Gain and Bandwidth Improvement of a Cylindrical Dielectric Resonator Antenna (CDRA) using Metamaterial Structures

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ABSTRACT:
Using metamaterials on the top of the antenna's accordance to magneto-dielectric superstrate and near zero refraction index theories causes improvement of radiation efficiency and gain of antennas. In this article, two novel metamaterial unit cells are proposed for gain and bandwidth improvement of Cylindrical Dielectric Resonator Antenna (CDRA). The first metamaterial unit cell is a negative magnetic structure including two rings implemented on both sides of RT/doroid 5880 substrate with dielectric constant of 2.2. Besides, the second metamaterial unit cell is a Double Negative Structure (DNG) realized consisting of two rings printed in one side and a thin wire in other side of RT/doroid 5880 substrate. Two 7×7 arrays of proposed unit cells are considered and used as superstrate layers on the top of a CDRA. Also, the CDRA is made of RT/doroid 6010 material with dielectric constant of 10.2 working at the frequency of 10 GHz. Using proposed metamaterial structures as superstrate layers on the top of the CDRA causes gain and bandwidth improvement up to 3.3 dB and 4.8%, respectively. CDRA in the presence of proposed metamaterial superstrates are analyzed using a 3D full-wave simulator.

KEYWORDS: Dielectric Resonator Antenna, Bandwidth, Metamaterial, Superstrate, Gain.

1. INTRODUCTION

Dielectric Resonator Antennas (DRAs) are good candidates to be used in modern wireless communication systems at microwave and millimeter frequency ranges due to their characteristics such as low profile, small size, light weight and low cost [1]. As compared to microstrip antenna, the DRA has many potential benefits including higher inherent impedance bandwidth, avoidance of surface waves, lower loss and higher radiation efficiency while feeding mechanisms of DRAs are as same as the patch antennas. Feeding mechanisms of DRAs can be divided into two different categories. First the antennas which are located directly on a ground plane and excited by coaxial probe or microstrip line are coupled to narrow slot. In this way, the only radiating element will be dielectric, and feeding effects can be ignored. The second one includes the antennas excited by microstrip line directly. In this case, it is not possible to ignore the feeding effects because the feed itself radiates as an antenna.

The Dielectric Resonators (DRs) are usually made of materials with high dielectric constant and low loss characteristic. Therefore, the unloaded Q-factor of DRs are usually between "50 – 500", however it can be higher. Using dielectric resonators as an antenna is proposed in 1983 by Long who studied cylindrical dielectric resonator antennas for the first time [2]. Then, different shapes of dielectric resonator antennas like hemispherical [3], rectangular [4], triangular [5] and etc. were investigated and studied. Researchers found that the fundamental mode of these antennas, independent of antenna's shape, radiates like a magnetic dipole. However, the resonance frequency of a dielectric resonator generally depends on operating mode, dielectric constant and physical shape [6].

In recent years, different works have been done to achieve the improvement of bandwidth [7-9], better radiation efficiency [10], [11], miniaturization [12] and low cost [13], [14] for DRAs in microwave and millimeter wave frequency ranges. According to increasing demand for wireless systems with higher speed and capability, need for effective antennas with

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higher radiation efficiency increases. So, metamaterials have been widely used for this purpose. Metamaterials are artificial periodic structures made of unit cells with dimensions much smaller than wavelength (about $\lambda/4$). The electromagnetic characteristics of these structures can be represented with other parameters like electric permittivity and magnetic permeability. Metamaterials can show just negative electric permittivity (ENG) or negative magnetic permeability (MNG) as a single negative (SNG) material or negative refractive index as a double negative (DNG) material leading to unconventional properties.

As investigated before, magneto-dielectric superstrate and near zero refractive index theories can be used for gain enhancement instead of using high permittivity dielectric materials. The thickness of nonmagnetic superstrate should be almost half-wavelength for gain enhancement while using magneto-dielectric materials as the superstrate leads to lower profile structure by decreasing wavelength [15], [16]. Various types of superstrates such as dielectric slab, Electromagnetic Band Gap (EBG) structure, high reflective surfaces and magneto-dielectric materials [16], [17] are used for improvement of gain and other radiation characteristics in different types of antennas.

In this article, the possibility of gain and bandwidth improvement of the special shape of dielectric resonator antenna by locating two arrays of new metamaterial structures on the top of the antenna are investigated. The antenna works at the frequency of 10 GHz with 6.3% bandwidth. Besides, both unit cells are also designed to work on the same operating frequency as antenna. Full-wave simulator is used to validate response of unit cell and antenna structure. The substrate used for metamaterial unit cells is RT/doroid 5880 with 0.4 mm thickness, dielectric constant of 2.2 and loss tangent of 0.0009. The cylindrical antenna is composed of RT/doroid 6010 with dielectric constant of 10.2, loss tangent of 0.0023, 3mm height and radius of 4 mm. Firstly, resonance frequency and scattering parameters of resonant metamaterial unit cells and proposed antenna are analyzed independently and then constitutive parameters are investigated. Then, antenna in presence of metamaterial superstrates is analyzed and scattering parameters and radiation patterns are compared with the situation in which any superstrate is present above the structure.

2. DESIGN AND SIMULATION

2.1. Design of Metamaterial Unit Cell Structure

The structure of metamaterial unit cells is depicted in Fig. 1. As seen from Fig. 1-a, the cell includes two square and hexagonal rings printed on both side of 3.15×3.15 mm RT/doroid 5880 substrate. In this structure, the length and width of the substrate is 9 mm, the width of rings is equal to 0.5 mm and air gap is chosen equal to 0.7 mm that this air gap acts as parallel plates capacitor. Also, for similarity with the practical aspects, the simulated unit cell is assumed to be made of copper with 0.35 mm thickness for all metal elements. Fig. 1-b, also shows another unit cell composed of two square and hexagonal rings realized on one side and a thin wire in opposite side of 3.25×3.25 mm RT/doroid 5880 substrate. For this structure, width of rings and air gap are chosen equal to 0.18 mm and 0.15 mm, respectively. The copper thickness is also considered 0.35 mm here. Due to the number of metals as well as the parallel plates capacitor created, the number of resonances of this cell is more than the previous. Therefore, this cell should be designed in such a way that the resonances due to the electric permittivity and magnetic permeability are placed on each other. Therefor the length and width of the substrate is chosen 8.5 mm until the resonance frequency continuous to occur at 10 GHz.

For analyzing these cells, they should be located in the middle of a TEM waveguide as shown in Fig. 2. PEC and PMC boundary conditions should be applied correctly on the cell boundaries until the most interaction happens between fields and unit cells. As shown in Fig. 2, PEC boundaries should be in along to the axis of Thin Wire (TW) and PMC boundaries should be in along to the normal axis of the plane consisting of rings. So, the infinite conditions are applied for the cells due to the theory of metamaterials. By applying boundary conditions and excitation ports, in Fig. 2-a, a resonating current is induced in the loops and generates a magnetic dipole moment resonating with capacitance caused by air distances. In other words, this phenomenon effectively, creates an inductance within the substrate, followed by the storage of magnetic energy in the unit cell. This inductive inductance, together with the capacitance within the structure, gives rise to a resonant structure. The resonant frequency of this cell can be adjusted according to the parallel plates capacitor, substrate material and inductive inductance. For example, by increasing the dielectric constant of the substrate and decreasing the thickness, the capacitance decreases and the resonance frequency increases. Also, due to the electric fields along the TW in Fig. 2-b, a current is induced along the wire creating an equivalent electric dipole moment. Resonance frequency of these cells can be adjusted with changing the air distances, material type of substrate, width and length of thin wire and rings to use them in different frequency bands. Constitutive parameters of unit cells are calculated by using the scattering parameters with recursive method introduced in [18].

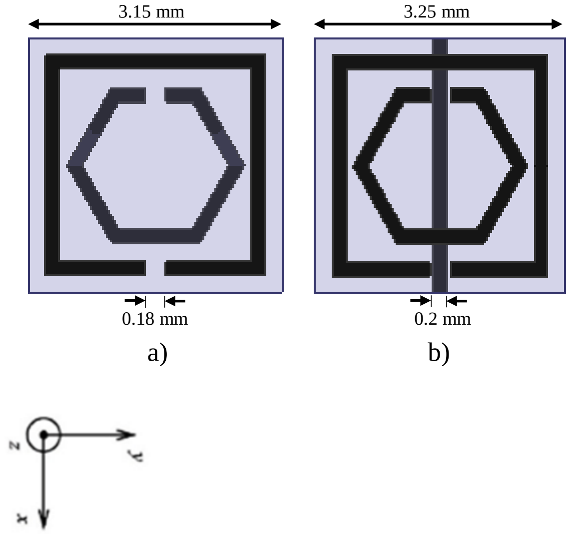


Fig. 1. 2D metamaterial layout of the a) first unit cell, b) second unit cell.

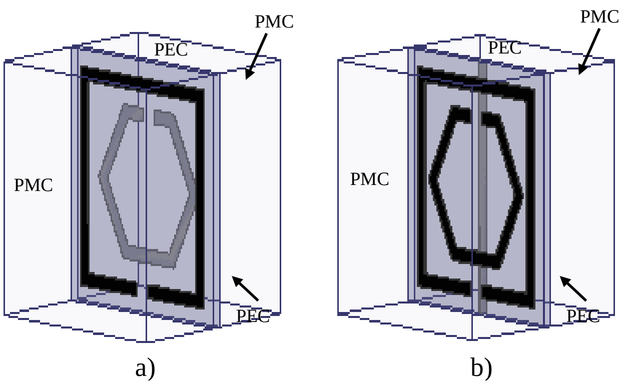


Fig. 2. Metamaterial waveguide model of the: a) first unit cell, b) second unit cell.

2.2. Cylindrical Dielectric Resonator Antenna

Configuration of the proposed cylindrical dielectric resonator antenna is shown in Fig. 3. Dielectric resonator is located on a ground plane and fed by a 50-ohm coaxial cable. A circular ground plane with 22.5 mm radius is used here. Besides, other antenna parameters are radius (a) and height (d) of cylindrical dielectric resonator and height of coaxial cable inside the dielectric resonator that are equal to 4.2 mm, 3 mm and 2.7 mm, respectively. This antenna is designed to work at the frequency of 10 GHz.

Since exact solution and analysis of cylindrical dielectric resonator need very complicated calculations, perfect magnetic wall is considered as an approximation method. This approximation is based on the fact that the reflection coefficient of a wave in a high dielectric constant region incident on an air-filled region approaches +1. The following equation for the reflection coefficient indicates this fact [2]:

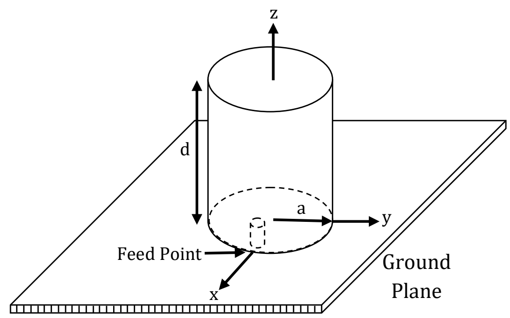


Fig. 3. Schematic of Cylindrical Dielectric Resonator Antenna (CDRA).

$$\Gamma = \frac{\eta_0 - \eta}{\eta_0 + \eta} = \frac{\sqrt{\varepsilon_r} - 1}{\sqrt{\varepsilon_r} + 1} \to 1 , \qquad as\, \varepsilon_r \to \infty \tag{1}$$

Where, η and η_0 are the intrinsic impedances of dielectric and air, respectively. As seen, this reflection coefficient is similar to what is obtained from a perfect magnetic wall or an ideal open circuit.

This antenna is fed so that the dominant mode is just excited. Resonance frequency of this antenna for TM_{110} dominant mode depends on cylindrical resonator equations and also propagation constant and is achieved as equation (2) [2]:

$$f_{110} = \frac{1}{2\pi a\sqrt{\mu\varepsilon}} \sqrt{1.841^2 + \left(\frac{\pi a}{2d}\right)^2} \tag{2}$$

Where, a is the radius and d is the height of dielectric resonator antenna.

Also, radiation patterns will be achieved by using the electric and magnetic fields equations for dominant mode with approximation of perfect magnetic wall which is considered as the exterior wall of dielectric resonator [2].

2.3. Simulation

A 3D full-wave simulator is used here for simulation of metamaterial unit cells and cylindrical dielectric resonator antenna. Simulation results for magnitude of the scattering parameters of unit cells are shown in Fig. 4. As seen, both cells radiate at the operation frequency of 10 GHz.

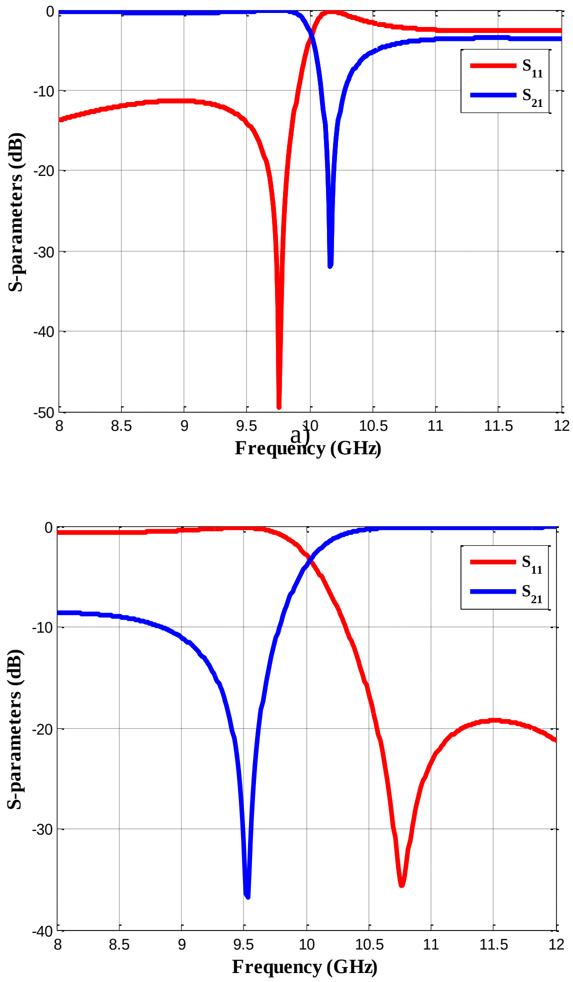


Fig. 4. Scattering parameters of the a) first unit cell, b) second unit cell, work at the operating frequency of 10 GHz.

Also, constitutive parameters including electrical permittivity, magnetic permeability and refractive index are shown in Figs. 5, 6 and 7, respectively. As shown in Fig. 5, magnetic permeability is negative in whole desirable operation frequency band while electrical permittivity is positive. So, the unit cell functions as single negative (SNG) with positive refraction index as shown in Fig. 7. However, as seen in Fig. 6, both electrical permittivity and magnetic permeability are negative in whole operation frequency band. Therefore, the unit cell functions as double negative (DNG) with negative refraction index as shown in Fig. 7.

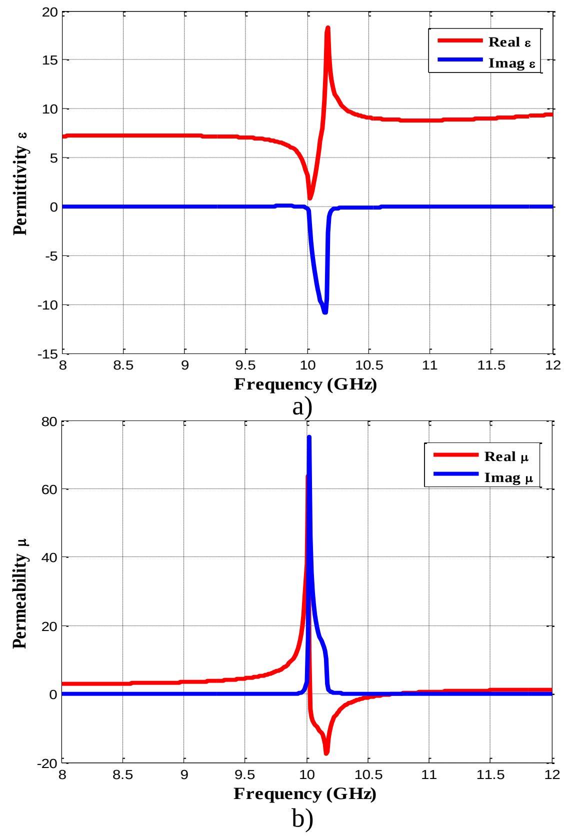
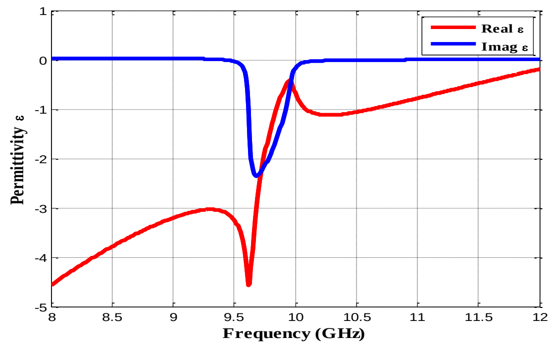
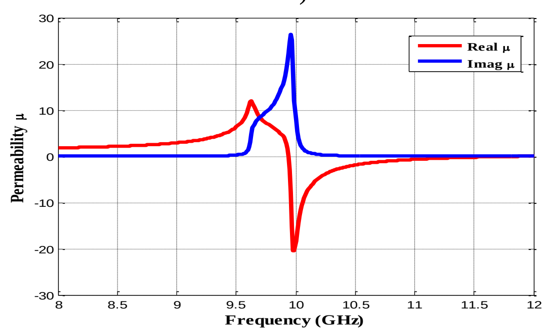


Fig. 5. Metamaterial constitutive constants of the first unit cell include real and imaginary of the a) electric permittivity, b) magnetic permeability.

The CDRA is analyzed using 3D full-wave simulator. Two arrays, functioning as a superstrate layers, have been realized using designed unit cells and located in about half-wavelength height on the top of the ground plane. Distribution of electromagnetic fields in these arrays is so that required appropriate boundary conditions for operating are as a metamaterial. After analyzing CDRA individually, two arrays of the proposed unit cells are considered on the top of the dielectric antenna as a superstrate. Increasing the number of metamaterial cells in the superstrate of the antenna will increase the gain. Of course, the number of cells must be selected in such a way that both the appropriate gain is obtained and the antenna dimensions do not increase significantly. Based on this, it seems appropriate to select an array of 7×7 metamaterial cells. Dimensions of DRA and specifications of coaxial cable are listed in Table 1.

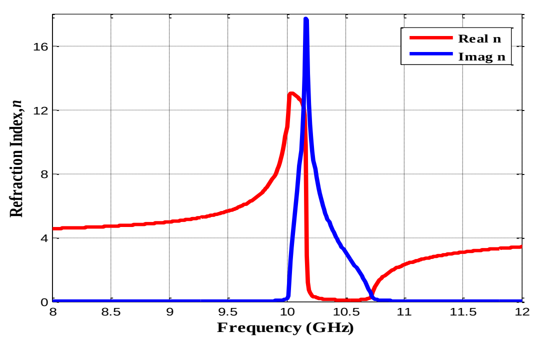


a)

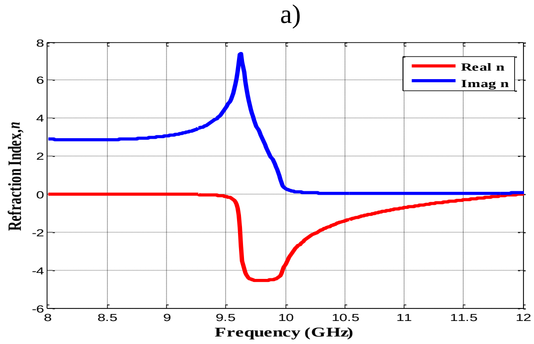


b)

Fig. 6. Metamaterial constitutive constants of the second unit cell include real and imaginary of the a) electric permittivity, b) magnetic permeability.



a)



b)

Fig. 7. Real and imaginary parts of the refractive index of the a) first metamaterial unit cell, b) second metamaterial unit cell.

Table 1. Dimensions of DRA and specifications of coaxial cable.

mm	Parameters
4.2	radius of antenna(a)
3	height of antenna(L)
2.7	length of coaxial cable (Lcore) core
0.125	diameter of coaxial cable (d) core
3.5	location of coaxial cable(df)
22.5	radius of ground (Rground) plane

Firstly, a 7×7 array of the first unit cell is located in distance of about half-wavelength from the ground plane on the top of the antenna as shown in Fig. 8. After analyzing antenna structure, unit cell parameters are optimized to have good frequency matching and better performance. Simulation results of scattering parameters and gain are shown in Figs. 9 and 10, respectively. As seen in Fig. 9, the magnitude of scattering parameters of the antenna have any significant changes either with or without metamaterial superstrate layer. Besides, the operating frequency is matched and operating frequency band is also as the same as previous used superstrate layer. Also as shown in Fig. 10, the antenna gain in the case without superstrate is equal to 3.81 (5.81 dB) and with the addition of metamaterial layer, is equal to 7.95 (9 dB). In other words, using metamaterial superstrate on the top of the CDRA improves the gain of the antenna up to 3.2 dB. Also, in this structure, by changing the distance of the metamaterial array from the antenna, the maximum value of the antenna gain at a distance of 19 mm reached 9.4 (9.73 dB).

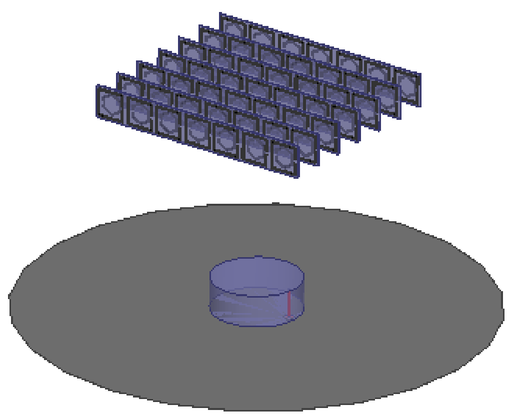


Fig. 8. Schematic of CDRA with 7×7 array of the first metamaterial unit cell working as superstrate.

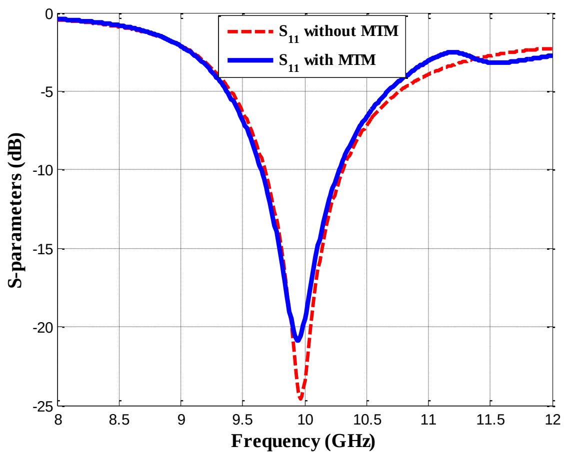


Fig. 9. Comparison of results of scattering parameters in presence of the first metamaterial array with respect to the case of without any metamaterial superstrate.

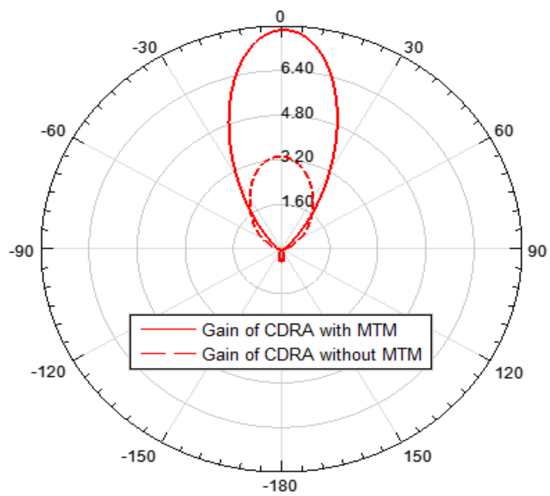


Fig. 10. Comparison of the gain in presence of the first metamaterial array with respect to the case of without any metamaterial superstrate in $\varphi = 0$ plane.

The radiation patterns of this antenna in two cases without and with metamaterial substrate are also shown in Figs. 11 and 12, respectively. Examining these two diagrams, it can be seen that the directivity and half power beam width of the antenna with metamaterial have been reduced compared to the state without metamaterial.

Then, the second 7×7 array of new unit cell is also located in about half-wavelength height on the top of the antenna, as shown in Fig. 13, and after optimization as the same as before, magnitude of the scattering parameters and gain results of this structure are shown in Figs. 14 and 15, respectively. Dimensions of DRA and specifications of coaxial cable are listed in Table 1. As shown in Fig. 14, operating frequency is almost the same as previous cell but by using this unit cell as a superstrate, bandwidth is improved up to 4.8% due to the wave reflections and resonance between superstrate layer and the ground plane. Besides, as shown in Fig. 15, gain of CDRA also increases up to 3.3 dB with respect to CDRA without any metamaterial superstrate.

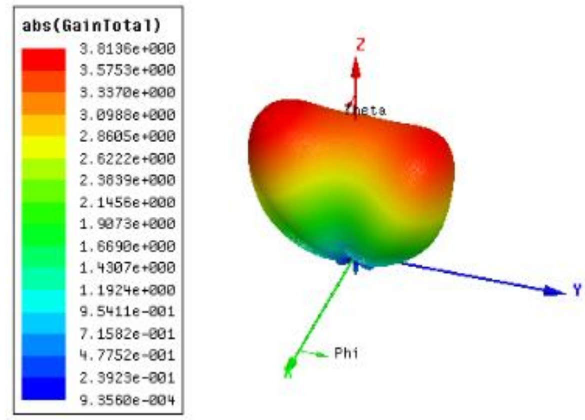


Fig. 11. Radiation pattern of cylindrical DRA antenna without metamaterial superstrate.

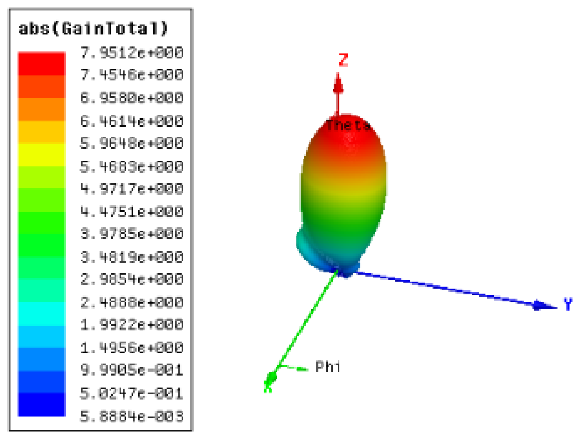


Fig. 12. Radiation pattern of cylindrical DRA antenna with metamaterial superstrate.

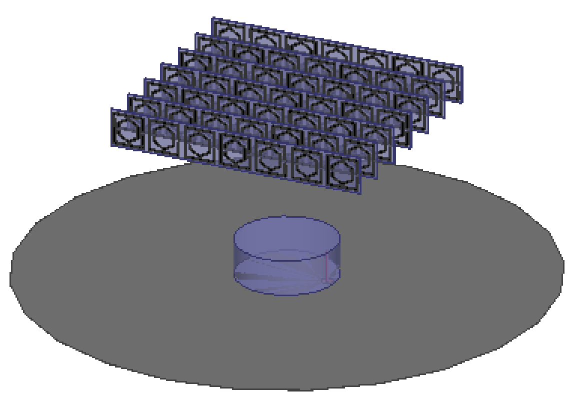


Fig. 13. Schematic of CDRA with 7×7 array of the second metamaterial unit cell working as superstrate.

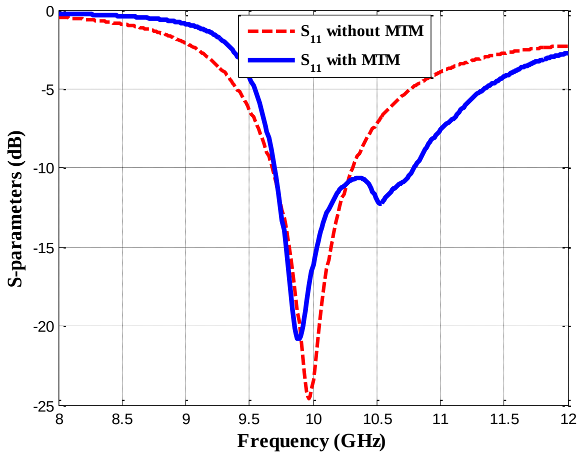


Fig. 14. Comparison of results of scattering parameters in thr presence of the second metamaterial array with respect to the case of without any metamaterial superstrate.

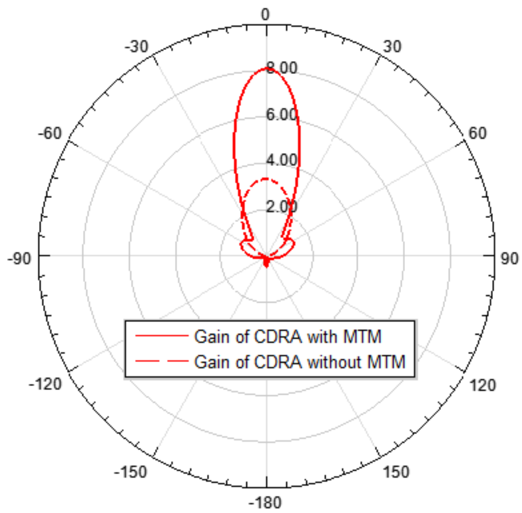


Fig. 15. Comparison of the gain in the presence of the second metamaterial array with respect to the case of without any metamaterial superstrate in $\varphi = 0$ plane.

The radiation patterns of this antenna in two cases without and with metamaterial substrate are also shown in Figs. 16 and 17, respectively. Examining these two diagrams, it can be seen that the directivity and half power beam width of the antenna with metamaterial have been reduced compared to the state without metamaterial.

3. CONCLUSION

Based on the magneto-dielectric superstrate theory and also near zero refractive index theory, two metamaterial unit cells have been designed and investigated on the top of a cylindrical dielectric resonator antenna as superstrate layers. The simulation results of the CDRA show that the first unit cell causes just 3.2 dB gain improvement with respect to the state of without any metamaterial unit cell on the top of the antenna. However, the second unit cell causes improvement of both scattering parameters and gain as 10% and 3.3 dB, respectively, with respect to the case in which any metamaterial superstrate is present on the top of the resonator antenna.

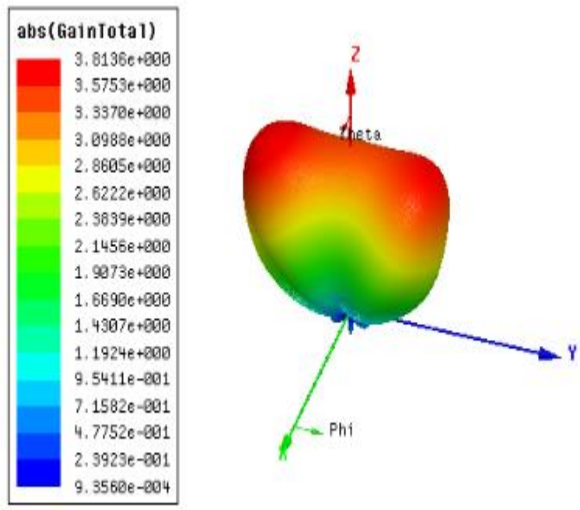


Fig. 16. Radiation pattern of cylindrical DRA antenna without metamaterial superstrate.

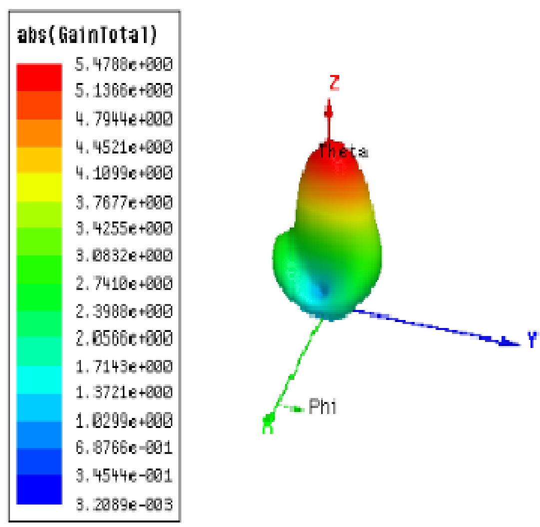


Fig. 17. Radiation pattern of cylindrical DRA antenna with metamaterial superstrate.

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