The Characteristic of a 3.5 GHz Circular Patch Antenna Using Open-Ring Artificial Dielectric

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ABSTRACT
The circular patch microstrip antenna is a device that supports 5G technology because it has a low profile and small dimensions. The circular patch antenna generally constructs of 3 layers of an electromagnetic material. The materials are a good conductor as the radiator and the ground plane and a natural dielectric as the substrate. Along with telecommunication developments, research in the field of antennas is significantly growing. The characteristics of the antennas must be adaptive to these telecommunication developments. One of the antenna research as the solution is an introduction to artificial electromagnetic material. Artificial dielectric is one of the artificial electromagnetic materials. As we have known, a single circular patch antenna has a narrow bandwidth (less than 5% of the center frequency) and a low return loss. This paper proposes an open-ring artificial dielectric. The proposed artificial dielectric is used to improve the bandwidth and the return loss. Furthermore, the circular patch antenna with and without the open-ring dielectric is proposed and conventional. The result shows that the proposed antenna has a wider bandwidth, 8.94%, a higher gain, 0.78 %, and a higher return loss at the center frequency, 5.25% higher than the conventional antenna. From these results, the open-ring artificial dielectric can improve the characteristics of the conventional antenna.

Keywords: *5G antenna, circular patch, open-ring artificial dielectric.*

1. INTRODUCTION

5G is the fifth-generation network used for mobile operating systems at very high speeds. The speed is expected to be almost 100 times faster than 4G. Currently, 5G cellular systems are expanding their spectrum to support high data rates. In the World Radiocommunication Conference (WRC) in 2015, 5G candidate frequency bands below 6 GHz were widely discussed, and the following frequency ranges were suggested: 470–694, 1427–1518, 3300–3800, and 4500–4990 MHz. 3.5 GHz has been widely considered among them, as it is acceptable in most countries [1].

Reliable telecommunications devices are needed to support the 5G, including antennas. An antenna is a device that plays an essential role in the 5G signal transmission process. Antenna functions as a device that transmits and receives electromagnetic waves [2]. Microstrip antenna is one of the 5G technology antennas because it has a low profile and small size. The smaller the antenna used, the better it is used because it is also more economical and supports the needs of portable telecommunications devices.

As we have known, a microstrip antenna has low gain, efficiency, return loss, and narrow bandwidth (less than 5% of the center frequency) [3]. In addition, this microstrip antenna will have large dimensions when arranged into several elements to support 5G technology, namely a multiple-input multiple-output (MIMO) antenna composed of more than one antenna. One solution to reduce the sizes and improve the antenna's performance is replacing the natural dielectric substrate with artificial dielectric material. Kock introduced this method in 1946 [4]- [5].

Ikuo Awai has proposed another method. The method is to insert thin conductor layers on top of the natural substrate layer. This research is aimed at increasing the permittivity of the microwave resonator for filter miniaturization. The very high effective permittivity will contribute to significantly reducing the dimensions of the resonator. Nevertheless, the decrease in this dimension causes the Q factor to decrease [6].

1.1. Related Work

A dielectric material is one type of electromagnetic material widely used in telecommunications equipment. One of which is an antenna. In microstrip antennas, a dielectric is used as insulation between the radiator and the ground plane. The properties of this dielectric material are between that of a conductor and an insulator. When a dielectric material is given an electric field, bounded electrons are distributed. This phenomenon is called polarization [7]. This polarization will result in polarization between positive and negative electric charges, giving rise to the distinctive properties of dielectric materials, namely storing electrical energy. The ability of a dielectric to store or bind charge is called permittivity.

Another material used in this study is conductor material. In contrast to the dielectric material, when the conductor material is given an electric field, the electric charge will be distributed across the entire surface of the conductor. Electric charges will freely move to produce a conduction current. The properties of a conductor are expressed in terms of conductivity. The higher the conductivity value, the electric charge will move more freely and quickly from one point to another.

Artificial dielectric material (ADM) is made from natural dielectric material but modified through an electromagnetic process to produce different parameter values from the natural dielectric. By adding small conductor wires, the electrons will be bound in the dielectric material. These electrons will not move freely as in a dielectric, so if this conductor wire will act as a dielectric and strengthen the host material's natural permittivity. This phenomenon is known as polarization [8]. Polarization is the gathering of electric charges according to their polarity so that an electric potential occurs.

Various studies have been carried out on artificial dielectric materials. The first literature is research on miniaturization of circular resonators waveguide at a frequency of 5.2 GHz. Modification is done by implanting a conductor wire that penetrates the resonator of floral foam material. This method can reduce the cavity dimensions by 31.4%. However, floral foam dielectric material is not suitable for use in small dimensions because adding conductor wire will be difficult [9].

The second literature is research on circular patch antenna substrate with styrofoam material host was modified by attaching a number of thin conductor wires through the substrate in 82 and 110 pieces. This research can prove an increase in relative permittivity of 167% for 82 wires and 270% for 110 wires [10].

The third literature is research on circular patch microstrip antenna made from natural FR4 Epoxy substrate. FR4 Epoxy natural substrate is modified by inserting a number of thin conductor wires into the dielectric substrate. The results show that the use of 82 wire conductors causes the resonant frequency to be 16.3% lower than conventional antennas. While the use of 110 conductor wire causes the resonant frequency to be 24.8% lower than conventional antennas [11].

In addition to the above method, inserting thin conductor strips on the substrate has also been carried out. This literature was developed using vertically inserting thin conductor strips to increase the permittivity of the host material on a 1.8 GHz microstrip antenna. This research was conducted using acrylic substrate materials and rectangular patches. The use of ADM with the addition of conductor strips on acrylic brings an antenna miniaturization effect of 22.8%, and the resulting bandwidth is 1.83% of the center frequency [12].

1.2. Our Contribution

In this paper, the microstrip circular patch antenna consists of an ADM made of acrylic. Acrylic is a rigid material. So in this study, the dielectric substrate as the host material was modified by inserting two thin open-ring conductor strips between the dielectric substrates. These two open-ring strips are placed where the electric field intensity is strong from the TEM (Transverse electromagnetic) field distribution so that these strips are placed just below the patch but are still limited by the dielectric. In comparison, conventional microstrip circular patch antennas were also designed using the same dielectric substrate without modification. Performances such as resonant frequency, bandwidth, gain, and radiation pattern of the two microstrip antennas were compared and analyzed. The results of the performance analysis will be presented in the Results section of this paper.

2. METHODOLOGY

This study used quantitative research methods through empirical research. The approach taken was a simulation approach that analyzes the parameter data measured in the simulation. In this study, a single element circular microstrip patch antenna works at a frequency of 3.5 GHz with a microstrip line feeding technique.

The microstrip antenna is designed using two primary materials, that is acrylic and copper plates. Acrylic dielectric material is used as the antenna substrate. Copper plates are used as patches, ground planes, microstrip lines, and artificial strips inserted between the substrates. The following are the characteristics of the acrylic dielectric:

a. Relative permittivity (ε_r) : 3.4

c. Total thickness (h) : 4.5 mm

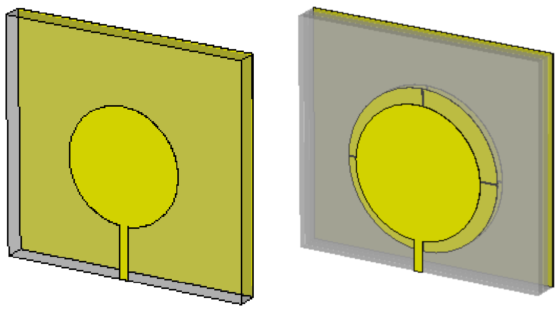
d. Thickness per substrate : 1.5 mm

In designing the antenna, the first thing to do was to calculate the dimensions of the antenna. After calculating the dimensions of a conventional antenna (using a natural substrate), a simulation was carried out to obtain the optimum parameter results. To achieve optimum results, the process carried out was optimization. It was taken to get an impedance match so that the resulting antenna parameters are optimal. Optimization was done by varying the value of the antenna dimensions in the form of patch radius (a), substrate, and ground plane width (W_g), substrate and ground plane length (L_g), microstrip line width (W_f), and microstrip line length (L_f).

Conventional microstrip antenna was used as a reference for a comparison of artificial microstrip antennas. To make an artificial microstrip antenna, conventional microstrip antennas was inserted a thin conductor strip between the substrates. Then the simulation was carried out again to get the maximum results. The results of the artificial microstrip antenna parameters were compared with conventional microstrip antennas. The parameters compared were dimension reduction, return loss, bandwidth, and antenna gain.

The antenna consists of 3 layers of substrate. Top view layer 1 is a patch and microstrip line. A patch is a radiator element, so it is located at the very top. This element serves to radiate electromagnetic wave energy into free space and receive electromagnetic waves from free space. The type of patch used is a circular patch. Conductor strips are inserted between layer 2 and 3 substrates and between layer 1 and 2. This conductor strip will serve to increase the permittivity of the dielectric material. The lowest layer is the ground plane. This ground plane serves to terminate the electrons coming from the patch.

Figure 1(a) is a design of a conventional microstrip antenna and Figure 1(b) is a design of an artificial dielectric microstrip antenna.



(a) (b)

Figure 1 (a) Conventional antenna (b) Artificial dielectric antenna

Figure 2 is a top view of a conventional and artificial microstrip antenna and Figure 3 is a bottom view of a conventional and artificial microstrip antenna. Both antennas have the same top and bottom view. There are several symbols used. a is a patch radius, W_g is a substrate and ground plane width, L_g is a substrate and ground plane length, W_f is a microstrip line width and L_f is a microstrip line length.

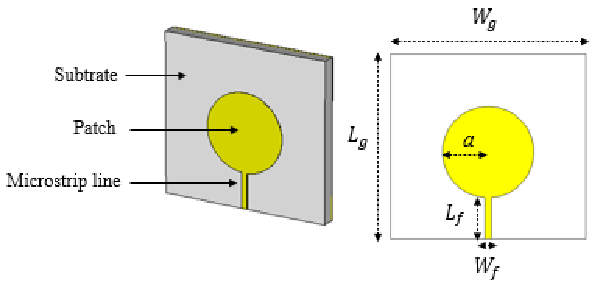


Figure 2 Top view of microstrip antenna

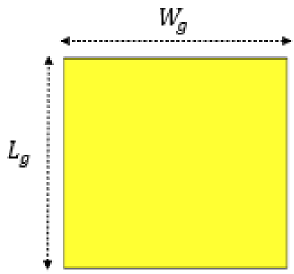


Figure 3 Bottom view of microstrip antenna

The difference between conventional microstrip antenna and artificial dielectric lies in the substrate. In Figure 4, a side view of a conventional microstrip antenna can be seen, while Figure 5 is a side view of an artificial dielectric microstrip antenna. In Figure 5, it can be seen, there is a modification of the substrate using a conductor strip that is inserted between the substrates.

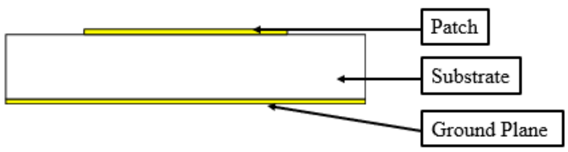


Figure 4 Side view of conventional antenna

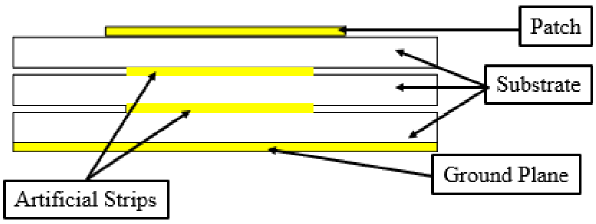


Figure 5 Side view of the artificial dielectric antenna

In this study, we used an open-ring strip. There are two strips on each layer. This strip is centered in the center of the antenna patch. Figure 6 shows the open-ring strip used. There are several symbols used. l is used for strip width, d is strip spacing, and s is slot width. The strip has a width of 5 mm, the distance between the strips is 5.5 mm, and the slot width is 0.1 mm.

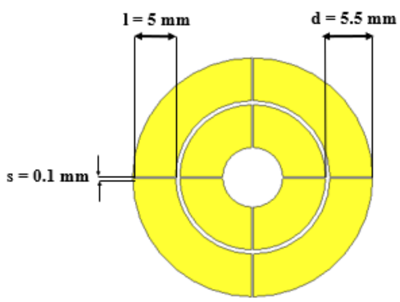


Figure 6 Open-ring artificial dielectric

The dimensions of the designed antenna are obtained based on the results of calculations and antenna simulations. The size of the antenna dimensions based on the calculation is obtained through the following equation: [3].

a. Patch radius (a)

The microstrip antenna patch radius (a) is calculated using equation (1) and F can be calculated by equation (2) [3].

$$a = \frac{F}{\left\{1 + \frac{2h}{\pi.\varepsilon_r.F}\left[ln\left(\frac{\pi.F}{2h}\right) + 1.7726\right]\right\}^{\frac{1}{2}}} \quad (1)$$

In the above equation, a is the radius of the patch, F is the logarithmic function of the radiating element, h is the thickness of the substrate (cm), f_r is the resonant frequency or working frequency and ε_r is the relative permittivity of the substrate material. F can be calculated by equation (2) below [3] :

$$F = \frac{8.791 \times 10^9}{f_r\sqrt{\varepsilon_r}} \quad (2)$$

b. Ground plane and substrate

Substrate and ground plane can be calculated using the equation (3) and (4) below [3]:

$$W_g = 6h + \frac{\pi}{2}a \quad (3)$$

$$L_g = 6h + a \quad (4)$$

W_g is a substrate and ground plane width, L_g is a substrate and ground plane length.

c. Microstrip line

Microstrip line width (W_f) can be calculated using the equation (5) below [3]:

$$\frac{W_f}{h} = \frac{8e^A}{e^{2A} - 2} \quad (5)$$

Where A can be determined by the equation (6) [3]:

$$A = \frac{Z_0}{60}\sqrt{\frac{\varepsilon_r+1}{2}} + \sqrt{\frac{\varepsilon_r-1}{2}}\left(0{,}23 + \frac{0.11}{\varepsilon_r}\right) \quad (6)$$

Where Z_o is the antenna impedance. To calculate the length of the microstrip line (W_f) using the equation (7) [3]:

$$L_f = \frac{1}{4} \times \lambda_g \quad (7)$$

With the value of the guided wavelength (λ_g) obtained from equation (8) [3]:

$$\lambda_g = \frac{\lambda_o}{\sqrt{\varepsilon_r}} \quad (8)$$

Where λ_o is the value of free space wavelength. (λ_o) obtained from equation (9) [3]:

$$\lambda_o = \frac{c}{f} \quad (9)$$

c is the speed of light in a vacuum with the value is 3 x 10^8 m/s.

3. RESULTS AND ANALYSIS

3.1. Antenna Dimensions

Table 1 is the dimensions of conventional and artificial antennas after undergoing optimization. Optimization is a step taken to get an impedance match so that the resulting antenna parameters are optimal. Optimization is done by varying the value of the antenna dimensions in the form of patch radius (a), substrate, and ground plane width (W_g), substrate and ground plane length (L_g), microstrip line width (W_f), and microstrip line length (L_f).

Table 1. Antenna dimensions

Symbol	Description	Conventional (mm)	Artificial (mm)
a	radius	12.402	11.7
L_g	substrate length	50	40
W_g	substrate width	53	45
L_f	microstrip line length	11.078	5.3
W_f	microstrip line width	1.8	1.5

Figure 7 is the shape of the artificial dielectric microstrip antenna after optimization.

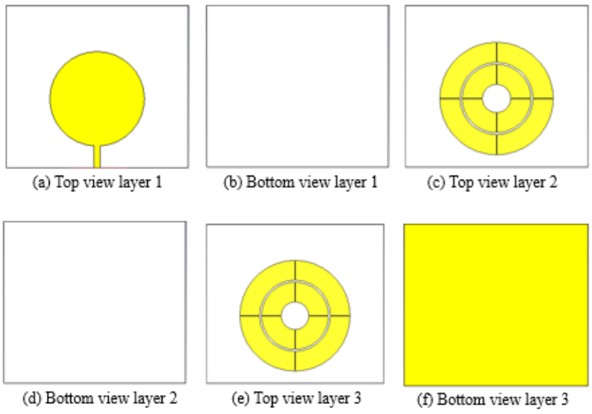


Figure 7 The shape of the artificial dielectric antenna

To get antenna performance at 3.5 GHz, the artificial antenna has a patch area dimension of 11% smaller than conventional antennas and a substrate area of 32.08% smaller than conventional microstrip antennas. The decrease in patch dimensions will affect the relative permittivity of the artificial microstrip antenna. So it is necessary to calculate the relative permittivity of the artificial microstrip antenna. To determine the new relative permittivity value, can use the equation (10) [3]:

$$\frac{f_{rk}}{f_{ra}} = \frac{a_a\sqrt{\varepsilon_{ra}}}{a_k\sqrt{\varepsilon_{rk}}} \qquad (10)$$

f_{rk} is a resonant frequency of the conventional antenna, f_{ra} is a resonant frequency of the artificial antenna, ε_{rk} is a relative permittivity of conventional antenna, ε_{ra} is a relative permittivity of artificial antenna, a_k is a conventional antenna radius, and a_a is an artificial antenna radius

f_{rk} = 3.5 GHz $\quad$ a_k = 12.402 mm $\quad$ ε_{rk} = 3.4

f_{ra} = 3.5 GHz $\quad$ a_a = 11.7 mm

$$\frac{f_{rk}}{f_{ra}} = \frac{a_a\sqrt{\varepsilon_{ra}}}{a_k\sqrt{\varepsilon_{rk}}} = \frac{3.5 \times 10^9}{3.5 \times 10^9} = \frac{11.7\sqrt{\varepsilon_{ra}}}{12.402\sqrt{3.4}}$$

ε_{ra} = 3.82

Based on the above equation, the new permittivity value is 3.82, where this relative permittivity value increases by 12.24% compared to the relative permittivity of a conventional microstrip antenna, which is 3.4. This proves that the use of conductor strips in artificial dielectric microstrip antennas can increase the relative permittivity of the material and reduce the dimensions of the antenna.

3.2. S_{11} Parameter

Figures 8 and 9 can be seen in the graph of S_{11} Parameters of conventional microstrip antennas and artificial microstrip antennas. There are several symbols in the picture. There is f_L which is the lower limit frequency, f_C is the center frequency, f_U is the upper limit frequency, R_L is the return loss, and B_W is the bandwidth. Bandwidth is a frequency area where the lower limit frequency and upper limit frequency intersect with the value of return loss of 10 dB.

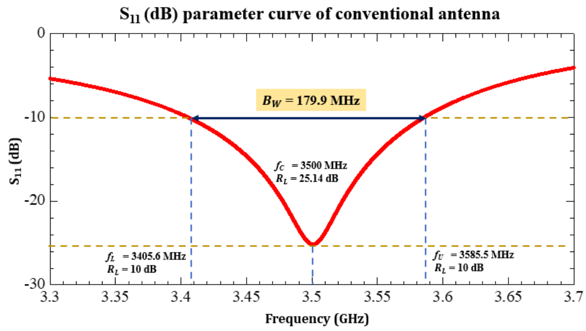


Figure 8 S_{11} parameter curve of a conventional antenna

From graph S11 in Figure 8, it can be seen that a conventional antenna has a center frequency of 3.5 GHz with a return loss of 25.14 dB. While the resulting bandwidth is 179.9 MHz at a return loss of 10 dB.

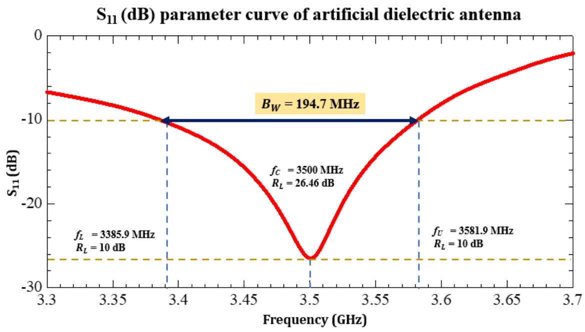


Figure 9 S_{11} parameter curve of an artificial antenna

From the S11 graph in Figure 9, it can be seen that an artificial antenna has a center frequency of 3.5 GHz with a return loss of 26.46 dB. At the same time, the resulting bandwidth is 194.7 MHz at a return loss of 10 dB. From these results, the artificial microstrip antenna has a wider bandwidth and a greater return loss than conventional microstrip antennas. The results show that the proposed antenna has a wider bandwidth of 16.1 MHz or 8.94% and a higher return loss at the center frequency of 1.32. dB or 5.25% higher than conventional antennas.

3.3. Gain

Figures 10 and 11 show the gains of conventional and artificial antennas. The color variation in the following figure is a variation of the gain magnitude. The highest gain magnitude is shown in red.

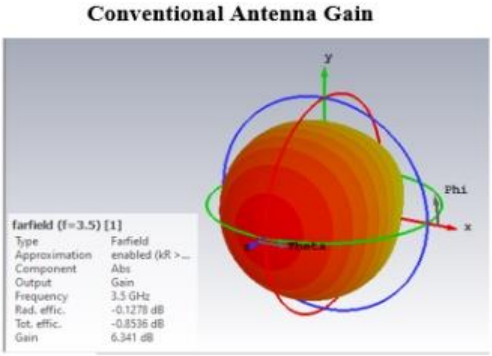


Figure 10 Gain of a conventional microstrip antenna

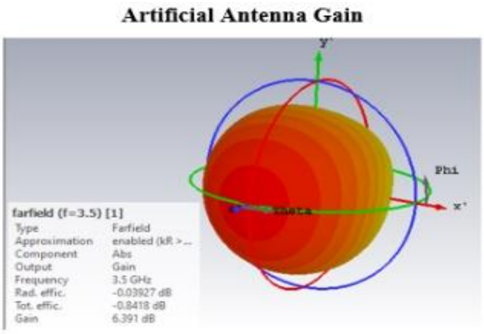


Figure 11 Gain of an artificial microstrip antenna

Based on Figure 10, it is found that a conventional antenna has a gain of 6.341 dBi, while Figure 11 shows that an artificial antenna has a gain of 6.391 dBi. Based on these results, artificial antennas have a gain of 0.78% greater than conventional antennas.

3.4. Radiation Pattern

Figures 12-15 are radiation patterns of conventional and artificial microstrip antennas. Figure 12 is the radiation pattern for the E-plane of a conventional microstrip antenna, while Figure 13 is the radiation pattern for the E-plane of an artificial microstrip antenna.

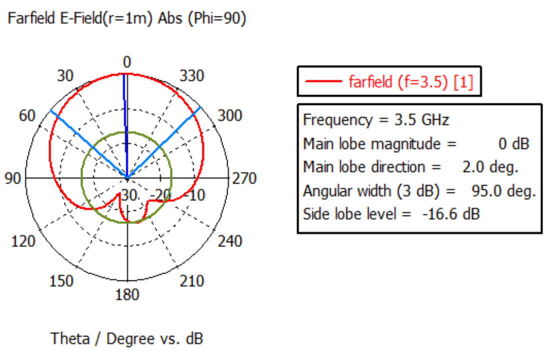


Figure 12 E-field radiation pattern of a conventional antenna

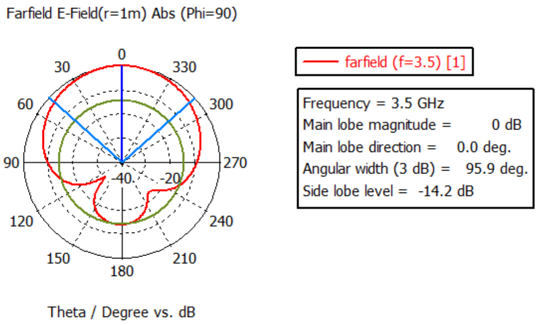


Figure 13 E-field radiation pattern of an artificial dielectric antenna

Conventional antennas have an E-plane HPBW (Half-Power Beamwidth) of 95^0, while artificial antennas have a larger HPBW of 95.9^0. Figure 14 is the radiation pattern for the H-plane of a conventional microstrip antenna, while Figure 15 is the radiation pattern for the H-plane of an artificial microstrip antenna.

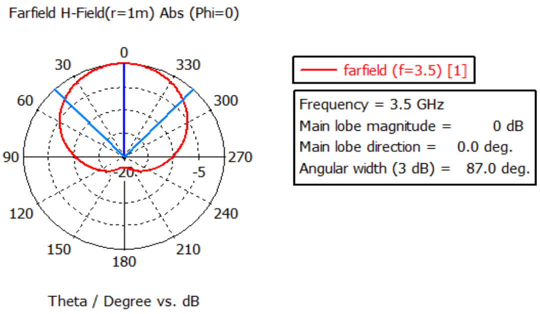


Figure 14 H-field radiation pattern of a conventional antenna

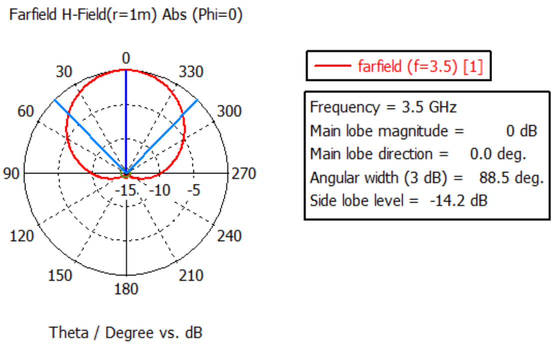


Figure 15 H-field radiation pattern of an artificial antenna

In the H-plane, the conventional antenna has an HPBW of 87^0, while the artificial antenna has a higher HPBW of 88.5^0.

Table 2 is a comparison of the parameters of a conventional microstrip antenna and an artificial microstrip antenna. It can be seen in Table 2 that besides being able to increase the acrylic permittivity, this artificial dielectric microstrip antenna is also able to increase the antenna parameters.

Table 2. Antenna parameter comparison

Parameter	Conventional	Artificial
Bandwidth	179.9 MHz	196 MHz
Gain	6.341 dBi	6.391 dBi
HPBW E-Plane	95^0	95.5^0
HPBW H-Plane	87^0	88.5^0

4. CONCLUSION

The paper describes the characteristics of a 3.5 GHz circular patch antenna using an artificial open-ring. The acrylic natural dielectric material substrate has been modified by inserting a thin conductor strip on top of the substrate to increase the permittivity of the acrylic. The results show that the proposed antenna has a wider bandwidth of 16.1 MHz or 8.94%, a higher gain of 0.05 dBi or 0.78%, and a higher return loss at the center frequency of 1.32 dB or 5.25% higher than conventional antennas. The artificial antenna has a patch area dimension of 11% smaller than conventional antennas and a substrate area of 32.08% smaller than conventional microstrip antennas. The relative permittivity of acrylic increased from 3.4 to 3.82 or 12.24%. From these results, the open-ring artificial dielectric can improve conventional antennas characteristics and can miniaturize antenna dimensions.

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