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79 GHz three stacked cylindrical dielectric resonator antenna array for automotive radar systems

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ABSTRACT

Very high gain and sharp radiation beam of an original antenna array design, made of 16 linear three stacked cylindrical dielectric resonator antennas (three ScCDRA), is proposed in this work for automotive short-range radar (SRR) applications operating at 79 GHz. Firstly, a single antenna which functions around 79 GHz and reaches a gain value up to 11.8 dB is designed with success by piling three cylindrical DRA having permittivity values, respectively, 17.9, 16.9, and 9. However, relatively near peak values, of the main and the side lobs, makes the preliminary design less efficient for vehicle radar applications. To get a radar design with enhance properties, such as lower return loss, higher gain and especially reduced radiation pattern side lobs, we proceeded with an array design of 16 linear antenna-elements (1×16). As results, the three ScCDRA array structure provides 21.3 dB as gain peak value, a very narrow angular half power beam width (HPBW) of radiation pattern of 0.7 degree at 79 GHz. Feeding network design and positions of the sixteen linear antenna-elements, within this array, have been extensively investigated to carry out an optimal design still resonating around 79 GHz with a lower S11 parameter value up to -40 dB and hilly directional characteristics of radiation diagram.

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1. INTRODUCTION

Since the end of the second world war [1], radars have become essential in civilian and military domains. They are used in many fields, from meteorology [2] to air traffic control. In cars [3]-[7], radars are used for distance regulation systems or reversing maneuvers. Ant-collision system [8], [9] or collision avoidance system (CAS) is designed to prevent or reduce the severity of a collision. The anti-collision system is an electronic device enabling the vehicle to detect an imminent collision with another vehicle, a pedestrian or any other obstacle, to alert the driver and, without any reaction from the driver, to activate the automatic emergency braking (AEB) with which it is linked.

Tested in the mid-1990s and appeared for the first time on luxury cars in 2003 [10], automatic emergency braking system, which works via a radar distance sensor located in the grille or behind the bumper, is now fitted to a quarter of new vehicles on the market. Given its effectiveness, the authorities, in different countries, have planned to make it mandatory for all new vehicles since 2022, for the United States as example, and in the following years for Europe.

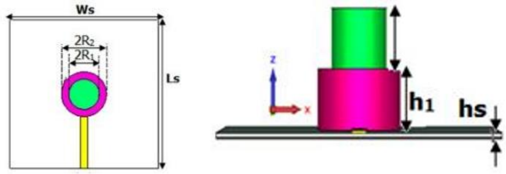
Collision avoidance systems, dedicated to short and long range radars (SRR, LRR) and working at 24 GHz, 77 GHz, and 79 GHz frequency bands, have attracted extensive attention from industrials and researchers, that why many of their standards have been published latterly. In particular, 24/79 GHz SRR norm [11]-[15] can offer many passive and safety options like parking aid, blind-spot detection and rear-crash collision prevention. Patch antennas technology [16], [17], within arrays configurations, has dominated the automotive radar industry for a long time because of their low cost when produced massively. However, conductor losses, caused by Joule effect, make these metallic aerials suffering from power dissipation. As result, their efficiency is restricted in particular at mm-Wave spectrum. At the beginning of 1980s decade, a new competitive antenna radiator technology with enhanced efficiency has been discovered thanks to the works of S. A. Long in 1983 [18]. This was the dielectric resonator antenna (DRA) which has been very popular in wireless communication systems. We have to mention that, before 1983, dielectric resonators (DRs) have been known as efficient components in microwave circuits such as filters, oscillators and resonators [19], [20] operating at very high frequencies. DRAs present many advantages over their counterpart patch antennas [21] mainly because of low losses especially at mm-wave bands, thanks to low dielectric material dissipation factor, high radiation efficiency, lower size, high freedom degree of design, and the ability of multiple excitation mechanisms (microstrips, coaxial probes, and apertures).

Based on our previous study of 2018 [22], this extended work will explain, firstly, the need of designing a three stacked cylindrical DRA, and then, will present the process to get an optimal array, of this new antenna design, dedicated to 79 GHz automotive radar systems applications. Firstly, we designed a single antenna of two and, then, of three stacked cylindrical dielectric resonator antennas (ScCDRA) elements, and we have remarked that the three ScCDRA configuration gives a higher gain, higher directivity and lower reflection coefficient compared to the two stacked cylindrical dielectric resonator antenna design, although they are resonating around the same frequency. Secondly, a series of simulations of the 1×16 three ScCDRA array, fed by a suitable architecture of microstrip lines using power dividers, have been performed to explore the enhancements on radiation pattern in term of single three-ScCDRA number and distance between two elements of this array. Up to author’s knowledge, our published study in 2018 [9] was one of the first works investigating DRA within array structure for automotive radars applications at mmWaves spectrum (24 GHz) as an alternative solution which can substitute efficiently microstrip antennas technology for automotive radars.

This manuscript is organized as follow: in the coming section we will explain the 2 ScCDRA design and we will present its main simulated characteristics. Then, we will introduce the 3 ScCDRA in the section 3 where its properties will be calculated and compared to that of the first design. Array configuration of the three ScCDRA single antenna will be discussed in the fourth section. After, we will conclude by a summary of this work.

2. TWO STACKED CYLINDRICAL DRA CONFIGURATION

In this first stage, we present the two ScCDRA optimal design proposed for automotive SRR applications, as illustrated in Figures 1(a) and (b). The two cylindrical DRAs have different radii, R1=1.5 mm and R2=1 mm, respectively, but the same height: h_1=h_2=1.5 mm. Their dielectric constant are taken to be, respectively, Eps1=17.9 and Eps2=16.9.



(a) (b)

Figure 1. Top view; (a) and side view and (b) of proposed two ScCDRA structure for SRR

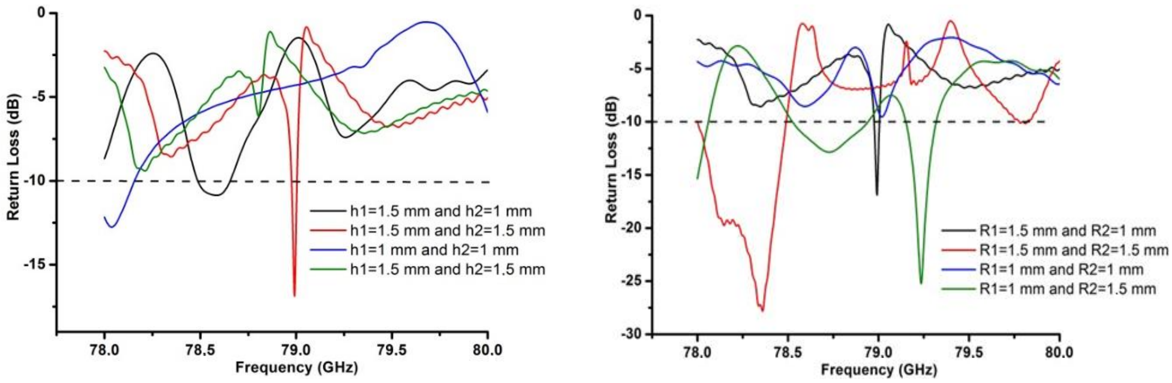
The hall stacked DRAs are excited through a conventional microstrip line of length 5 mm, width 0.5 mm and characteristic impedance of 50 Ohm. The ground backed substrate is an FR-4 material having a permittivity of 4.3. Utilizing the cost-effective FR-4 substrate, radar systems operating at 79 GHz achieve affordable solutions without compromising performance. Recent studies, such as [23]-[26], have successfully demonstrated the efficacy of FR-4 in automotive radar applications at mm-wave spectrum.

2.1. Parametric study

The aim of this work is to get an optimal structure having a good level of impedance matching around 79 GHz, which corresponds to low values of S_{11}, and directional radiation pattern for radar applications purposes. Thanks to the higher freedom degree of design offered by DRAs structures, numerous physical and geometrical parameters can be checked during simulations. So, our reported study in this paper will focus on the effect of the substrate thickness (h_{sub}), and other three parameters of the two ScCDRA: radius, height, and their dielectric constant values. In this context, it is necessary to mention that our design process has been driven by the need to a DRA of, relatively, lower dielectric constant values, because, in one hand, higher values of permittivity will lead to very small DRA size at 79 GHz, which will be difficult for fabrication actually. In the other hand, DRA with some higher dielectric constant has to be synthetized.

2.1.1. Effect of height and radius of the two ScCDRA

In case of cylindrical DRA, two geometrical parameters can be investigated: height and radius. Reflection coefficient of the two ScCDRA is plotted in Figure 2(a) in term of their height, h_1 and h_2. Four combinations of couples of height (h_1, h_2), which can be got from the height values 1 mm and 1.5 mm, have been considered in simulation, but only the following combination (h_1=1.5 mm, h_2=1.5 mm) which can lead to desired response of proposed DRA at 79 GHz. In the second stage, we kept the optimal values of h_1 and h_2, and we tested four combinations of the couple of radii (R_1, R_2) as shown in Figure 2(b). Interesting simulated result is obtained when (R_1, R_2)=(1.5 mm, 1 mm).



(a) (b)

Figure 2. Two ScCDRA: (a) return loss vs height values (h_1 and h_2) and (b) return loss vs different values of R_1 and R_2

2.1.2. Effect of substrate' thickness

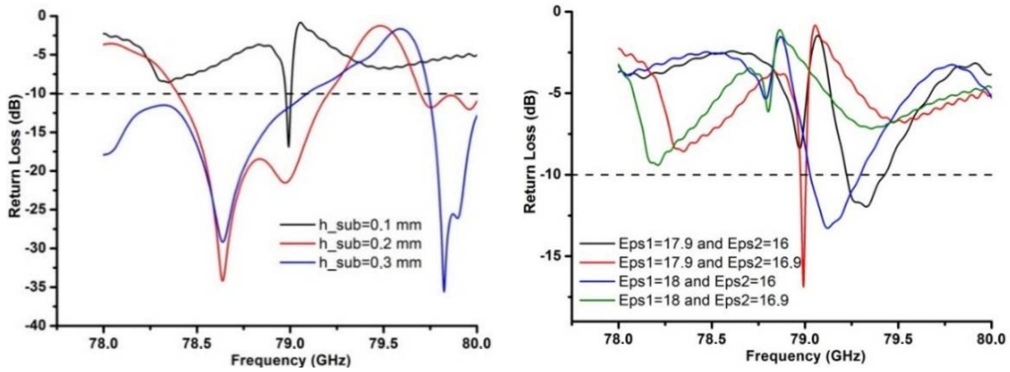
At mm-wave bands, substrate thickness cannot exceed a fraction of one mm. Here return loss parameters is evaluated for a thickness varying between 0.1 mm and 0.3 mm with a step of 0.1 mm. Figure 3(a) shows a sharper response around 79 GHz, of the two ScCDRA, with values of S_{11} less than -15 dB.

2.1.3. Effect of permitivities

As mentioned above, DRA can offer higher freedom degree of design. Besides geometrical parameters involved, designer can check material dielectric constant leading to lower reflection parameter values around 79 GHz. In this study we found that the two permittivities Eps_1 and Eps_2 with values, respectively, equal to 17.9 and 16.9, can lower the S_{11} values, at 79 GHz, much inferior than -10 dB as depicted in Figure 3(b).

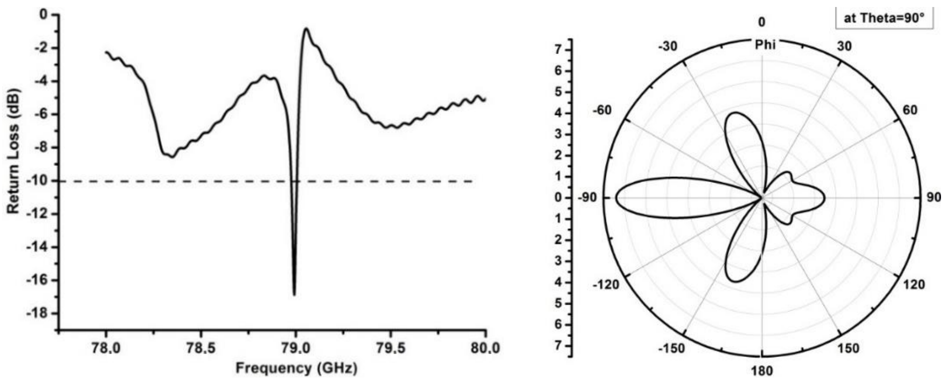
2.2. Two ScCDRA optimal design characteristics

To get an idea on the performances of this first optimal CDRA design, composed of two stacked cylindrical DRA, Figures 4(a) and (b) present, respectively, its return loss results and pattern of radiation diagram. As conclusion of this first parametric study, we can say this design illustrates a very selective antenna property, at 79 GHz, whereas radiated power is, mainly, spread on three directions with about 2 dB as power difference between their maximums. This is not appropriate for radar applications where the most of power has to be radiated toward a specific direction to make the radar-antenna more directional. So, inspired by the idea of Yagi antenna design, we decided, in the next stage, to stack a third cylindrical DRA with the same height $h_3=h_2=h_1$ but having lower radius, R_3, than previous ones.



(a) (b)

Figure 3. Two ScCDRA: (a) return loss vs substrate thickness values h_{sub} and (b) return loss vs radiators permitivities

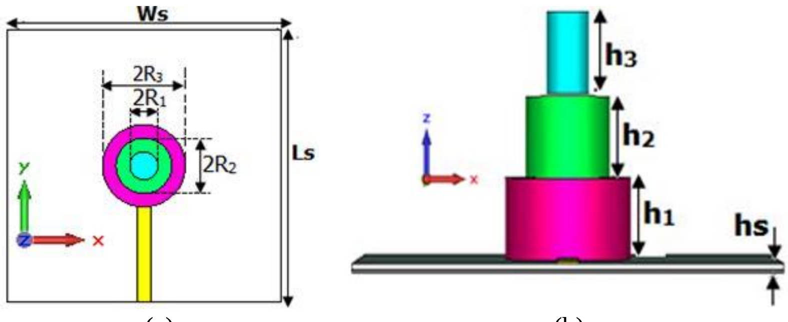


(a) (b)

Figure 4. Two ScCDRA: (a) return loss of optimal design and (b) directivity of optimal two ScCDRA (in linear scale)

3. THREE STACKED CYLINDRICAL CDRA' DESIGN

Increasing the gain, reducing the side lob' magnitudes, and lowering the return loss values as possible, are main objectives of the second design of SDRA (three ScCDRA). The third stacked CDRA has lower value of dielectric constant material, $Eps_3=9$, the same height, $h_3=1.5$ mm, and lower radius $R_3=0.5$ mm. Figures 5(a) and (b) show the three ScCDRA design.

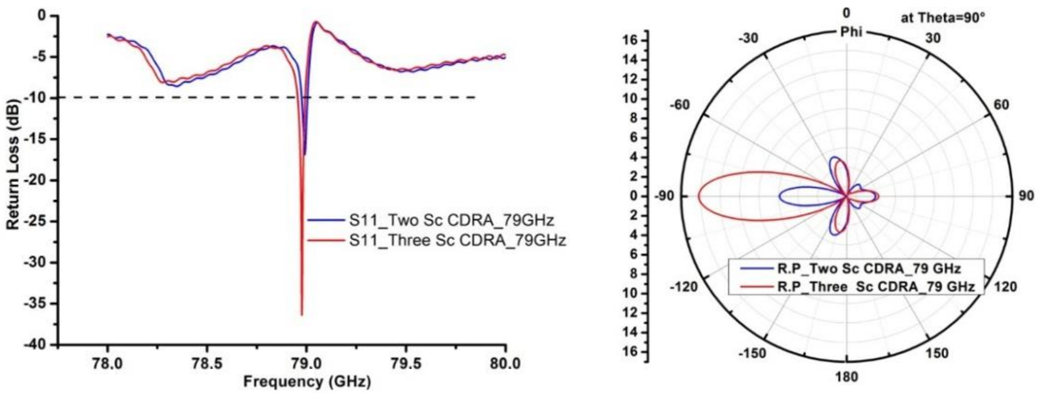


(a) (b)

Figure 5. Three ScCDRA proposed geometry: (a) top view and (b) side view

3.1. Three ScCDRA performances

Return loss parameter variations, versus frequency, of the two and the three ScCDRA structures are shown in Figure 6(a), while Figure 6(b) depicts their radiation patterns diagrams. This latter single antenna structure provides an improved level of impedance matching at the same resonant frequency, as its reflection coefficient values are reduced by 20 dB around 79 GHz. The S_{11} dip reaches below -35 dB, compared to -15 dB in the first design, meaning that more power is transmitted to the antenna, leading to higher radiated energy.



(a) (b)

Figure 6. Comparison between two and three ScCDRA: (a) return loss and (b) gain, in linear scale, at 79 GHz

However, even with this return loss parameter achievement, it is still early to recommend the designed antenna for radar applications before checking its radiation pattern, the second crucial parameter. A radar-antenna has to have directional radiation pattern diagram with a main lob direction and lower magnitudes of side lobs as possible. Figure 6(b) illustrates the two radiation pattern diagrams, representing the gain in linear scale, plotted in XY-plane at 79 GHz. As concluded, the second design, with three stacked cylindrical DRs, presents a highly directional far-field pattern where angular beamwidth is equal to 36.8 degree, its main lob amplitude has been hugely augmented compared to that of side lobs which kept previous levels values. This means more power will be emitted through the main radiation direction, and hence, more antenna efficiency will be reached. To confirm the feasibility of our study, gain and directivity curves of the two designs have been plotted in term of frequency as illustrated in Figure 7: significant enhancement in gain and directivity, of the second design, is observed around 79 GHz, their peak values are, respectively, 11.1 dB and 11.8 dBi.

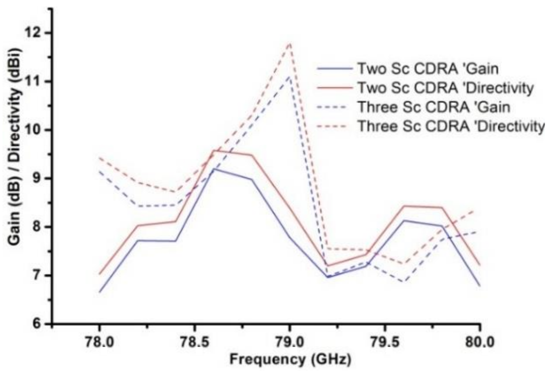


Figure 7. Simulated gain directivity of two and three ScCDRA

Despite the improved performance of the second design, this single antenna still cannot meet the requirements for automotive radars. Specifically, it falls short in terms of gain level, and its half-power beam width (HPBW), or angular width, is too large. To achieve a sharper antenna array pattern with a reduced HPBW and higher rate of radiated RF energy, the antenna needs to be implemented into a suitable array network.

4. THREE STACKED CYLINDRICAL CDRA ANTENNA ARRAY

4.1. Array configuration

To satisfy international standards concerning radar' systems the gain of designed systems has to be enough higher. This can be accomplished by grouping the single antenna elements in a suitable array set. Since the DRA elements are of small size, we have proposed a linear array configuration with 16 elements as shown in Figure 8. This antenna array is designed using FR-4 substrate having the following dimensions $L_{sub} \times W_{sub} \times h_{sub} = 100 \times 10 \times 0.1$ mm^3, and a dielectric constant value of $\varepsilon_{sub}=4.3$. A huge effort has been investigated to optimize the microstrip network feeding thereby ensuring a maximum of power transfer. The optimal spacing between antenna elements has been found to be X_spc=9.16 mm=2.41 λ (where λ=3.8 mm is the associated wavelength in free space of 79 GHz). To show details of feeding microstrips dimensions, parts (1) and (2) of Figure 8 have been reproduced with a zoom in as illustrated in Figure 9.

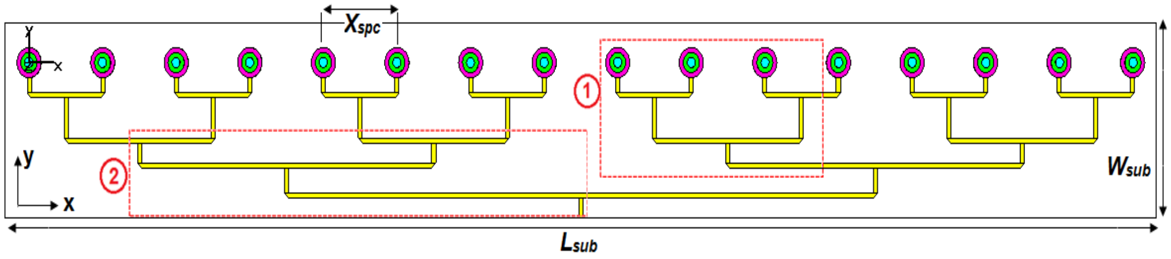


Figure 8. Configuration of 3 ScCDRA array

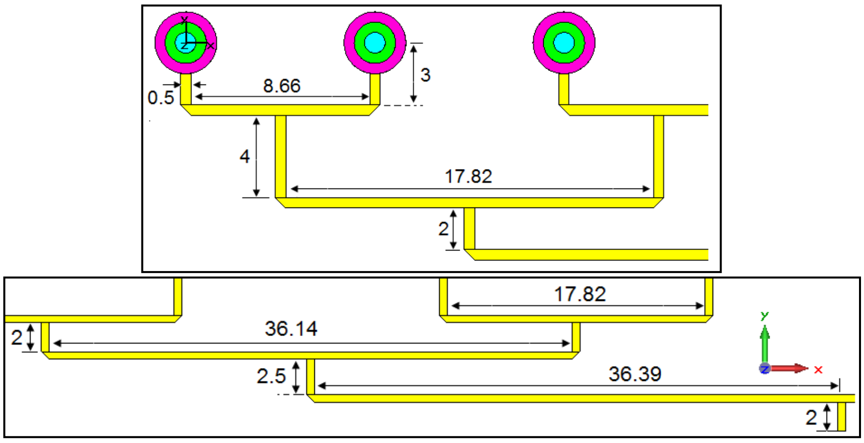


Figure 9. Dimensions of feeding network given in mm. Parts 1 end 2 of Figure 8

4.2. Effect of antenna elements' spacing

In order to achieve better return loss parameter response of this array structure, numerous geometrical factors, of the array, can be explored. In this study, we will present just the effect of the spacing distance between two neighbor antenna elements. Figure 10 illustrates the calculated S_{11} versus three values of antenna elements spacing, X_{spc}=15; 16 and 17 mm. As it is observed, this parameter affects significantly the variations in resonant frequency. The case of $X_{spc}=9.16$ mm$=2.41\times\lambda$ corresponds, exactly, to the desired resonant frequency (79 GHz) where λ is the corresponding wave length in free space.

4.3. Array optimal design

Return loss S_{11} versus frequency for optimal design of the 1×16-elements three ScCDRA array is shown in Figure 11. These results confirm that operating frequency of this antenna array structure is, precisely, around 79 GHz with a lowest value, near to -40 dB, and a slightly wider bandwidth of 152 MHz at -10 dB return loss. Although return loss remains a key factor, we must also evaluate the radiation characteristics of the optimal design in the following sections, as it is intended to function as an automotive radar.

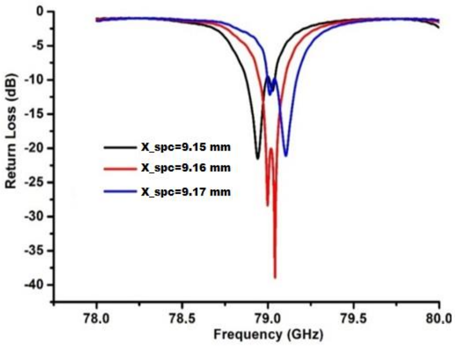


Figure 10. Return loss of the antenna array with different values of antenna elements' spacing

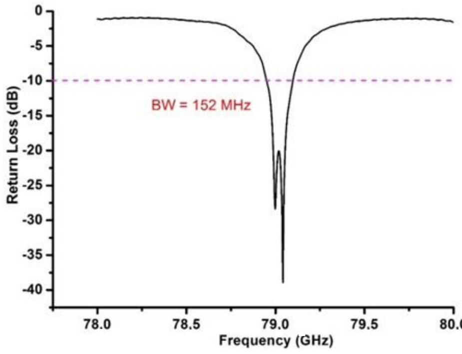


Figure 11. Return loss of the optimal antenna array

4.4. Three ScCDRA array' radiation pattern

To highlight the directional characteristics of the three ScCDRA array structure, its radiation pattern is plotted in linear scale at xy-plane, as depicted in Figure 12. As expected, a very sharp beam profile, of the sixteen linear antenna elements, is formed toward y-axis direction with a peak gain value about 21.3 dBi at 79 GHz and an unprecedented angular beamwidth (at -3 dB) of 0.7°. These features will provide a high radar resolution capability and will improve, significantly, interferences avoiding with other vehicles' radars.

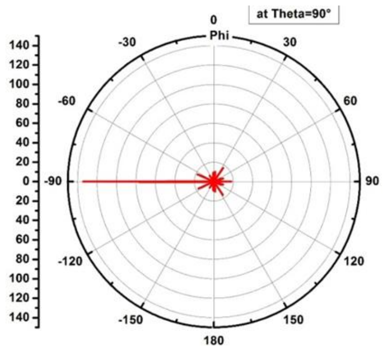


Figure 12. Radiation characteristics, in linear scale, of the optimal three ScCDRA 1×16-array at 79 GHz

4.5. Gain, directivity and radiation efficiency versus frequency

Stability of radiation parameters values over the considered bandwidth is of interest when involving an electromagnetic (EM) radiating structure into a system. This is why Figure 13 shows the simulated gain, directivity and efficiency, versus frequency, of the proposed array structure where gain, directivity and efficiency values are, respectively, 17.7 dB, 21.3 dBi, and 83.1% at 79 GHz. From the plotted graphs, it can be concluded that the new designed antenna array shows very high radiation levels (gain, directivity, and efficiency) around the operating frequency and over the entire frequency range of the bandwidth.

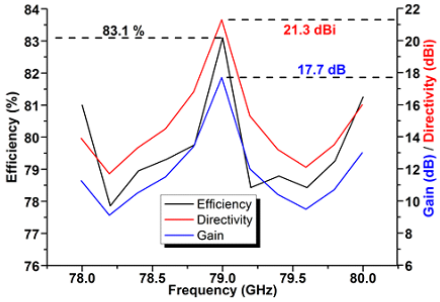


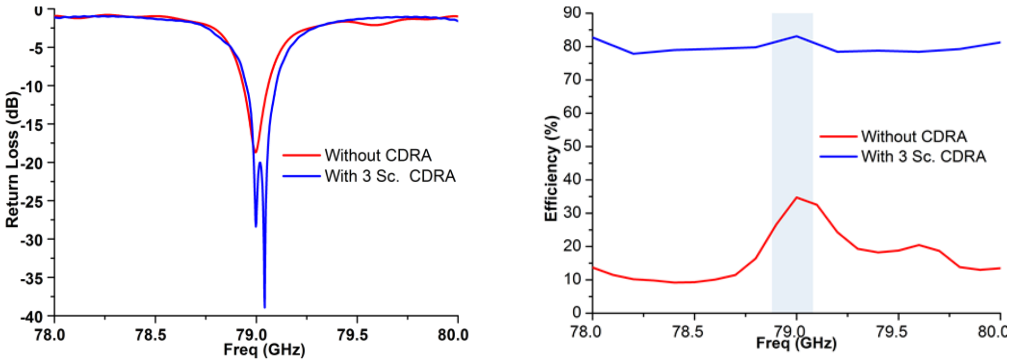
Figure 13. Simulated gain and directivity of the proposed three ScCDRA array

4.6. Which part of the array structure is radiating?

In this section we will examine the contribution of the array feeding network on the radiation shown in Figure 12. For this purpose, we eliminated all ScCDRA antennas, in simulation process, and we kept just the feeding network excited through the same waveguide port. Figure 14(a) shows the response of the structure, in term of S_{11} parameter, with and without considering the three ScCDRA elements.

The results of Figure 14(a) confirm clearly that microstrips feeding lines can accept power from the RF source even if they are not loaded with the ScCDRA elements. However, this power is transmitted with a very less rate because the return loss, in this case, is about -18 dB, at 79 GHz, whereas it is near to -40 dB when the feeding network is loaded with ScCDRAs. Furthermore, accepted power by an aerial structure doesn't mean, necessarily, that it will be radiated with enough efficiency unless if some conditions are satisfied.

So, to confirm if these microstrip lines can radiate efficiently we have plotted the structure efficiency parameter, with and without ScCDRAs, in Figure 14(b). As mentioned by these last results, the efficiency of the design, without ScCDRAs elements, is about 35% while it is about 85% with the three ScCDRA elements. So, we can say that the sixteen loaded three ScCDRAs, in designed microstrip feeding array, are the origin of the most elctromagnetic (EM) radiated power observed through radiation pattern of Figure 12.



(a) (b)

Figure 14. Antenna characteristics of the 1×16 ScCDRA array: (a) return loss and (b) radiation efficiency

5. CONCLUSION

In this work a compact Shree ScCDRA array, of 100×10 mm^2 dimensions, which operates at 79 GHz, has been designed for short range radar (SRR) vehicle applications. The structure of 16 linear ScCDRA array elements presents attractive electrical and radiation features. Return loss parameter is very low at 79 GHz and goes to -40 dB. Antenna array gain and directivity are very high (21.3 dBi and 17.7 dB respectively) and satisfy, largely, the most international standards concerning automotive radars industry. We have investigated the involved number of stacked cylindrical DR in the first part of this work, and we have concluded that the three stacked dielectric cylinders design leads to higher gain, directivity and lower reflection coefficient than the two stacked cylinders configuration; furthermore, they are, also, resonating around the same frequency. This ScCDRA array has an unprecedented simulated HPBW of 0.7° making it perfect for steerable-beam antenna within a phased array system. Efficiency values of the three ScCDRA single antenna, at 79 GHz, are higher (about 94%) than those corresponding to the array structure based on the same single antenna element (83.1%); this is due to the use of the microstrip network feeding, in the array case, which leads to more power dissipation inside the feeding microstrip lines. However, the actual efficiency values, of the array antenna, remain higher compared to those of the conventional equivalent antennas - microstrip patch arrays - dedicated for the same usage, while the compactness of this CDRA array remains unreachable.

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