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60 GHz Polarization Reconfigurable DRA Antenna

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Abstract

This paper outlines a new polarization reconfigurable EBG (Electromagnetic Band Gap) antenna in the 60 GHz millimeter waves band. The proposed hybrid antenna is composed of a multilayer pyramidal DRA (Dielectric Resonator Antenna) exciting source covered with a FSS (frequency Selective Surface) superstrate. The device can switch between circular and linear polarization by a simple 45˚ mechanical rotation of the pyramidal DRA. This structure has the advantage that it maintained stable bandwidth, gain, efficiency and radiation properties when switching between the two configurations of circular and linear polarization.

Keywords

Multilayer DRA, EBG Antenna, Reconfiguration, Polarization, Millimeter Wave

1. Introduction

The fast development of wireless communication systems involves the development of new equipment and devices to meet the requirements of the new multimedia applications. These modern devices are essential for the improvement of communication performance in harsh environments where the interferences due to multipath wave propagation limit significantly the data rates. Reconfigurable antennas, either in frequency, radiation patterns or polarization are potential candidates to fulfill the requirements with a minimum of clutter and complexity. The basic advantage of such antenna over conventional ones where the parameters are fixed, is that the application of electrical, mechanical or optical switching technology extend the capabilities and improve the performance of these wireless devices with a minimum impact on the complexity and cost of these systems [1] [2]. Integration of polarization reconfigurable antennas in wireless communication is becoming increasingly popular and growing. The polarization configurability property must be achieved while maintaining the same frequency behavior (same resonance frequencies) and even radiation patterns since only the vectorial orientation of the ***E*** field is subject to change. Polarization diversity helps to reduce the negative influence caused by multipath fading, avoiding loss problems therefore offering better efficiency in receiving communication signal.

Many studies have been made to obtain polarization configurability, for example, in [3] [4] [5] [6]. However, several challenging problems still exist in the conceptions of these antennas, especially bandwidth, gain, design complexity and symmetry of performance when switching.

Due to their physical and geometric properties, an EBG structure is a very good candidate to realize reconfigurable functions [7] but one of the main problems of EBG antennas with high gain is usually their narrow bandwidth. This work presents a novel hybrid approach to improve the radiation properties of EBG antennas using a combination between dielectric resonator [8] and FSS superstrate [9]. The aim is to design, study numerically and experimentally these new EBG antennas and characterize their potential in terms of bandwidth, gain, efficiency and polarization for an optimum performance around 60 GHz. The major objective is to exploit these properties to design reconfigurable antennas operating at 60 GHz and able to switch between linear and circular polarization, while still exhibiting high gain, high efficiency and wide operating band.

In the first part of this paper, a new hybrid approach to enhance both the gain and the frequency bandwidth of the EBG antenna simultaneously is introduced, which uses the concept of FSS superstrate for enhancing the gain. Furthermore, a wider bandwidth can be achieved by exciting the EBG structure with multilayer cylindrical dielectric resonator antenna (MCDRA) and a parametric study has been carried out to optimize the design properties of the multilayer DRA covered with a FSS superstrate. A prototype has been fabricated using printed circuit technology and results are reported. In the second part, a reconfigurable polarization EBG antenna excited with a multilayer pyramidal DRA is studied in view of achieving a double polarization device. It will be shown that two polarization configurations are achievable by a simple mechanical rotation of the DRA source, being linearly polarized when the angle of rotation $\theta = 0$ and circularly polarized when $\theta = 45^{\circ}$.

2. Design of a Multi Layered DRA Covered with a Superstrate

2.1. Modelization of the FSS Superstrate

The design reference EBG antenna, shown in **Figure 1**, is configured with a superstrate based on a frequency selective surface (FSS) placed in front of a multilayer cylindrical dielectric resonator antenna (MCDRA), which acts as an excitation source. **Table 1** summarizes the parameters of the proposed antenna.

Initially, a design method based on a detailed parametric study is presented. Two main points are described, the characterization of the appropriate excitation source as well as the development of the upper surface with the characteristics necessary to achieve the desired gain over a given bandwidth.

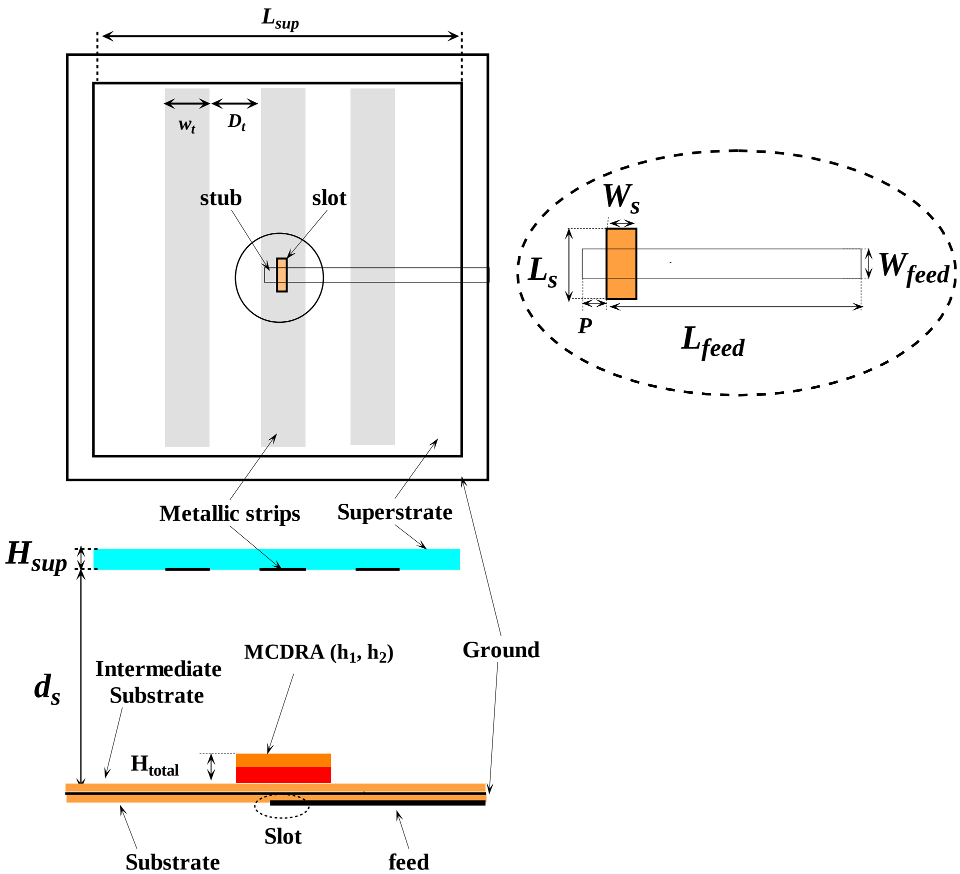


Figure 1. Antenna configuration.

Table 1. Geometrical parameters of the reference antenna.

Superstrate	L_{sup} = 14 mm, W_{sup} = 14 mm, H_{sup} = 0.381 mm, d_s = 2.5 mm
Intermediate substrate	L = 25 mm, W = 25 mm, h_3 = 0.127 mm
Dielectric resonators MCDRA	D = 3.5 mm (diameter), h_1 = 0.254 mm, h_2 = 0.254 mm
Slot	L_s = 1.27 mm, W_s = 0.2 mm
Substrate	L = 25 mm, W = 25 mm, h = 0.127 mm
Fed microstrip line	L_{feed} = 12.5 mm, W_{feed} = 0.4 mm

In order to obtain a compact EBG structure, thin and easy to manufacture while achieving an acceptable gain, a parametric study, using CST Studio Suite 2014, is performed on the geometric properties of the superstrate FSS.

2.1.1. Width Variation of the Metallic Strips

Figure 2 shows the gain variation as a function of frequency for different strip widths 1.1, 1.4, 1.8 and 2.2 mm, whereby the spacing between the metal strips is kept constant at D_t = 2.6 mm. The variation in the width of the strips w_t has a significant effect on the gain achieved; the more one increase the width of the strips, the more the gain of the

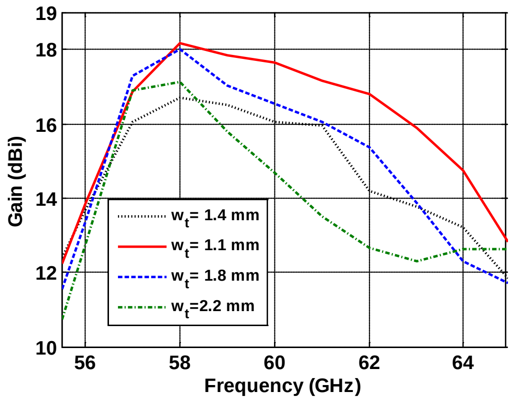


Figure 2. Simulated gain as a function of the width variation w_t.

antenna decreases. At the frequency of 60 GHz, the gain is reduced from 17.75 to 14.75 dBi, when the width changes from 1.1 to 2.2 mm.

2.1.2. Spacing Variation between the Metallic Strips

In order to deduce its influence on the gain realized, the variation of the spacing between the rods must be carefully studied. Figure 3 shows the variation of the gain as a function of the frequency for different spacing between the strips of 1.8 mm, 2.2 mm, 2.6 mm and 3 mm. The width w_t is kept constant to a value equal to 1.1 mm, which the best value of the gain is realized when D_t = 2.6 mm. It can also be realized that the gain takes unstable values on the operating band beyond 2.6 mm.

2.1.3. Variation of the Dielectric Constant ε_r

Figure 4 shows the curves of the gains as a function of dielectric constant variation ε_r. The superstrates have dielectric constants of ε_r = 4.2, 6.15 and 10.2. An improvement of the gain with the increase of the dielectric constant has been observed. Gain is improved by 2 dBi when the dielectric constant ε_r is increased from 4.2 to 10.2. The thickness of all the upper layers is chosen moderately low, namely 0.381 mm. The width w_t and the spacing between the metallic strips D_t are kept constant at w_t = 1.1 mm and D_t = 2.6 mm.

2.2. Source of Excitation

Our choice for the excitation of the EBG antenna is a multilayer cylindrical dielectric resonator (Figure 5) that is recognized for broadband applications. Indeed, it is possible to stack several resonators so that each of them can resonate at a slightly different frequency and, therefore, the system generates a wider bandwidth.

The aim of this experiment is to show the increase in bandwidth when passing from the excitation of the BEG structure by a conventional cylindrical DRA to an excitation by a multilayer cylindrical DRA.

Figure 5(a) shows the homogenous cylindrical DRA geometry with a dielectric constant ε_{r1} = 6.15 and a thickness H_{tot} = 0.508 mm. Figure 5(b) shows two element multilayer cylindrical DRA geometry with a dielectric constant ε_{r1} = 6.15 and ε_{r2} = 2.2 a

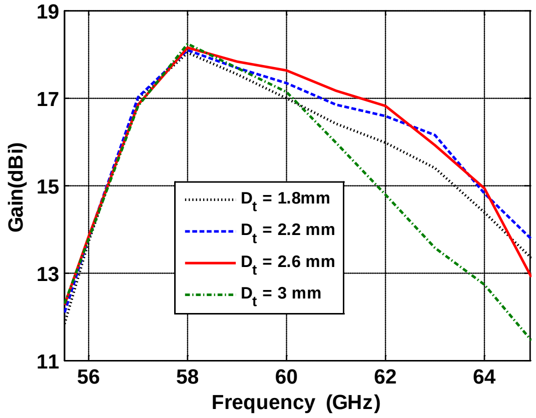


Figure 3. Simulated gain as a function of the spacing variation D_t.

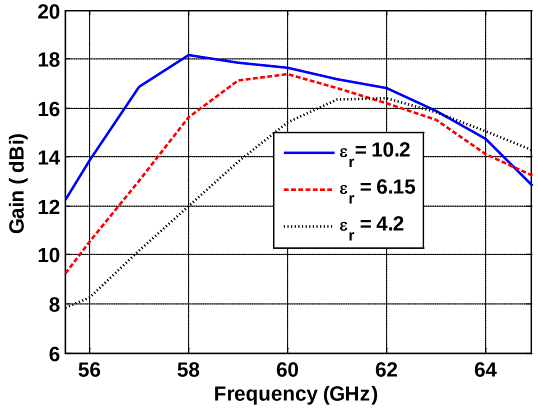


Figure 4. Simulated gain as a function of the dielectric constant variation ε_r.

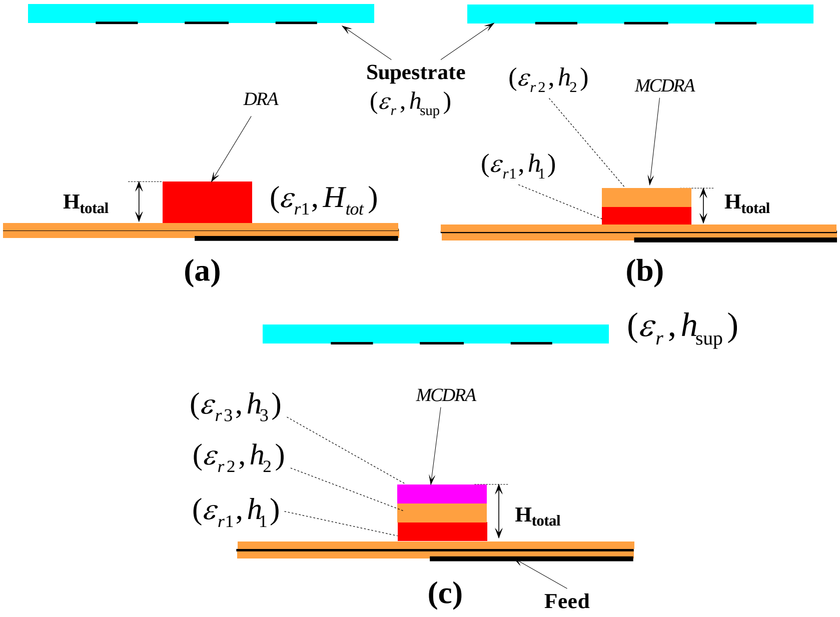


Figure 5. Geometry of: (a) Homogeneous cylindrical DRA; (b) Two element multilayer cylindrical DRA; (c) Three element multilayer cylindrical DRA.

thickness $h_1 = h_2 = 0.254$ mm. Finally **Figure 5(c)** shows three element multilayer cylindrical DRA geometry with a dielectric constant $\varepsilon_{r1} = 6.15$, $\varepsilon_{r2} = 2.2$, $\varepsilon_{r3} = 9.8$ and thickness $h_1 = h_2 = h_3 = 0.254$ mm.

Numerical results in **Figure 6** show that the matching frequency band corresponding to the homogeneous cylindrical DRA is from 58.1 to 63 GHz, when VSWR ≤ 2, which is equivalent to a bandwidth of 8.1%. The matching band corresponding to two element multilayer cylindrical DRA is from 58.1 to 64.2 GHz which is equivalent to a bandwidth of 10.5%. For a three element multilayer cylindrical DRA, the matching band is from 57 to 66 GHz which is equivalent to a bandwidth of 15%.

The width of the adaptation band is therefore improved by 2.4% when changing the homogeneous cylindrical DRA by two elements MCDRA, and also improved by 4.5% when passing from two elements to three. It is clear that the bandwidth of the three elements MCDRA will be higher than that of the homogeneous cylindrical DRA.

2.3. Antenna Performance

After the nature and geometry of the upper interface of the EBG resonator and its source of excitation were chosen for the three elements multi-layer cylindrical DRA, the proposed antenna has been fabricated and measured. The final structure of the proposed EBG antenna is shown in **Figure 7**. For comparison and verification purposes, the simulations were generated by two different electromagnetic simulators (CST Studio Suite 2014 and Ansoft HFSS 13).

The EBG antenna's measured and simulated reflection coefficient (S_{11}) is depicted in **Figure 8**. As it can be seen, two resonances are observed; the first is close to 60 GHz and the second is around 65 GHz. The impedance bandwidth is large enough to cover the entire ISM band (Industrial, Scientific, and Medical band), the measured matching band ranges from 57.5 to 66.5 GHz, which corresponds to an impedance bandwidth of 15% ($S_{11} < -10$ dB). A good agreement is observed between the results of the numerical

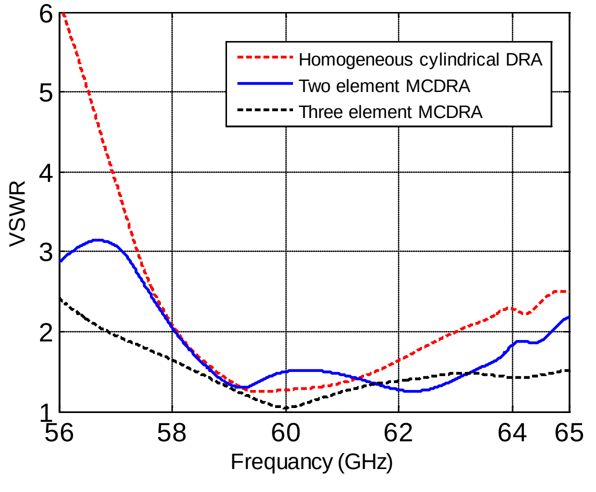
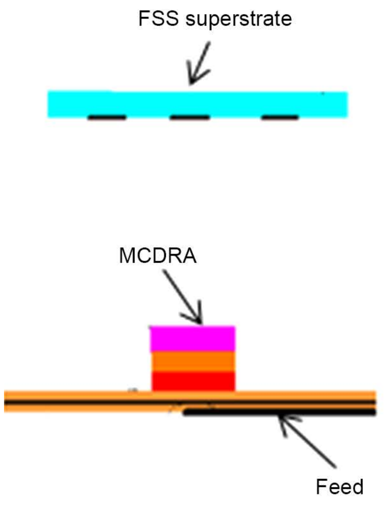


Figure 6. Comparison of simulated voltage standing wave ratios (VSWR) of the conventional cylindrical DRA and a multilayer cylindrical DRA.



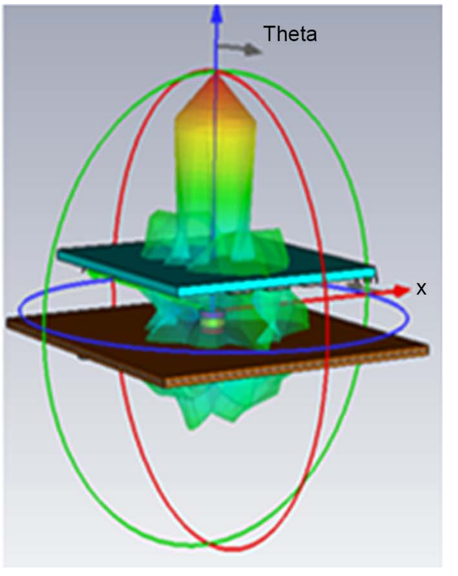


Figure 7. Structure of the final antenna.

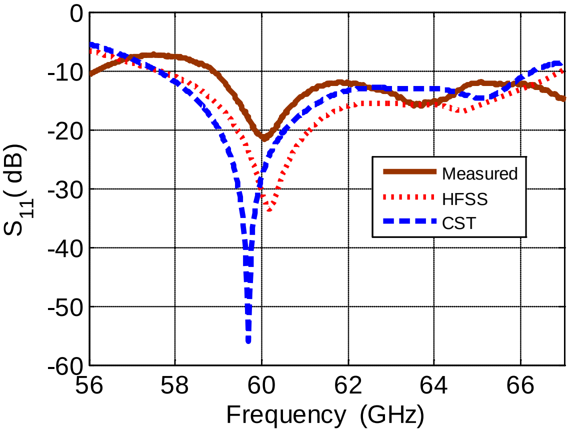


Figure 8. Measured and simulated return loss (CST and HFSS).

simulations and the experimental ones. It is obvious that those results show a bandwidth that meets the design goal.

The antenna gain as a function of frequency is illustrated in Figure 9. The most appealing feature of this antenna resides in its high gain, around 18 dBi, with a difference of 1 dB between the lowest and the highest values. The minimum gain is about 17 dB at 65 GHz while the maximum gain is 18 dB at 59 GHz respectively. It can be observed that the gain is very stable over the frequency range of 58 GHz to 65 GHz. The radiation patterns measured and simulated in the E-plane at 60 GHz is shown in Figure 10. These results show that the diagrams of the proposed antenna have low side lobes and that the main lobe is very directive. It is found that the simulated radiation pattern is considered to be stable and in good agreement with these measured. The results correspond to the objectives set at the beginning to get a highly directional reference antenna.

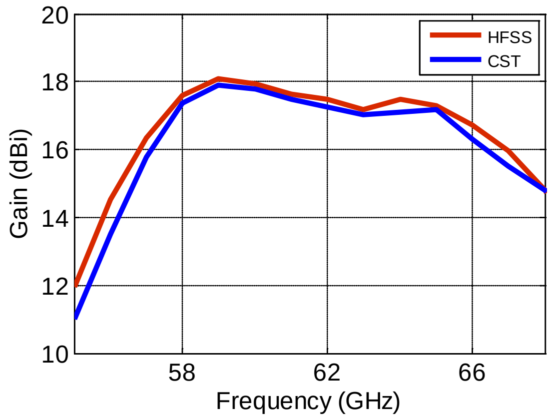


Figure 9. Simulated gain (CST and HFSS).

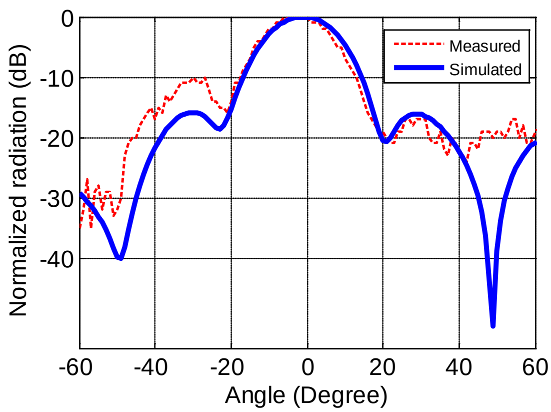


Figure 10. Measured and simulated (CST) radiation pattern at 60 GHz.

3. Reconfigurable Polarization Antenna

3.1. Antenna Design

In addition to the improvement of bandwidth necessary for the development of the EBG structures associated with the antennas, the challenge is to obtain reconfigurable structures. Currently, there is now a strong demand for antennas offering polarization diversity, that is to say switching between linear and circular polarization. In the previous section, a high EBG reference antenna excited with multilayer DRA has been designed to generate a wideband linear polarization. In this section, it will be demonstrated that by changing the multilayer cylindrical source by a pyramidal one and rotating it by $\theta = 45^\circ$ (Figure 11), two modes having equal amplitudes and a 90˚ phase difference can be excited, resulting in a circular polarization. The geometry of the proposed EBG antenna is numerically optimized so that it will be able to generate the circular polarization. The parameters of the structure proposed in this section are summarized in Table 2.

The geometry of the proposed source of excitation DRA is optimized numerically so that the radiated fields are equal in amplitude and 90˚ out of phase. Figure 12 illustrates a parametric study of the AR (axial ratio) with different length to width ratios of

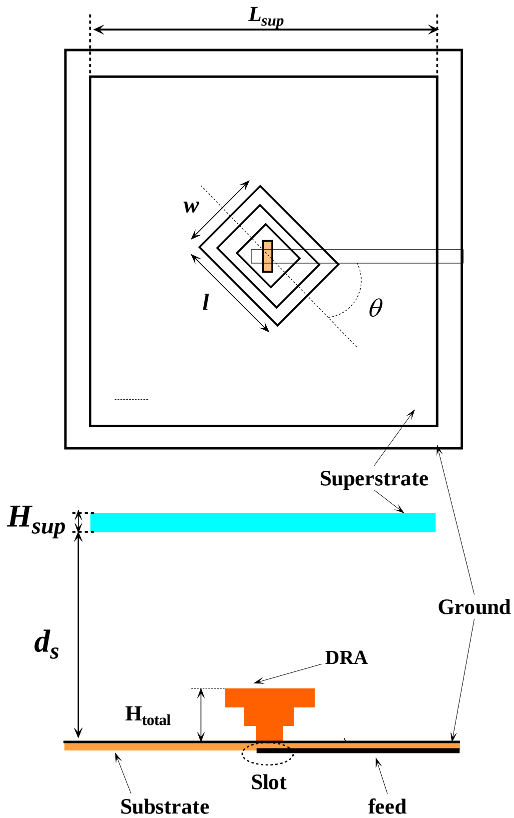


Figure 11. Antenna configuration.

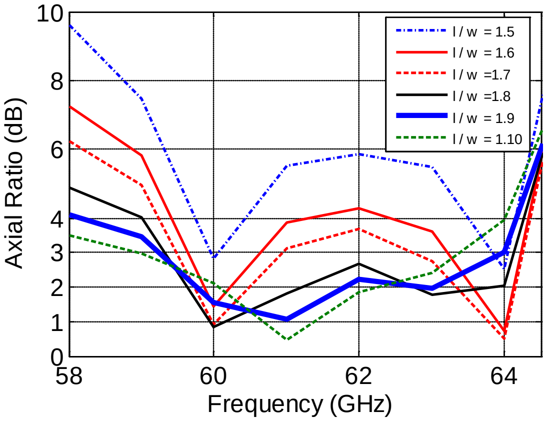


Figure 12. Axial ratio of the EBG antenna with different length to width ratios of the DRA.

Table 2. Geometrical parameters of the reconfigurable antenna.

Superstrate	L_{sup} = 14 mm, W_{sup} = 14 mm, H_{sup} = 0.381 mm, d_s = 2.5 mm
Multilayer pyramidal DRA	l_1 = 1.7 mm, w_1 = 0.89 mm, l_2 = 0.98 mm, w_2 = 0.51 mm, l_3 = 0.88 mm, w_3 = 0.46 mm, H_{tot} = 0.762 mm
Slot	L_s = 0.75 mm, W_s = 0.2 mm
Fed microstrip line	L_{feed} = 12.5 mm, W_{feed} = 0.4 mm

the multilayer pyramidal DRA. The optimum AR ratio is found when the length l to width w ratio is 1.9, corresponding to l_1 = 1.7 mm, w_1 = 0.89 mm, l_2 = 0.98 mm, w_2 = 0.51 mm, l_3 = 0.88 mm, and w_3 = 0.46 mm.

3.2. Results and Discussions

Simulation results such as a reflection coefficient S_{11}, gain, efficiency, radiation patterns, and axial ration for both linear and circular configurations shown here has been performed within CST Studio Suite 2014 and prove to be very attractive. Figure 13 shows the S_{11} simulated reflection coefficient for both linear and circular structures. As expected, the bandwidth in both cases is extended over a wide band thus covering the ISM band. The simulated bandwidth is from 56.5 to 64.5 GHz, which is equivalent to an operating band of 13.3%.

Three resonance frequencies were discerned at 57, 60 and 64 GHz, for both configurations with a few hertz offset. It can be concluded that the effect of switching between the linear/circular polarizations, does not greatly affect the operation of the antenna, such as bandwidth and resonance frequencies.

The maximum gain simulated for both linear and circular configurations is shown in Figure 14. For an antenna operating in linear polarization, a maximum gain of 18.4 dBi is achieved and the radiation efficiency vary between 0.78 and 0.85 over the entire operating band, as shown in Figure 15. When circular polarization is considered, one obtains an identical gain to that of the linear polarization and the efficiency achieved becomes more stable, taking a value between 0.80 and 0.86. It can be observed that the evolution of the gain in function of the frequency is approximately the same for both linear and circular configurations, with a slight advantage for linear polarization.

Switching between the linear and circular configurations has no major influence on the radiation of the proposed antenna. Indeed, the main lobes of the radiation patterns in the E plane for both configurations are almost identical (see Figure 16). The radiation pattern of the circularly polarized antenna shows some asymmetry in the side lobes, this asymmetry is due to the asymmetrical structure caused by the rotation of the pyramidal DRA by $\theta = 45^\circ$ (see Figure 11).

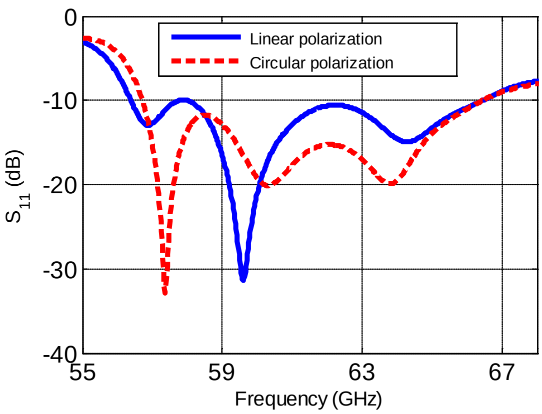


Figure 13. The reflection coefficient S_{11} for both linear and circular configurations.

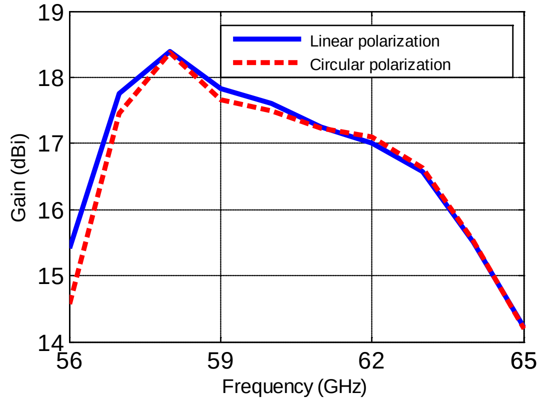


Figure 14. The maximum gain for both linear and circular configurations.

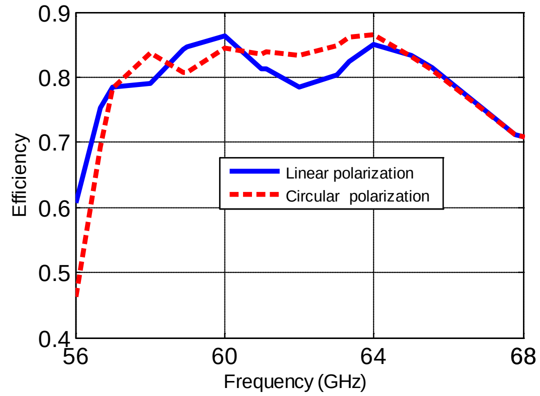


Figure 15. The radiation efficiency for both linear and circular configurations.

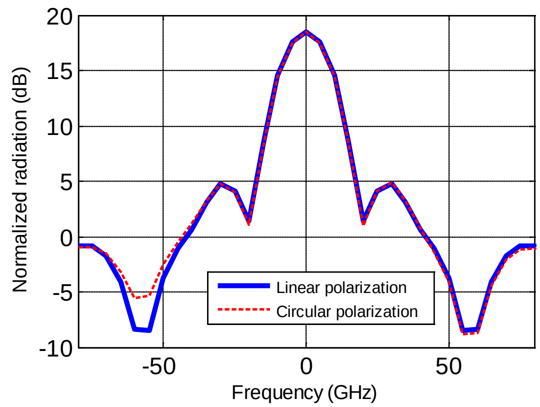


Figure 16. Radiation patterns E plane for both linear and circular configurations.

One can conclude that the proposed antenna switches between two linear circular polarizations, while maintaining stable radiation (Figure 17).

Figure 18 shows the axial ratio 3 dB bandwidth for the circularly polarized configuration. This allows to conclude that the effective bandwidth obtained for $S_{11} < -10$ dB and the axial ratio < 3 dB when the antenna radiates in circular polarization varies from 59.2 to 64 GHz, therefore covering both targeted applications.

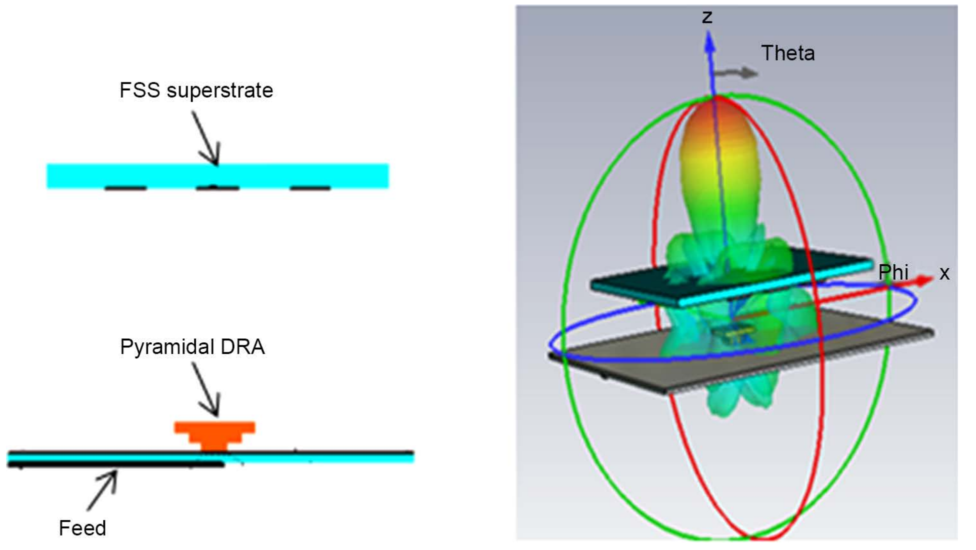


Figure 17. Antenna configuration and 3D radiation pattern visualization.

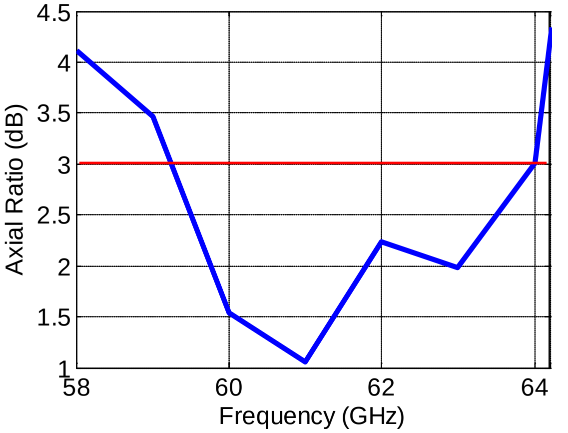


Figure 18. Simulated axial ratio.

4. Conclusions

In this paper, a performant EBG reconfigurable polarization antenna based on multilayer DRA for millimeter-wave has been proposed. By applying a mechanical rotation of 45˚ on the DRA source, the structure is able to switch between linear and circular polarization. In the first part of this paper, the aim was to design a reference antenna characterized by a wide bandwidth and high gain, which can be modified subsequently to have a reconfigurable structure able to switch between linear and circular polarization. For this purpose, a new approach for enhancing gain and bandwidth has been successfully developed. The technique is based on the combination of two techniques in order to benefit from the individual advantage of each of them, namely, FSS superstrate structures and multilayer DRA. The simulation and measured results showed a good agreement, with an obtained bandwidth of 9 GHz corresponding to an enhancement of 6.9% compared with homogeneous cylindrical DRA. Also a gain value of 18 dBi is obtained, an increase of 12 dBi compared to a DRA without FSS superstrate.

The second part of the paper has shown that by optimizing the length to width ratio of the multilayer pyramidal DRA source and applying a rotation to the pyramidal sides by $\theta = 45^{\circ}$ with the central axis of the microstrip line, it is possible to generate two configurations of polarization. The linear polarization is obtained when $\theta = 0^{\circ}$ while circular polarization is achieved when $\theta = 45^{\circ}$. The advantage is that, when switching between a circular and linear polarization, the structure maintains stable radiation characteristics such as bandwidth, resonant frequencies, gain, efficiency and radiation patterns. The proposed antenna can be used for transmission and reception simultaneously with the aim of combating the multipath effect. Further efforts must be pursued to manufacture the antenna and develop the numerical control system in order to make the device more flexible and smart.

Using a 60 GHz reconfigurable antenna polarization offers many new potential applications, especially in the next generation 5G mobile systems. Following this work, futures studies may be proposed like multiplying the number of dielectric resonators used as an excitation network, in the perspective that it would be possible to exploit the proposed antenna in the "Massive-MIMO" technologies dedicated for 5G.

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