Design and Analysis of Artificial Magnetic Conductor for Metal Shielding Applications in RFID Car Detection Applications

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Abstract

In this paper, the process of developing the reformulation equation of the Square AMC is conducted. The reformulation yielded results with less than a 5% difference for an AMC using FR-4 substrate with thickness of 3 mm. The equation for calculating capacitance was developed using the conformal mapping theory, with the assumption that inductance remains fixed at the thickness of the AMC. A comprehensive study analysis and integration of an Artificial Magnetic Conductor (AMC) tailored explicitly for metal shielding in Radio Frequency Identification (RFID) applications. The primary focus is to establish a stable and efficient communication link between RFID readers and tags, ensuring reliable data transmission within metallic environments. The proposed AMC structure exhibits a symmetrical design to facilitate seamless integration with RFID tags. This integration strategy aims to optimize communication stability and signal fidelity despite challenging metallic surroundings.

Keywords: Artificial Magnetic Conductor (AMC), RFID, Dipole Antenna.

1. Introduction

The Artificial Magnetic Conductor (AMC) belongs to the metamaterial structure group, specifically designed to enhance the performance of various antenna types, including dipole, monopole, and patch antennas [1], [2], [3]. Employing AMC as the ground plane serves to enhance the antenna's gain by minimizing undesirable back radiation and mitigating mutual coupling effects. The AMC is characterized by its high surface impedance, exceeding a thousand ohms, rendering it akin to an open circuit or lossless structure under these conditions. The reflection graph, which exhibits a phase angle of zero degrees and a magnitude of +1 when the system is in resonance, serves as a defining feature of AMC behaviour [4], [5], [6].

In [7] and [8], AMC-based antenna designs were explored to enhance gain and optimize radiation patterns by manipulating the top layer of the Perfect Electric Conductor (PEC) patch on a conductive substrate material. By applying the lumped circuit concept in [9], the modelling strategy based on characteristic modes, a generic smartphone antenna's impedance characteristic can be achieved. The research was further extended by [10], who employed a similar circuit model to calculate the resonant frequency and reflection phase of structures based on Jerusalem crosses for artificial magnetic conductors (JC-AMC) to intercept waves that would typically strike the structure.

In the paper presented by [11] includes the analysis of a new equation model of resonant frequency for absorber based on the AMC structure composed an array of square patch. Using an equivalent LC circuit model to analyse the square patch array's physical dimensions and material properties, the resonant frequency is determined. The comparable LC circuit model formula was derived using the conformal mapping theory for neighbouring co-planar square patches. While the Gauss' law and the Faraday's law are applied to the square patch that is parallel to the ground plane. This paper proposed a modification of the standard equation of square patch

AMC for different parameters and produce smaller discrepancy between the simulated and calculated resonant frequency. The new equation was modified by introducing the correction factor based on the parametric analysis conducted. The difference of formulation for capacitive element of the proposed structure based on the parametric analysis of patch width, substrate width and gap size.

2. Methodology

The method of RFID tag for metal object detection presented in the paper is divided into two parts; single AMC design and array AMC with dipole antenna integrations.

2.1. Single 2.45 GHz AMC design

The single AMC structure consists of three layers of patch, substrate, and ground plane. The size of the patch must be smaller than the substrate to allow some gap between the patches when integrating with the dipole antenna in array arrangement. The resonant frequency and bandwidth of the standard AMC structure presented in square shape can be calculated using Eq. (1) and Eq. (2) where the L and C represents the inductive and conductive elements of the structure which determine by the Eq. (3) and Eq. (4). Fig. 1 shows the structure of the basic square AMC with square patch on a FR-4 substrate with 3 mm thickness and backed with a full ground plane.

$$f = \frac{1}{2\pi\sqrt{LC}} \quad (1)$$

$$Bw = \frac{1}{\eta_0}\sqrt{\frac{L}{C}} \quad (2)$$

$$C = \frac{w_p \varepsilon_\circ (1+\varepsilon_r)}{\pi} cosh^{-1}\left(\frac{w_s}{g}\right) \quad (3)$$

$$L = \mu_\circ h \quad (4)$$

where w_p= patch width, w_s= substrate width, g=gap around patches, ε_r=substrate permittivity, h =substrate thickness.

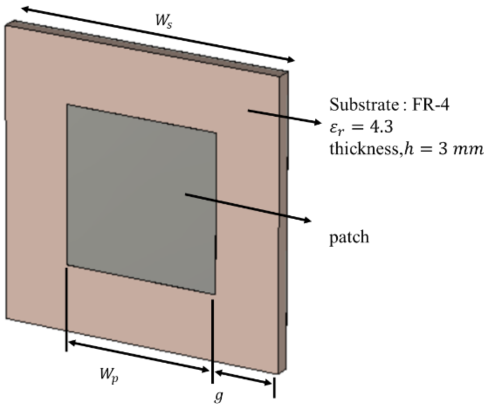


Fig. 1 Structure of the basic square patch AMC, SP-AMC

The flowchart in Fig. 2 show the design steps of designing the Square AMC using CST software. The single structure is simulated using the frequency domain solve with modified boundary setting shows in the flowchart. The simulated result should meet the characteristics of the AMC by achieving the zero-reflection phase and high impedance at resonant [12], [13].

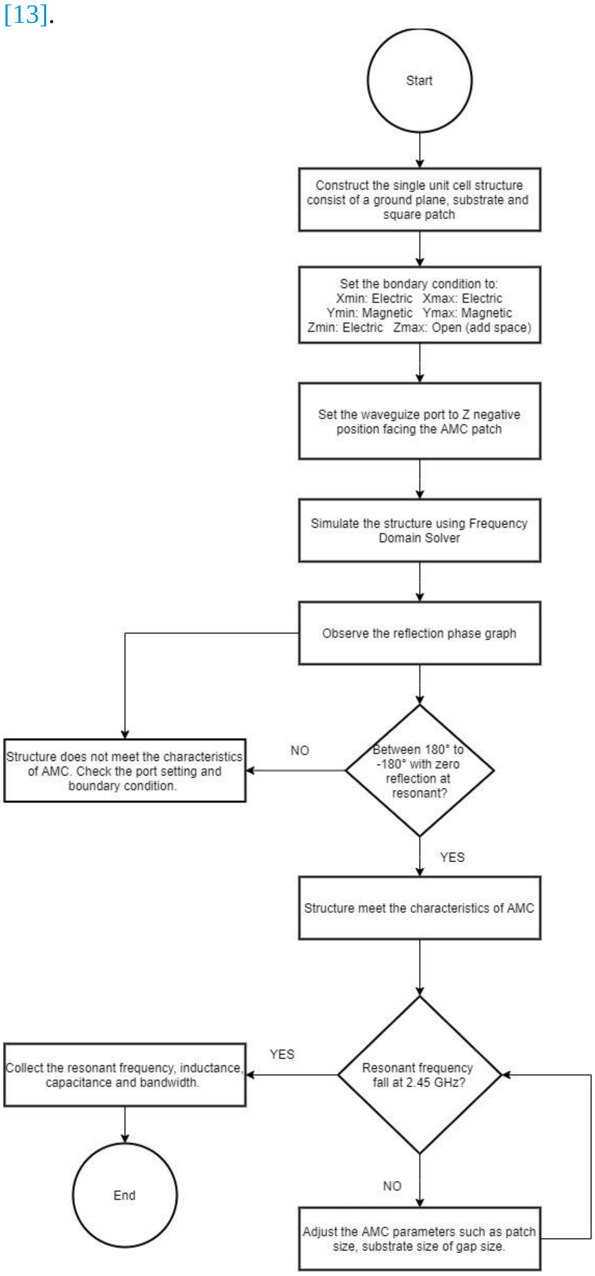


Fig. 2 The flowchart of single unit AMC design using CST software.

2.2. Dipole antenna and Array AMC integration

The second part discussed about the proses of dipole and array AMC integration. A simple dipole antenna will be used to replicate the RFID Tag antenna. The 50Ω discrete port is used to replace the RFID chip at the center of the dipole antenna [14]. The single unit cell

AMC will be arranged in 2 × 2 and 3 × 3 arrangement and will be presented Section 3.

Fig. 3 shows the flow chart of the dipole antenna and array AMC integration. To maintain the symmetrical structure, the array arrangement used in this chapter will be in constant multiplication of 2 × 2 and 3 × 3 arrangement. It is important to analyze the effect of adding the dipole antenna at different positions on the two different array SP-AMC to see the effect of different metallization around the dipole antenna.

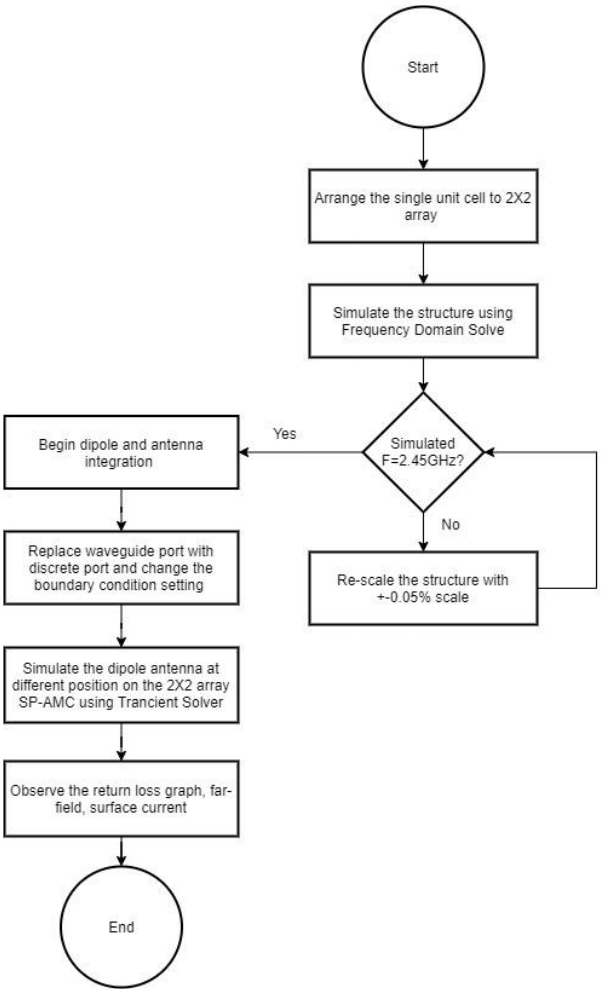


Fig. 3 Flow chart of the dipole and array AMC

3. Results and Discussion

3.1. *Analysis of single unit cell AMC*

In this section, the characteristics of the capacitive and inductive components will be investigated through the simulated frequency. Then, the capacitance value is calculated based on the resonant frequency. By applying the conformal mapping theory, the inductance of the Square AMC use in this paper will be based on the fixed thickness of 3 mm and Fr-4 as substrate. By using the Eq. (4), the inductance value is maintained at 3.77 nH. With this, the capacitance value can be calculated using the Eq. (1) and Eq. (3). The capacitance obtained from both equations will be compared and the Eq. (3) will be reformulated again using the curve fit method. The reformulation of Square Based AMC has been conducted by [11] and produced a maximum deviation of 9.59%. In this paper, the new formulated proposed is expected to be less than 5% by using the MATLAB curve tools.

Table 1 shows the comparison of simulated and calculated resonant frequency of the AMC with substrate size of 50 mm and patch size varied from 18 mm to 21 mm. The calculated frequency using the standard formula displays a significant disparity with percentage different more than 30% when compared to the simulated frequency. The reformulation of the Eq. (5) was conducted using the curve fit tools in MATLAB. The reformulated resonant frequency (R) shown in Table 1 produce smaller discrepancy less than 1%. Fig. 4 shows the comparison between the standard formula, simulated and reformulation resonant frequency of the square AMC with different patch size.

Table 1: Comparison of the S=simulated, C=Calculated, R=Reformulated and percentage different CS= calculated and simulated and RS = reformulated and simulated.

Patch size	Frequency (GHz)			Percentage Different	
	S	C	R	CS	RS
18	3.62	4.81	3.58	33.0%	0.9%
19	3.44	4.59	3.43	33.5%	0.3%
20	3.27	4.38	3.28	34.0%	0.3%
21	3.15	4.19	3.15	33.1%	0.1%

$$C = \left(\frac{1.63 w_p \varepsilon_0 (1+\varepsilon_r)}{\pi}\right) \times cosh^{-1}\left(\frac{ws}{0.9(w_p - w_{s)}}\right) \quad (5)$$

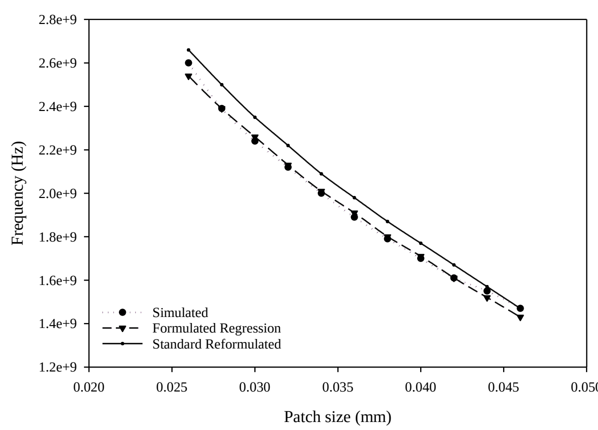


Fig. 4 Comparison of frequency based on standard formula, simulated, and reformulated for the Square AMC with different patch ($\boldsymbol{w_p}$) and gap (g) size.

The Eq. (5) is used to recalculate the frequency based on the proposed structure in [15] and [16] respectively. Table 2 shows the comparison of calculated frequency based on the proposed equation and the actual resonant frequency presented in the paper. Both use the same substrate but with different thicknesses. The comparison yields a percentage difference below 15%.

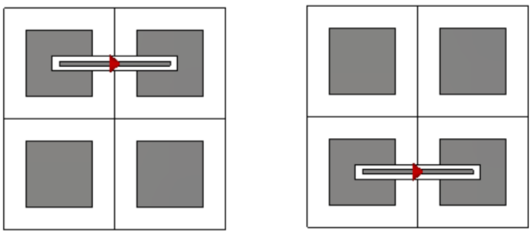
Table 2: Comparison of frequency the Square Patch AMC based on the previous papers.

Paper	Structure dimension	F_R, GHz	F_A, GHz	Percentage Different
[15]	10.8 × 12.4 × 1.6	3.40	3.90	12.8%
[16]	25.6 × 28.1 × 1.25	2.22	2.45	9.54%

where F_R = calculated frequency based proposed reformulation in Eq. (5) and F_A =actual resonant frequency

3.2. *Dipole and AMC Integration and Analysis*

This section will discuss the performance of the dipole antenna on two different AMC array integrations. Dipole antenna is placed at different positions on the array antenna to obtain optimized results in term of gain, directivity and efficiency. Fig. 5 shows the structure of dipole antenna placed at two different positions on the 2 × 2 array AMC. Based on the simulated graph shows in Fig. 8, the dipole antenna on the 2×2 array SP-AMC affects its interaction with the metallization components of the structure, leading to changes in impedance, radiation pattern, near-field effects, and resonance behavior. The overall structure for 2×2 array SP-AMC is measured at 92 mm × 92 mm.



(a) (b)

Fig. 5 Placement of the dipole antenna with optimized performance at the top center and bottom center on the 2 × 2 array AMC

As the dipole antenna position changed around the 2×2 array SP-AMC, the coupling and interaction with the near-field area due to the patches of gap between the patches has different effect to the efficiency of the energy and radiation characteristics. For example, when the dipole is placed at the top center and bottom center of the 2×2 array SP-AMC, the center of the dipole is in contact with the gap between the patches. The placement of the dipole antenna on the 2×2 array SP-AMC also affects the effective capacitance and inductance of the SP-AMC, hence modifying the mutual coupling and impedance of the structure. Based on the simulated graph, the optimized result obtained when the dipole is place at the center top and bottom of the 2×2 array SP-AMC with return loss -28.03 dB.

Fig. 6 shows the surface current distribution of the dipole antenna on the 2×2 array SP-AMC. More inducted current from the dipole antenna was distributed around the top AMC structure compared to the bottom. The AMC structure placed at the back of the dipole antenna helps to realign the surface current to be in-phase with the dipole antenna. Hence, overcome the problem of metal object detection in RFID application.

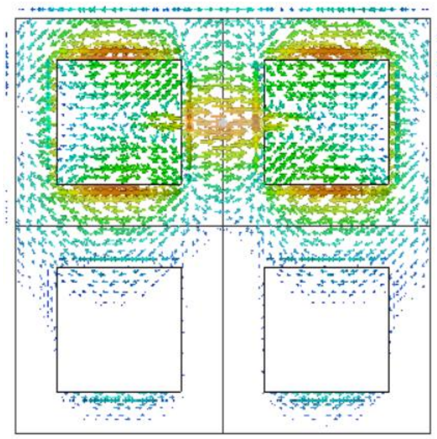
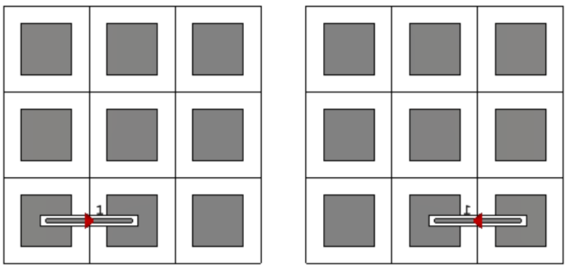


Fig. 6 Surface current distribution of the dipole antenna backed with 2 × 2 array AMC.

The next analysis discussed on the performance of dipole antenna on the 3 × 3 array AMC. The dipole is placed at the top and bottom of the gap between patched on left and right of the array the structure as shown in Fig. 7. The overall structure for 2×2 array SP-AMC is measured at 138 mm × 138 mm. Table 3 shows the comparison of the performance of the dipole antenna on two different square AMC array arrangements.



(a) (b)

Fig. 7 Placement of the dipole antenna with optimized performance on the 3 × 3 array AMC

Table 3: Comparison of the dipole antenna performance with different AMC array arrangements.

Structure	Gain (dB)	Directivity (dB)
Dipole only	1.87	2.02
Dipole with 2 × 2 SP-AMC	3.32	8.21
Dipole with 3 × 3 SP-AMC	3.75	7.58

Fig. 9 shows the surface current distribution of the dipole antenna on the 3 × 3 array SP-AMC. More inducted current from the dipole antenna was distributed around the top AMC structure compared to the bottom. The induced current are lesser as the distance between the dipole and array cell increased due to the large gap used in this structure. Therefore, for structure with big gap, it is recommended to limit the array cell to achieve compact structure.

The return loss in Fig.8 shows the comparison between the dipole antenna with and without the array AMC. It is observed that the use of AMC degrades the bandwidth of the dipole antenna. However, the integration of dipole and AMC shows in Table 3 improved 77% of gain and 275% of directivity compared to dipole antenna without AMC.

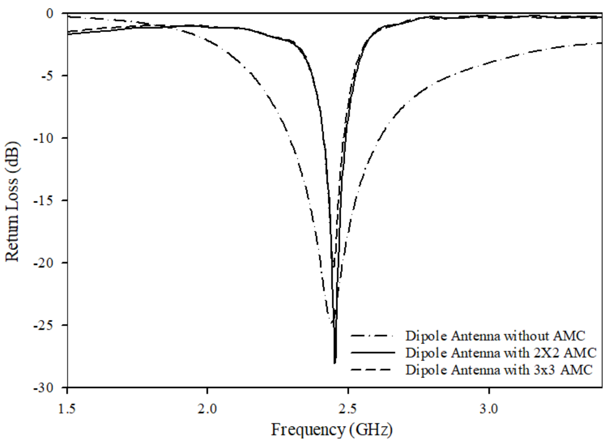


Fig.8: Return loss of the dipole antenna with and without the AMC

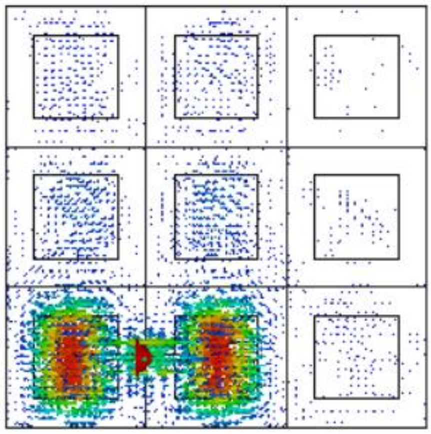


Fig.9: Surface current distribution of the dipole antenna backed with 3 × 3 array AMC

4. Conclusion and Recommendations

To conclude, the first part of this paper the new reformulation of square AMC has been proposed with smaller discrepancy of less than 1% compared to the simulated resonant frequency in CST software. The second part discussed the performance of the simple dipole antenna on two different arrays with optimized results obtained at the top and bottom center of the SP-AMC structure.

The dipole and array AMC structure proposed in the paper can be used as metal shielding in RFID applications such as car detection for parking or toll-system. The use of AMC to the dipole RFID tag can improve the detection range as the AMC helps to reduce the back radiation of the dipole and improve the directivity and gain of the structure. The array arrangement in this paper is limited to 3 × 3 to minimize the overall structure.

A bigger array is recommended for any application which has no objection on the size limits. For low frequency such as UHF RFID, the AMC structure with slots can be introduced to achieve compact size.

References

1. Capolino, Filippo. Theory and phenomena of metamaterials. CRC Press, 2017.
2. Zharov, Alexander A., Ilya V. Shadrivov, and Yuri S. Kivshar. "Nonlinear properties of left-handed metamaterials." Physical Review Letters 91, no. 3 (2003): 037401.
3. G. V. Trentini, “Partially reflecting sheet arrays,” IRE Trans. Antennas Propag., vol. AP-4, pp. 666–671, 1956.
4. E. Carrubba, A, Monorchio, and G. Manara “Artificial Magnetic Surface for Circular Polarization Movemenent” Microwave and Optical Technology Letters, Vol 5, pp.1782-1786, Aug 2010.
5. M Elena de Cos, Yuri Alvarez and Fernando Las-HEras, “Design and Characteristics of Planar Artificial Magnetic Conductor in the RFID SHF Band” Proceeding of Forth European Conference on Antenna and Propagation 2010, pp. 1-5, Apr 2010

6. Sievenpiper D. F. "High Impedance Electromagnetic Surface" PHD Thesis, University of California at Los Angeles 1999.
7. D. SievenpiperLijun Zhang, Romulo F. Jimenez Broas, Nicholas G. Alex´opolous, and Eli Yablonovitch, "High-Impedance Electromagnetic Surfaces with a Forbidden Frequency Band" IEEE Transactions On Microwave Theory And Techniques, Vol. 47, No. 11, November 1999, pp: 2059 – 2074.
8. Constantin R. Simovski, Peter de Maagt, and Irina V. Melchakova, "High-Impedance Surfaces Having Stable Resonance With Respect to Polarization and Incidence Angle" IEEE Transactions On Antennas And Propagation, Vol. 53, No. 3, March 2005, pp: 908-914.
9. Jafargholi, A,Atlasbaf, Z. And Kamyab, M., "Miniaturized dual-band dipole antenna loaded with metamaterial based structure," 2011 19th Iranian Conference Electrical Engineering (ICEE), pp.1-4, 17-19 May 2011.
10. Sujatha, M. N., and K. J. Vinoy. "A stacked ring-patch artificial substrate for surface waves suppression and in phase reflection." In Industrial and Information Systems (ICIIS), 2010 International Conference on, pp. 75-79. IEEE, 2010.
11. Kurniawan, Adit, Achmad Munir, and Levy Olivia Nur. "Theoretical Analysis of Resonant Frequency for AMC-based Absorber Composed of Square Patch Array." International Journal on Electrical Engineering & Informatics 7.2 (2015).
12. Abu, M., E. E. Hussin, A. R. Othman, Fauzi Johar, Norhidayah M. Yatim, and Rose F. Munawar. "Design Of 0.92 GHz Artificial Magnetic Conductor For Metal Object Detection In RFID Tag Application With Little Sensitivity To Incidence Of Angle." Journal of Theoretical & Applied Information Technology (2014).
13. Abu, M., E. E. Hussin, A. R. Othman, N. M. Yatim, F. M. Johar, and R. F. Munawar. "Design of stacked wafers AMC at 920 MHz for metallic object detection in RFID application." In 2013 IEEE Symposium on Wireless Technology & Applications (ISWTA), pp. 236-239. IEEE, 2013.
14. Abu, M., E. E. Hussin, M. S. M. Isa, Z. Zakaria, and Z. A. Baharudin. "Designing artificial magnetic conductor at 2.45 GHz for metallic detection in RFID tag Application." International Journal of Engineering and Technology (IJET) 6, no. 1 (2014): 427-435.
15. Askari, Hussain, Niamat Hussain, Domin Choi, Md Abu Sufian, Anees Abbas, and Nam Kim. "An AMC-Based Circularly Polarized Antenna for 5G sub-6 GHz Communications." Computers, Materials & Continua 69, no. 3 (2021).
16. Eardprab, Sanchai, Chuwong Phongcharoenpanich, and Danai Torrungrueng. "Improvement of a circular microstrip antenna excited by four feeds and suspended with artificial magnetic conductors." International Journal of Antennas and Propagation 2013 (2013).

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