.

B. MANUFACTURING AND PCB ETCHING PROCESS

The slotted waveguide is manufactured, thanks a low-cost and multilayer process based on an FR4 material used as primary support of the serpentine waveguide. First, an FR4 substrate of thickness a (width of the broad wall of the waveguide) is drilled with the print of the serpentine shape before to be chemically metallized with copper. The manufacturing after this first step is presented in Figure 5. This open serpentine waveguide is after closing using microwave substrates (Rogers RT Duroid 5880, $h = 0.127$ mm) on which the feeding microstrip line (bottom layer) and the radiating slots (top layer) are printed, respectively, as represented in Figure 6. A silver layer film (50 μm) with the print of slots (Figure 6c) is added between bottom/top layers and metallized serpentine waveguide (FR4) to ensure the metallic contact and close the waveguide. The final multilayer PCB process is summarized in Figure 7. As a PCB process is used to drill the serpentine waveguide, the manufactured antenna has low weight compared to a classical one made with metallic material. Moreover, the waveguide is filled with air allowing to improve antenna's efficiency if we compare with the one designed with substrate integrated waveguide.

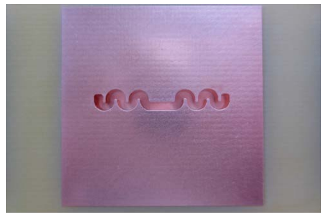

FIGURE 5. Manufacturing of serpentine slotted waveguide using a PCB etching process—drilling and metallizing of FR4 substrate to manufacture the serpentine shape.

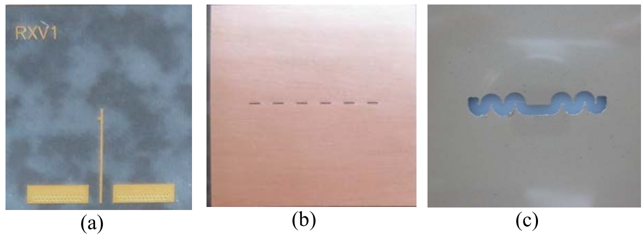

FIGURE 6. Manufacturing of serpentine slotted waveguide using a PCB etching process—chemical etching of the bottom layer (a), top layer (b), and silver layer film (c).

III. BASIC DESIGN OF LINEAR SERPENTINE SLOTTED WAVEGUIDE

A. DESIGN OF A SIX-RADIATING-SLOT ARRAY

The design of a basic linear serpentine slotted waveguide with six radiating slots is detailed in this section. The waveguide is fed from a 50 Ω microstrip line through a microstrip to waveguide transition with a feeding slot in the bottom layer (Figure 8). As represented in Figure 7, the bottom- and top-layer substrates are Rogers RT Duroid 5880 ($\varepsilon r = 2.23$ and $h = 0.127$ mm), and the serpentine waveguide is drilled in an FR4 material with thickness $a = 2.54$ mm corresponding to the broad width of the waveguide.

The lengths of the curved and straight parts of the waveguides have been optimized with CST Microwave Studio to ensure a good excitation of radiating slots with the same phase to have a broadside radiation (in Z direction). The end of the waveguides is short circuited.

B. SIMULATION AND MEASUREMENT RESULTS

The results of the first slotted waveguide (antenna 1) with six radiating slots are given in this section. The simulations are

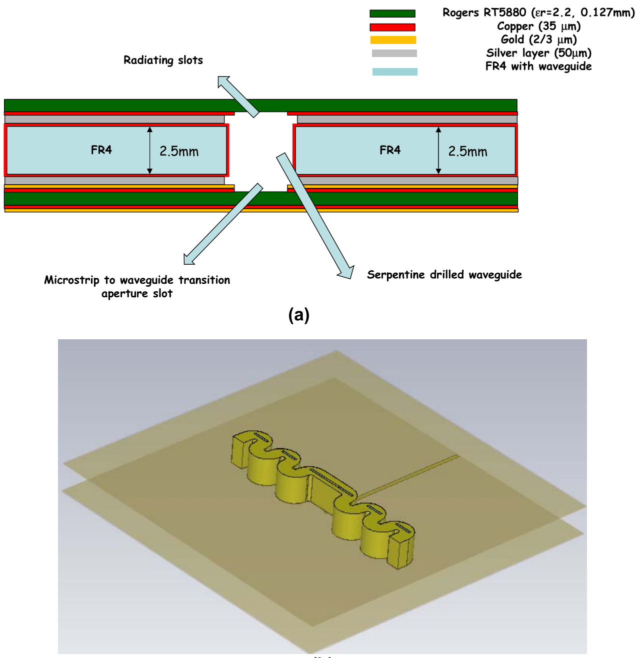

FIGURE 7. Manufacturing of serpentine slotted waveguide using a PCB etching process – (a) Stacking of the different layers to manufacture the final prototype, (b) 3D structure (CST View).

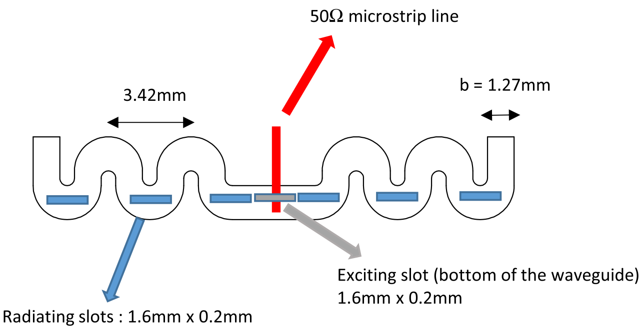

FIGURE 8. Antenna 1: Designed serpentine waveguide with dimensions. b is the narrow width of the waveguide. Radiating slots are in blue, and the center slot is on the bottom of the waveguide to excite it from the 50-Ω microstrip line.

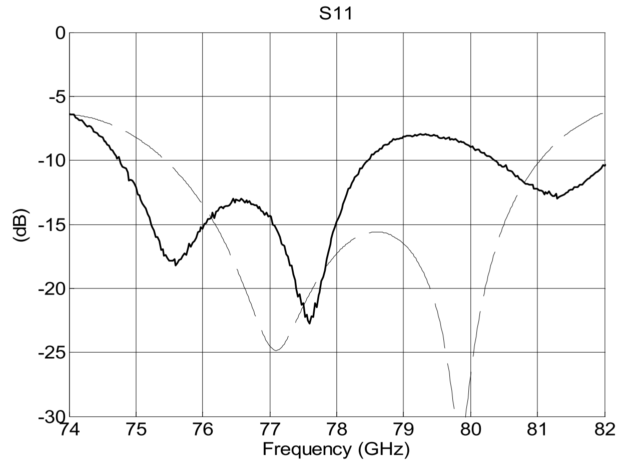

FIGURE 9. Simulated (dotted line) and measured (solid line) magnitude of S11 parameter between 74 and 82 GHz.

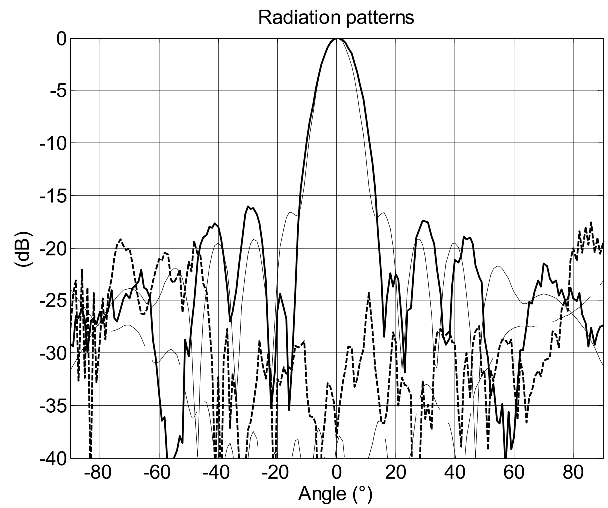

FIGURE 10. Co-polar (thick solid line) and cross-polar (thick dashed line) of measured radiation pattern in H plane at 76 GHz. Co-polar (thin solid line) and cross-polar (thin dashed line) of simulated radiation pattern in H plane at 78.5 GHz.

done, thanks to CST Microwave Studio software. The S11 simulated is better than −10 dB between 75.5 and 81 GHz, whereas for the measurement, the S11 is relatively good on the same bandwidth, even if there is a small increase up to −8 dB around 79.5 GHz. This discrepancy can be due to the impact of W connector on the input impedance of the antenna. This effect is not taken into account during simulation. Moreover, there is a frequency shift (close to 1.5 GHz) between the two results that can be explained by the tolerances of manufacturing and the misalignment of the different layers composing the antenna.

The measured gain (in broadside direction) is 8.8 dBi at 76 GHz, but it is shown in Figure 11 (E plane) that the gain in broadside direction is reduced to 1.5 dB compared to the highest one. Thus, the measured maximum gain is, in fact, close to 10.3 dBi, and it can be compared to the simulated value of theoretical directivity (12.4 dBi). The loss is mainly due to the feeding microstrip line (length of 15 mm). The measured gain of this slotted waveguide is stable (variation less than 1dB) between 75 and 77.5GHz.

Concerning the radiation patterns (simulated and measured), they are given in Figures 10 and 11, respectively, for H and E planes. The radiation patterns are given for the frequency where the gain is maximum, respectively, 76 GHz for measurement and 78.5 GHz for simulation.

In the H plane, the side lobe level is lower than −16 dB for measurement, and the cross-polarization level is lower than −20 dB compared to the main beam.

In E plane, for simulation, the result is quite good with a very wide beam for the radiation pattern as it was expected to design future arrays with beam scanning capability. For measurement, there appears

- a ripple for negative angle, which is due to reflexion of the impinged wave in the metallic support of W connector.
- a high reduction of gain for $\theta > 50°$ because of the metallic support that hides the slotted antenna array for these angles.

To demonstrate that the dissymmetry of the radiation in E plane is effectively due to the W connector and its metallic support, the authors have manufactured another prototype (antenna 2) with a bended feeding line (Figure 12). In this case, the W connector is put in the H plane of the antenna and will not disturb the radiation pattern of the E plane. We can observe the measured radiation pattern in the E plane at 76 GHz in Figure 11 (antenna 2, blue curves). Even if it exists again, a ripple (limited magnitude), the radiation pattern is now well symmetric, and this measurement demonstrates the very wide beam behavior of this antenna in E plane. It will be used to synthetize an antenna with beam scanning capability in E plane when an alignment of such serpentine slotted arrays is done as shown in the following section.

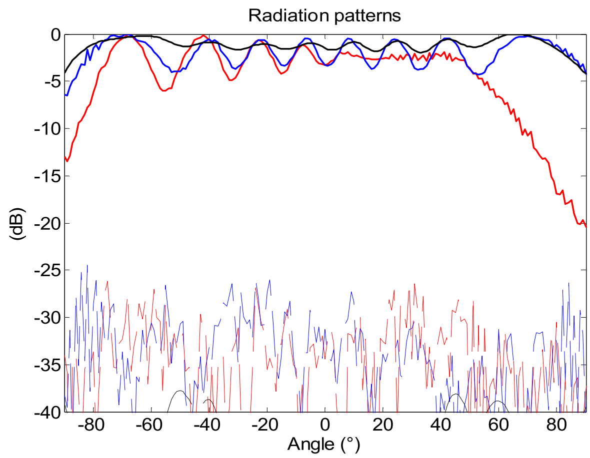

FIGURE 11. Co-polar (red solid line) and cross-polar (red dashed line) of measured radiation pattern in E plane for antenna 1 at 76 GHz. Co-polar (blue solid line) and cross-polar (blue dashed line) of measured radiation pattern in E plane for antenna 2 at 76 GHz. Co-polar (thin solid line) and cross-polar (thin dashed line) of simulated radiation pattern in E plane for antenna 1 at 78.5 GHz.

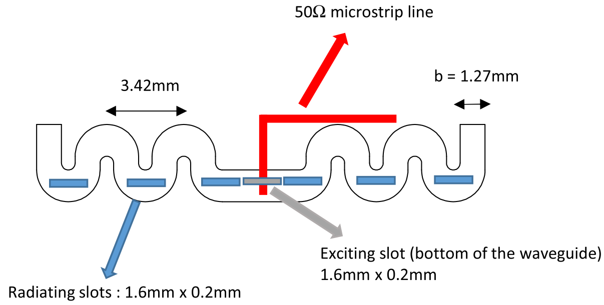

FIGURE 12. Antenna 2: Designed serpentine waveguide with dimensions. b is the narrow width of the waveguide. Radiating slots are in blue, and the center slot is on the bottom of the waveguide to excite it from a bended 50-Ω microstrip line (antenna 2).

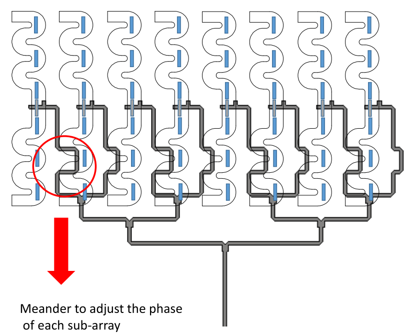

FIGURE 13. Topography on an array of eight subarrays (slotted waveguides) in E plane to scan the beam.

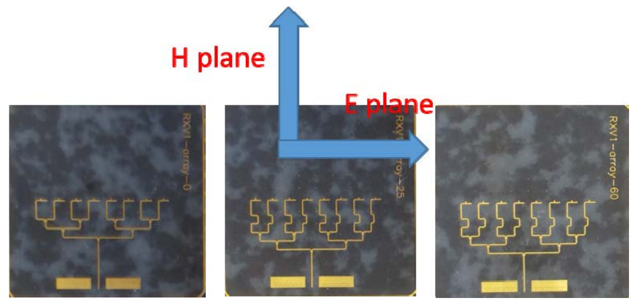

FIGURE 14. Photograph of the three prototypes after manufacturing and showing the feeding line network.

IV. ARRAYS OF SLOTTED WAVEGUIDE TO SYNTHESIZE BEAM SCANNING ANTENNAS

In this section, the authors design some arrays of slotted waveguides, and by adding a feeding line network between the subarrays, it gives the opportunity to scan manually the beam in the E plane. The topography of such array (eight subarrays) is given in Figure 13 (with one example of a feeding line network).

Depending on the feeding line network and especially the length of each meander line (Figure 13), the phase shift between the subarrays is changed and therefore the beam tilt angle in E plane. The distance between two consecutive subarrays is 4.94 mm (1.25 λ_0 at 77 GHz). A network of three different feeding lines has been considered in this work, respectively, to tilt the beam at $\theta_0 = 0°$, 25°, and 60°. The photograph of the prototypes after manufacturing is shown in Figure 14.

A. RESULTS FOR THE THREE DIFFERENT CONFIGURATIONS

For the first configuration ($\theta_0 = 0°$), the simulated and measured radiation pattern in the E plane are presented in Figure 15 at 77 GHz. The main beam tilt angle is effective at 0°, and there appear two grating lobes at $+/-52°$ as a result of the spacing between subarrays (1.25 λ_0). For the

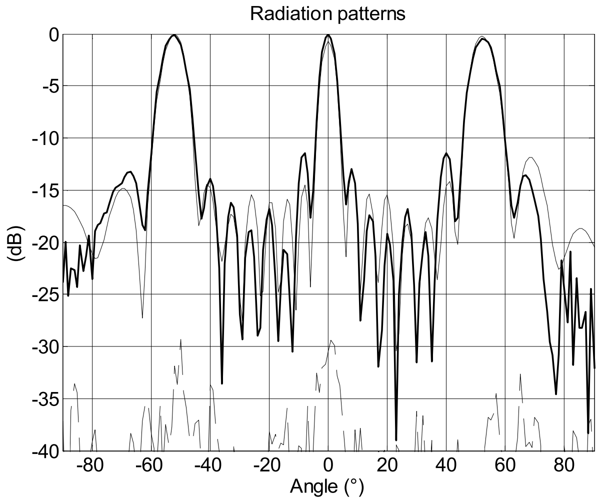

FIGURE 15. Co-polar (solid line) and cross-polar (dashed line) of the measured (thick line) and simulated (thin line) radiation patterns in E plane at 77 GHz ($\theta 0 = 0°$).

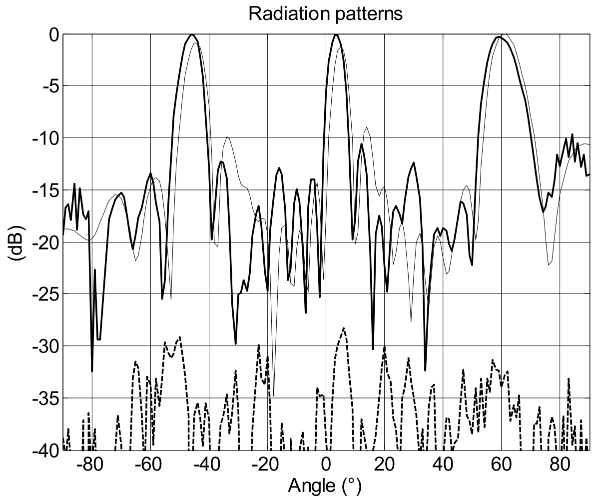

FIGURE 17. Co-polar (solid line) and cross-polar (dashed line) and simulated (thin line) radiation patterns in E plane at 77 GHz ($\theta 0 = 60°$).

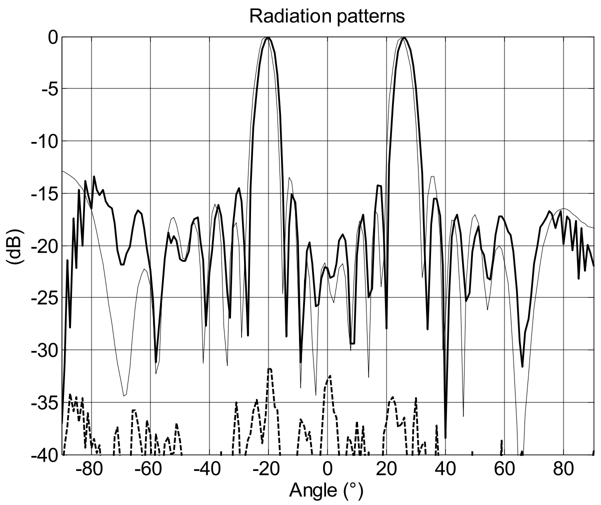

FIGURE 16. Co-polar (solid line) and cross-polar (dashed line) and simulated (thin line) radiation patterns in E plane at 77 GHz ($\theta 0 = 25°$).

two others cases, we give also the simulated and measured radiation pattern, at 77 GHz and, respectively, for $\theta_0 = 25°$ (Figure 16) and $\theta_0 = 60°$ (Figure 17). The agreement is quite good between simulations and measurements even if we can see a little tilt angle that can be due to the alignment of prototypes in the anechoic chamber during measurements. All the manufactured prototypes are well matched in the considering bandwidth. The maximum gain (at each θ_0) is stable between 14.5 and 15.5 dBi showing the interest of having a very wide beam in the E plane for an elementary slotted waveguide as it has been demonstrated in section III.

V. DISCUSSION ABOUT TECHNICAL CONTRIBUTION OF THIS WORK

This research work was to design efficient slotted waveguide antennas in millimeter wave band with two main objectives:

1) The design of a unitary slotted waveguide antenna with a very wide pattern in the E-plane to then allow beam steering over a wide sector without gain drop by combining several elementary slot guides. To achieve this result the design with a serpentine shape of the waveguide and the placement of radiating slots on the narrow wall is efficient and this work is new compared with recent papers on serpentine waveguides used to increase the scanning angle versus frequency [16]–[18].
2) The use of a simple PCB technology with air-filled waveguides to improve the efficiency.
   A lot of papers concerning slotted waveguide in millimeter wave have demonstrated good capabilities in term of gain and efficiency using diffusion bonding [10], [11], SIW technology [19] or ridge gap waveguide [15]. But these technologies are not always easy to implement (diffusion bonding for example) or do not allow to design air-filled waveguide (SIW for example). Our design is based on an innovative and classical multilayer PCB technology with a low cost substrate (FR4) to manufacture the metallized air-filled waveguide.

VI. CONCLUSION

An innovative concept of serpentine waveguide is detailed in this article to improve the behavior of slotted waveguides in millimeter waves. The serpentine shape is added in order to excite the radiating slots (put on the narrow wall) with the same phase, whatever the chosen spacing between slots. A multilayer PCB technological process is used to manufacture such waveguide antennas, and it gives the opportunity to place active components for the design of new radar or communication systems. To validate the concept of serpentine waveguide and the technological process, different slotted waveguides have been designed, manufactured, and measured around 77 GHz. The agreement between simulated and measured radiation pattern demonstrates that this concept and its associated technology are appropriate for millimeter wave applications.

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