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1×16 Rectangular dielectric resonator antenna array for 24 Ghz automotive radar system

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ABSTRACT

This paper presents the design of a 1×16-elements RDRA array for anti-collision radar SRR application at 24 GHz. A single RDRA with high dielectric constant of 41, fed by a simple microstrip line feeding technique, is initially designed to operate around 24 GHz. The RDRA element is further used within an array network structure made up of 16 linear antenna elements to cover the same frequency band. The simulated 1×16 RDRA array can reach a high gain, up to18.6 dB, very high radiation efficiency (97%), and ensure enough directional radiation pattern properties for radar applications with a 3-dB angular beam width of 6°. To validate our design, RDRA array' radiation pattern computed results are compared to an equivalent fabricated patch antenna array reported in the literature.

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1. INTRODUCTION

At nowadays automobile accident avoidance issue attracts extensive academia and industrial research efforts because of the increasing annual number of victims due to vehicles' crash. From 70's years the most of investigations on road safety solutions were focusing on improving powerful and integrated radar systems [1]-[3] for detection of obstacles and moving vehicles for, mainly, efficient anti-collision applications and other applications like driving assistance, and parking aide. The accumulated know-how in radar' relevant domains like RF and microwave field, MMICs, conformal antennas and high speed embedded computing systems, made achievable the use and commercialization of first automotive radars since the 90's [4].

Miniaturized planar antennas, hair and eye of any radar system, for small automotive radars have known a huge progress since 50's. Microstrip antenna arrays are used by the most automobile manufacturers for radars [5]-[7] because of light weight and low cost fabrication for massive production however their main weakness is the loss of energy due to the Joule effect and their narrow bandwidth, this limits the use of patch antennas especially at mm-waves and beyond. However a hard competitor of microstrip antennas and excellent candidate for radar systems [8] has been discovered after the famous experiment of long at 1983 [9], this is dielectric resonator antennas (DRA) where the metallic radiator is replaced by a dielectric material. Traditionally, dielectric resonators were used successfully for mm-wave resonators and microwave filters but no one thought of using them to radiate electromagnetic waves.

DRAs have seen a remarkable evolution in several domains, especially telecommunications [10]-[12]. Over the advantages of small size [13], lightweight, low profile, and low cost [14]. It is a low loss antenna due to the low dissipation factor of the dielectric materials. DRAs can be fabricated in different shapes such as rectangular, cylindrical, hemispherical, and have more design flexibility. It offers high gain, and high efficiency due to the absence of conductors and surface wave loss [15]. It can be excited by various feeds such as microstrip feed-line, probe, slot, dielectric image guides, coplanar lines and waveguide slot [13].

In this extended study, based on the work done in 2016 [16], we will present the design of a dielectric resonator antenna array operating around 24 GHz for SSR automotive applications. First, the dielectric waveguide model (DWM) method [17] has been used to predict the RDRA' dimensions for a resonant frequency around 24 GHz; return loss parameter, antenna gain and efficiency have been carried out to evaluate the feasibility of this model structure for radar applications. Then a 2×2 and a 1×16-element arrays, using our designed RDRA with appropriate microstrip feeding network, have been simulated to study the radiation pattern improvement in terms of DRA elements' number and their spacing distance parameter.

2. THEORY

2.1. Initial dimensions of RDRA

We are accustomed to design an RDRA at 24 GHz using the DWM method. To determine the first values of the DRA dimensions, the equations established for DWM can be used if we consider a rectangular dielectric resonator in free space [16]. When applying the perfetc magnetic conductor (PMC) condition $\vec{E}.\vec{n} = 0$ at the faces of the resonator, $|x| = \frac{a}{2}$ and $|y| = \frac{b}{2}$, the components of the wave-number, k_x, k_y and k_z, verifiy the following equations for the dominant mode TE_{111}^{Z}:

$$k_x^2 + k_y^2 + k_z^2 = \varepsilon_r \quad (1)$$

$$k_z tan\left(\frac{k_z h}{2}\right) = \sqrt{(\varepsilon_r - 1)k_0^2 - k_z^2} \quad (2)$$

Where $\vec{E}$ and $\vec{n}$ are, respectively, the electric-field vector and the normal to the boundary faces of the resonator, $k_x \left(= \frac{\pi}{a}\right), k_y \left(= \frac{\pi}{b}\right)$ and k_z are the components of the wave-number following, respectively, the x, y, and z directions inside the rectangular DRA antenna which has *a, b,* and *h* as dimensions.

2.2. Resonant frequency of RDR

In DRA field, the resonant frequency is mainly a function of shape, dimensions and medium permittivity. In 1998, Antar *et al.* [17] was the first talking about effective dimensions of an RDRA when they proposed the the concept of modified wave guide model (MWGM). This approach can provide enhanced results when the value of dielectric constant of material is near to ε_r=37.84 [17], [18]. MWGM associtaes to each dimension, *p*, of the RDRA an effective one, p_{eff}, expressed as:

$$p_{eff} = p(1 - \varepsilon_r^{-1}) \quad (3)$$

Wher *p* in (3) can be replaced by *a*, *b*, or *h*

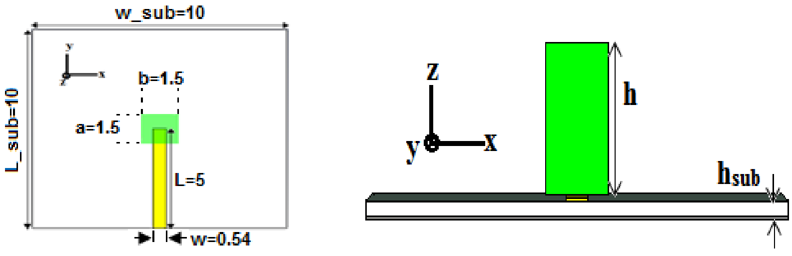
An aplicable expression has also reported by Neshati and Wu [19] using conventional dielectric waveguide model (CWGM) to predict the resonnat frequency of an RDRA having a×b×h as dimensions. According to their work, this resonant frequency can be obtained as:

$$f_r = \frac{c}{2a\sqrt{\varepsilon_r}}\sqrt{1 + q^{-2} + p^{-2}\delta_{CDWM}^2} \quad (4)$$

Where, $\delta_{CDWM} = (0.35 + 0.38p - 0.078p^2) + (0.41 - 0.11p)exp\left(-\frac{q-0.09-0.01p}{0.31+0.26p-0.06p^2}\right)$, *c* is the velocity of light in free space, and *p* and *q*, in (4), are expressed as follow $p = \frac{b}{a}, q = \frac{2h}{a}$.

3. ANTENNA CONFIGURATION

As reported in [16] Figures 1(a) and (b) shows the optimized geometrical parameters a, b and h of the proposed RDRA [16] where dielectric constant value of material is chosen to be ε_r=41 and a×b×h are equal to 1.5×1.5×3.02 mm^3. Electromagnetic energy is guided to the antenna through a microstrip feed-line with length and width values equal, respectively, to 5 mm (L_f) and 0.54 mm (W_f). The fully grounded substrate material is FR-4 having permittivity and a thickness equal, respectively, to 4.3 (ε_{sub}) and 0.3 mm (h_{sub}). FR-4 it's a low-cost fiberglass reinforced material ; it has been used with success as single layer substrate of microstrip antennas for low-cost 24 GHz radars systems [20]-[22] and also as middle layer along with a stacking layers substrates technology, for others 24 GHz antenna arrays systems, to implement a firm PCB [23]-[25].



(a) (b)

Figure 1. Geometry of the proposed single RDRA, (a) top view and (b) side view [19]

4. SIMULATED RESULTS AND DISCUSSION

4.1. Single RDRA

4.1.1. Return loss and 3D radiation pattern

In this section we present a summary of the simulation works done on the single proposed RDRA [16]. After calculating the required antenna dimensions (a, b and h) we have simulated the complete single antenna design where antenna is placed over the FR-4 substrate because the input impedance of the loaded DRA can vary upon physical and geometrical parameters of the substrate. In this stage we have checked the effect of substrate thickness and dielectric constant of the DRA material. Reported simulated results of the return loss parameter versus different values of substrate' thickness and DRA permittivity confirmed that DRA permittivity has a significant impact on the antenna resonant frequency than substrate thickness which approximatively doesn't affect the impedance bandwidth neither its central frequency. However, lower reflection coefficient values is obtained for the middle thickness value, h_{sub}=0.3 mm, where the S_{11} peak is of -26.36 dB around 24 GHz. Furthermore, simulation results of Figure 2 illustrate a quasi-linear relationship between RDRA resonant frequency and its dielectric constant value, which can be exploited and investigated for next eventual designs.

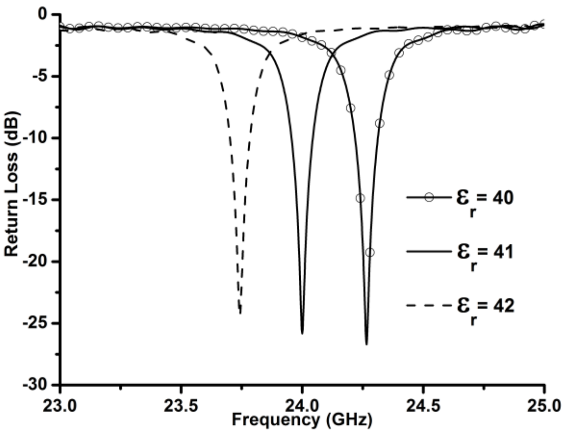
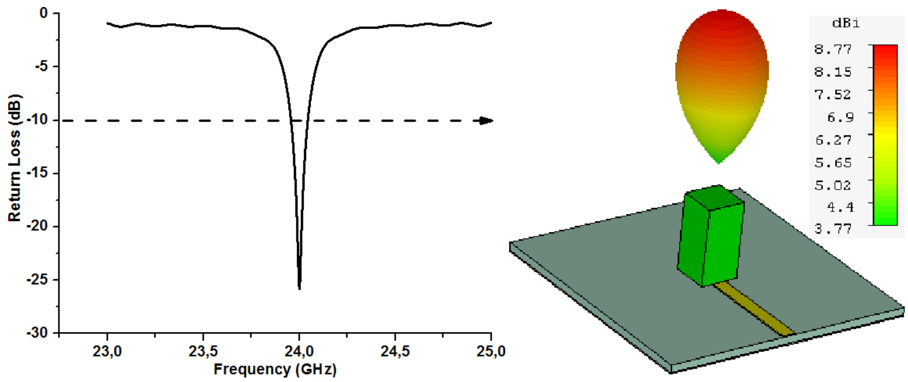


Figure 2. Single RDRA return loss vs. different values of ε_r with h_{sub}=0.3 mm [16]

Figure 3(a) shows the simulated return loss parameter corresponding to the optimal design of the single RDRA, where the S_{11} peak is of -26.36 dB around the desired resonant frequency. RDRA gain radiation pattern at 24 GHz is illustrated in Figure 3(b). The antenna presents a unidirectional beam property of important gain value up to 8.77 dBi. These encouraging results pushed us to look for an appropriate array structure accommodating a small number of RDRA antennas and able to generate a sharp antenna pattern beamwidth and high gain value as we are going to discuss in the next section.

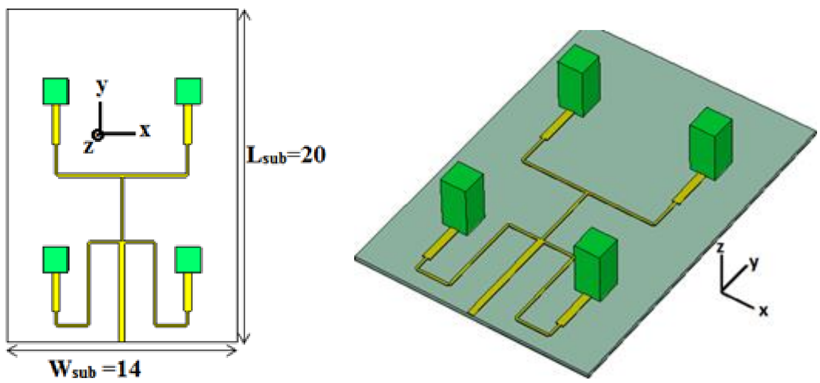


(a) (b)

Figure 3. Computed results of the optimized single RDRA with hsub=0.3 mm and ε_r=41, (a) return loss, and (b) radiation pattern (gain in dB) at 24 GHz [16]

5. RDRA ARRAY STUDY

In the most radar applications antennas are used within a specific array structure using a feeding network to get higher directional properties radiation pattern of the antenna (gain and directivity) thereby ensuring a long range and narrow angular resolution; these are required radar characteristics. In the following sections we present two array structures based on the proposed single RDRA: the first is 2×2-element RDRA array and the second is 1×16-element antenna array as shown in Figures 4(a)-(b) and 5. Furthermore, the 1×16-elements RDRA radiation pattern results will be later compared to its counterpart fabricated patch antenna array made up of 48 elements [26] to demonstrate our proposed RDRA array features.



(a) (b)

Figure 4. Geometry of proposed 2×2-element RDRA array, (a) 3D view and (b) top view

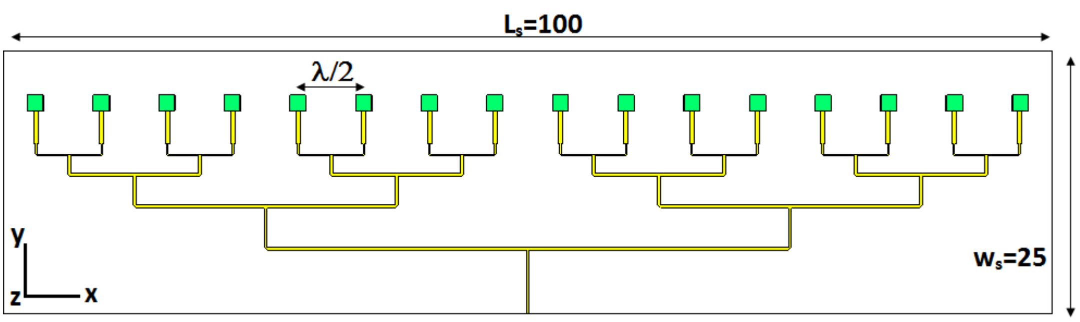


Figure 5. Geometry of proposed 1×16-element RDRA array top view

5.1. DRA arrays simulated results
5.1.1. Return loss parametric study

Different physical and geometrical parameters can be studied to obtain the optimal antenna array design operating around 24 GHz for automotive radar system. In this section we present only the effect of antenna' spacing parameter (**X**) chosen to be equal, respectively, to λ/3, λ/2 and λ where λ is the free space wave length corresponding to 24 GHz as shown by calculated results of Figure 6, this parameter plays a decisive role in enhancing the RDRA array performances. We can confirm that most of electromagnetic power is returned to the source when X=λ/3. However, when X=6.25 mm (=λ/2) the array structure functions pefectly arround 24 GHz where the return loss reaches a value of -20 dB as shown by Figure 6. When antenna' elements are spaced by a distance of λ the proposed DRA array can operate but around 23.25 GHz which is relatively far from desired frequency 24 GHz.

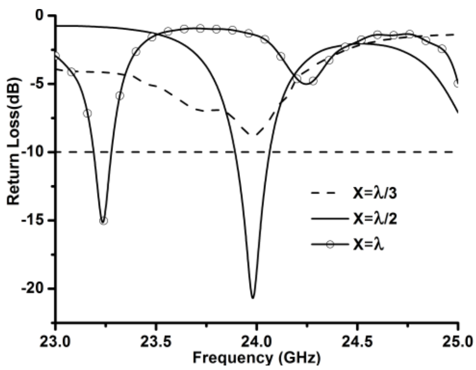


Figure 6. Return loss for various antenna elements' spacing (X) of RDRA array

5.1.2. Return loss parameter S_{11}

Figure 7 shows the variation of the return loss parameter magnitude of the two antenna arrays versus frequency. We note from this figure that the resonant frequency of the two RDRA array structures is exactly, as predicted, at 24 GHz with a peak of about -27 dB where the 1×16-element antenna array bandwidth is slightly larger (172 MHz).

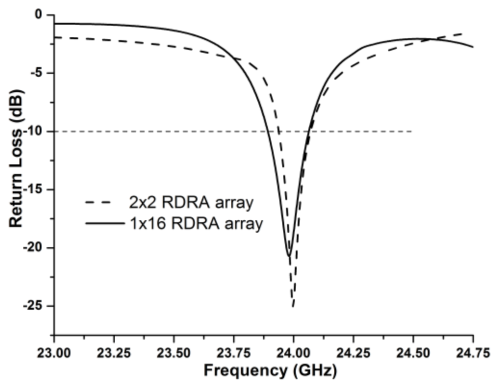
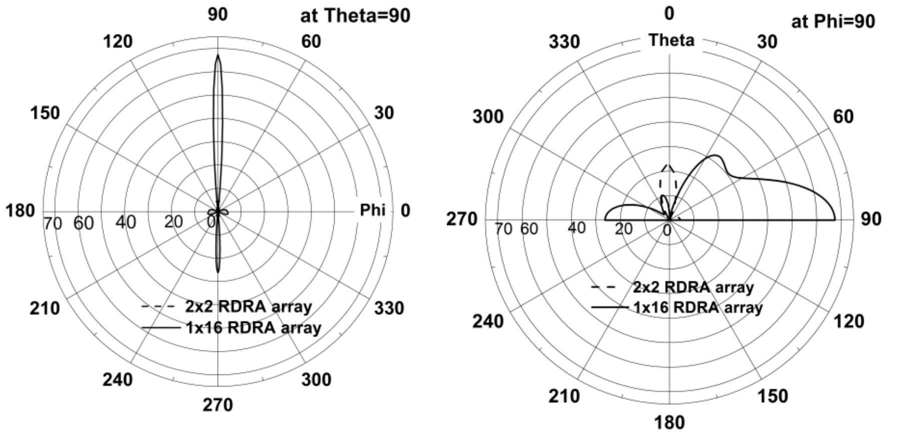


Figure 7. Return loss of 2×2 and 1×16-element RDRA arrays

5.1.3. RDRA arrays' radiation patterns

Radiation patterns of the two RDRA array structures are plotted in Figures 8(a) to (b), at the xy and yz-planes, in linear scale to illustrate their directional properties. The proposed 2×2-element antenna array has a good unidirectional z-axis beam with a maximum gain about 13.5 dBi and an angular beam width of 32° whereas 1×16-element antenna array presents a sharp y-axis direction beam with maximum gain of 18.3 dBi (18.6 dB), an efficiency of 97%, and a -3 dB angular beamwidth of 6°, at H-plane, which leads for a very low radar angular resolution. Theoretically 1×16-element RDRA array main lob direction should be toward z-axis direction but it has been influenced by the microstrip feeding network. Figure 9 shows a comparison in term of gain between simulated results of our proposed 1×16-element RDRA array and simulated/measured results of planar antenna 2×24-element array operating in the same frequency band around 24 GHz as reported in [26]; the second microstrip antenna 48-element array structure (three times elements number than our array) has a maximal gain of 21.75 dBi [26], an efficiency of 60% and a -3 dB angular beam width of 3.6° at H-plane. These results prove the potential talent of the proposed RDRA array which requires less number of elements to reach high performances compared to its counterpart microstrip antenna based arrays.



(a) (b)

Figure 8. Radiation pattern in linear scale of both 2×2 and 1×16-element RDRA arrays at 24 GHz: (a) xy plane (Theta=90) and (b) yz plane (Phi=90)

5.1.4. RDRA arrays gain characteristics

Figure 10 plots the gain simulation versus frequency of the two proposed RDRA array structures, for both cases the gain curve presents a peak value at 24 GHz, the maximal gain value corresponding to 16-elements linear array is 18.6 dBi whereas it is 13.5 dBi for the 2×2 antenna array configuration, theoretically the gain difference is expected to be 6 dBi if the two antenna array configurations had the same linear architecture.

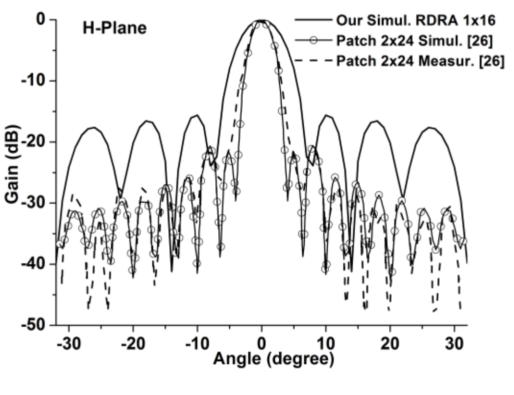


Figure 9. Gain comparison of our proposed RDRA 1×16-elements array and the 2×24-elements patch antenna array reported in [20]

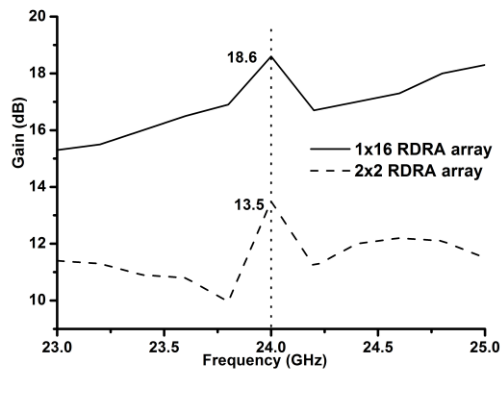


Figure 10. 2×2 and 1×16-element RDRA arrays gain versus frequency

6. CONCLUSION

The single RDRA and its based 2×2 and 1×16-element antenna arrays have been proposed and investigated. These RDRA arrays are excited by microstrip feed-line technique. The simulation results have been presented and discussed. The second proposed RDRA array, designed using just 16 elements, presents high directional radiation pattern at the H-plane with 3-dB angular beamwidth of 6°; has a very high gain value (18.6 dB) and exhibits extremely high efficiency (97 %) over the frequency band around 24 GHz. These performances make the RDRA array structure attractive and practical for anti-collision SRR applications.

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