Jurnal Teknologi

Full paper

# Bandwidth Widening, Gain Improvement and Efficiency Boost of an Antenna Using Artificial Magnetic Conductor (AMC) Ground Plane

Raimi Dewan[a,b*], Sharul Kamal Abdul Rahim[b], Siti Fatimah Ausordin[b], Dyg Norkhairunnisa Abang Zaidel[b], Bashir Muhammad Sa'ad[b], Teddy Purnamirza[c]

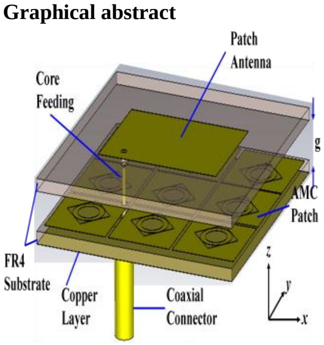
[a]*Department of Communication Engineering, Faculty of Electrical Engineering, Universiti Teknologi Malaysia, 81310 UTM Johor Bahru, Johor, Malaysia*
[b]*Wireless Communication Centre, Universiti Teknologi Malaysia, 81310 UTM Johor Bahru, Johor, Malaysia*
[c]*Department of Electrical Engineering, Faculty of Science and Technology, Universitas Islam Negeri Sultan Syarif Kasim, Pekan Baru, Indonesia*

*Corresponding author: raimidewan@gmail.com

**Article history**

Received :12 July 2012
Received in revised form :
4 April 2013
Accepted :15 April 2013

**Graphical abstract**




**Abstract**

In this paper, a standalone patch antenna operating at 2.3 GHz is initially designed as a reference antenna. Subsequently, the patch antenna is incorporated with an Artificial Magnetic Conductor (AMC) as the ground plane to obtain an Antenna with Artificial Magnetic Conductor (AAMC). Performance comparison is analyzed between the standalone patch antenna and the AAMC. The incorporation of AMC to the patch antenna successfully enhances the bandwidth of the standalone patch antenna by 520%, increases gain by 2dBi, and boosts the efficiency up to 30 % as compared to the reference antenna. As a result of the bandwidth enhancement, the AAMC is capable to cover several frequency bands within 2.19 GHz to 2.5 GHz. Hence, the new design is suitable for WiMAX, WLAN and RFID applications. The measurement results in terms of return loss, gain and radiation patterns agreed satisfactorily with the simulated ones. Moreover, the parametric studies of antenna dimensions and air gap are presented and discussed.

*Keywords:* Antenna; artificial magnetic conductor; bandwidth widening; efficiency boost; gain improvement

**Abstrak**

Antena tunggal telah direka sebagai antena rujukan yang beroperasi pada frekuensi 2.3 GHz. Kemudian, antenna tersebut diintegrasikan dengan Pengalir Magnetik Buatan (AMC) sebagai satah bumi untuk mendapatkan antenna bersepadu dengan Pengalir Magnetik Buatan (AAMC). Analisis telah dilakukan bagi perbandingan prestasi antenna tunggal dan AAMC. Persepaduan AMC dengan antenna berjaya meningkatkan lebar jalur antenna tunggal sebanyak 520%, kegandaan sebanyak 2 dBi, dan kecekapan sebanyak 30% dibandingkan dengan antenna rujukan. Antena yang dipertingkat prestasi, iaitu AAMC telah mampu merangkumi julat frekuenci daripdada 2.19 GHz ke 2.5 GHz, disebabkan oleh peningkatan lebar jalur. Maka, rekaan baru tersebut (AAMC) sesuai untuk aplikasi WiMAX, WLAN dan RFID. Kajian parametrik berkenaan dengan dimensi antena dan sela udara telah ditunjukkan dan dibincangkan. Keputusan pengukuran seperti kehilangan balikan, kegandaan dan corak radiasi bersetuju dengan memuaskan jika dibandingkan dengan keputusan simulasi

*Kata kunci:* Antena; pengalir magnetik buatan; peningkatan lebar jalur; penjanaan kecekapan; kenaikan kegandaan



## 1.0 INTRODUCTION

Metamaterial is an artificial resonant structure that is designed to obtain specific characteristics which are not naturally occurring in nature [1]. These unique characteristics of metamaterial have been used extensively in antennas and microwave applications in order to improve desired performances [2].

AMC is a type of metamaterial which introduces an in-phase reflection phase within the band gap of a desired frequency [3]. This behaviour of in-phase reflection phase is the properties of Perfect Magnetic Conductor (PMC) that does not exist in nature. Thus, by introducing in-phase reflection phase characteristic of PMC by AMC, radiation efficiency and gain of antennas can be improved [4], so the use of metamaterial gains increasingly interest in recent year [5].

Perfect electric conductor (PEC) is the common reflector used in antennas to obtain a directional radiation pattern. The main drawback of using PEC is the presence of image current generation which opposites the direction of source current. Thus, the image current interference with the source current causes degradation in the radiation efficiency of antennas. This degradation can be minimized by extending the distance of the PEC surface from antennas by λ/4. However, the inclusion of the corresponding distance reduces the low-profile structure of antennas, which is undesirable for most antenna applications. The use of AMC can be an alternative for PEC in antenna applications

Metamaterial is an artificial resonant structure that is designed to obtain specific characteristics which are not naturally occurring in nature [1]. These unique characteristics of metamaterial have been used extensively in antennas and microwave applications in order to improve the desired performances [2]. AMC is a type of metamaterial which introduces an in-phase reflection phase within the band gap of a desired frequency [3]. This behaviour of in-phase reflection phase is the properties of Perfect Magnetic Conductor (PMC) that does not existed in nature. Thus, by introducing in-phase reflection phase characteristic of PMC by AMC, radiation efficiency and gain of antennas can be improved [4]. The use of metamaterial increasingly gains interest in recent year [5].

Perfect electric conductor (PEC) is the common reflector used in antennas to obtain a directional radiation pattern. The main drawback of using PEC is the presence of image current generation which in opposites the direction of source current. Thus, the image current interference with the source current causes degradation in the radiation efficiency of antennas. This degradation can be minimized by extending the distance of the PEC surface from antennas by λ/4. However, the inclusion of the corresponding distance reduces the low-profile structure of antennas, which is undesirable for most antenna applications. The use of AMC can be an alternative for PEC in antenna applications.

Microstrip antennas are the preferable choice in the design of antennas due to the ease of fabrication, low cost, light weight and the low profile [6]. However, the drawbacks of microstrip antennas are typically narrow in bandwidth and low in gain [7-8]. The percentage bandwidth (%BW) of a microstrip antenna is usually around 5% [9]. The gain of a single patch antenna cannot be improved by merely extending the size of the ground plane [10]. Furthermore, microstrip patch antennas suffer from the low radiation efficiency which caused by the surface wave excitation [11].

A lot of researches have been done to improve the drawbacks of microstrip patch antenna [12-13]. A compact antenna was reported in [14] where two mitered corners and two slots to achieved dual band capabilities. The lower band at 2.4 GHz was obtained through the manipulation of a current path at U-slot of the antenna. However, the antenna achieves a corresponding bandwidth of only 0.2 GHz (2.30 GHz – 2.50 GHz) and a low gain of 1.85 dBi. A wideband antenna with 20 % bandwidth at 2.4 GHz was achieved in [15] which contributed by a horizontal microstrip arm and two small diamond-shaped patches. Although, the array antenna achieves a high gain of 6.8 dBi over the entire bandwidth, the overall structure is not low profile due to the positioning of aluminium ground plane that is 14.2 mm ($0.11\lambda_{2.4\ GHz}$) from the substrate of the radiating patches.

In [16], a new technique was proposed for enhancing the bandwidth of 2.45 GHz circular polarized antenna by means of defected ground structure (DGS) and parasitic split ring resonators (SRRs). However, the bandwidth improvement is only 51.3%. In addition, a superstrate was introduced in [17] to enhance the bandwidth of the antenna at 1.7 GHz (lower band) and 2.4 GHz (upper band). The corresponding bandwidth of the upper band is only 3.9%. The incorporation of superstrate manages to enhance and reduce the size of the antenna in the trade off gain reduction and decrease in efficiency.

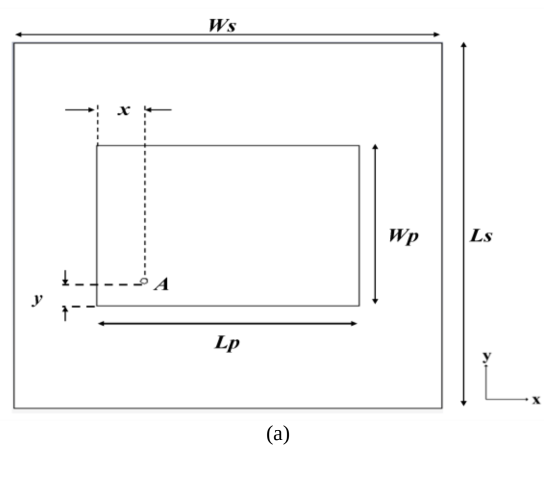
AMC unit cells have been integrated as a modified ground plane in [18] to a microstrip antenna which operates at 2.48 GHz. The bandwidth is only increased from 20 MHz to 46 MHz which corresponds to 130% bandwidth enhancement, when compared to reported reference antenna. The proposed design also uses lots of AMC which consist of 20 unit cells. Generally, lesser number of used unit cell contributed to a smaller periodic array of AMC structures. Hence , a more compact design can be achieved [19].

Additionally, in [20], a dual band array antenna operating at centre frequency of 2.44 GHz and 5.88 GHz band was proposed. The proposed antenna achieves the bandwidth of 9.83% and the array configuration gives a maximum gain of 7.6 dBi at the lower band. However, the use of filtering elements to permit dual band operation of the antenna adds complexity to the design of the array antenna.

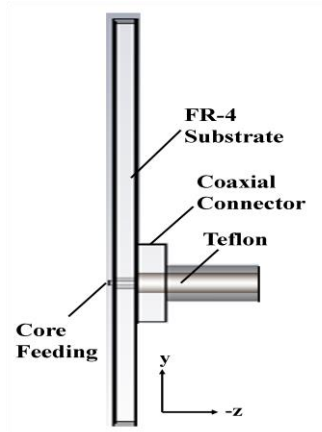
In this paper, a patch antenna with an AMC ground plane which consists of only single radiating patch is proposed. Nine AMC unit cells were used in the periodic AMC array which acts as an AMC ground plane to the antenna. The incorporation of the AMC unit cells into the patch antenna enhances the bandwidth to cover from 2.19 GHz and 2.50 GHz bands. This AMC integrated antenna is suitable to be used in multiple wireless services such as WLAN (2.45 GHz), WiMAX (2.3 GHz) and RFID (2.48 GHz).

## ■2.0 DESIGN OF THE STANDALONE ANTENNA

The standalone patch antenna was designed using computer simulation technology (CST) 2010 microwave software. An inexpensive FR4 substrate with dielectric permittivity of 4.5, thickness 1.6 mm, and loss tangent 0.0195 were used in all designs. The thickness of the copper layer which was used as a conductor layer is 0.035 mm. Figure 1(a) and Figure 1(b) shows the design of the standalone antenna which serves as a reference antenna.




(a)




(b)

**Figure 1** (a) Front view and (b) side view of the standalone antenna

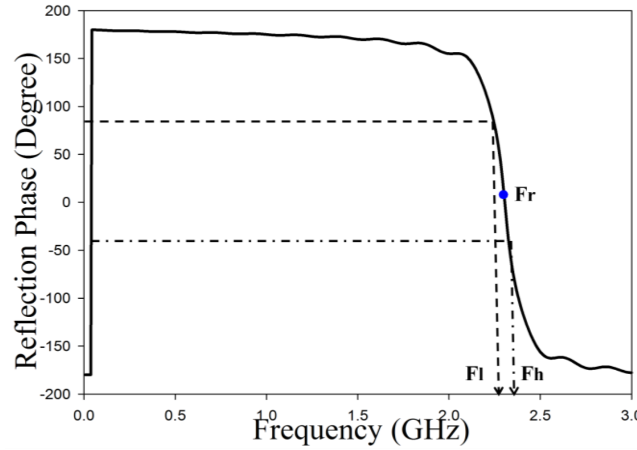



**Figure 2** Reflection phase curve from 0 to 3.0 GHz

As shown by Figure 1(a) and 1(b), the antenna is rectangular in shape and fed through a coaxial connector at point *A*. The diameter of the coaxial connector is 1.0 mm. The point A is offset at a distance of *x* mm and *y* mm from the edge of the patch. The patch has a width and length of *Wp* and *Lp*, respectively. The substrate width and length is *Ws* and *Ls*, respectively and the dimension is shown by Table 1. The antenna used a conventional copper ground layer.

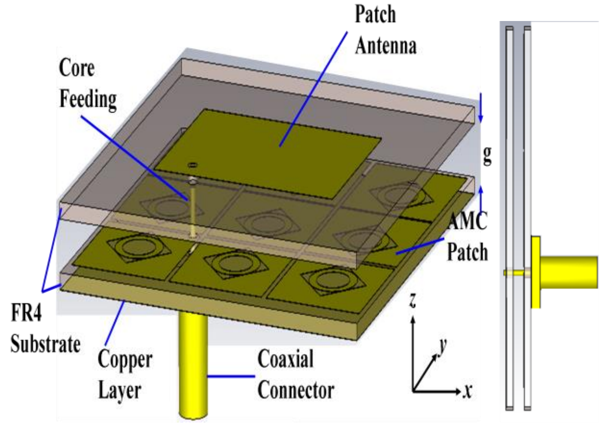
**Table 1** Dimension of the antenna

| Dimension | Standalone Antenna | AAMC |
|---|---|---|
| $L_p$ | 40.0 | 39.3 |
| $L_S$ | 67.6 | 67.6 |
| $W_p$ | 28.8 | 28.3 |
| $W_s$ | 65.0 | 65.0 |
| $x$ | 7.2 | 6.9 |
| $y$ | 4.7 | 4.4 |

## 3.0 DESIGN OF ANTENNA INTEGRATED WITH AMC GROUND PLANE (AAMC)

The design of AMC unit cells is adopted from [21] which exhibits triple band of reflection in three different operating bands of 2.3 GHz, 5.8 GHz and 8.3 GHz. Figure 2 shows the edited graph of the reported work which focuses on the single 2.3 GHz resonant frequency. $F_l$ and $F_h$ represent the lower and upper frequency of AMC which located at 90° and -90° of the reflection phase, respectively. The corresponding values of $F_l$ and $F_h$ are 2.23 GHz and 2.37 GHz. The selected 2.3 GHz band of the AMC reflection phase curve is utilized for the application of the antenna.

Figure 3(a)-(b) shows the antenna incorporated with 9 AMC unit cell. The AMC functions as an AMC ground plane for the antenna. The antenna integrated structure (top substrate) and AMC ground plane (bottom substrate) are separated with an air gap of *g* mm which is 2 mm. The corresponding air gap value is equivalent to $0.015\lambda_{2.3\ GHz}$. The simulated and measured dimension of the overall structure thickness is 5.31 and 5.38 mm, respectively.

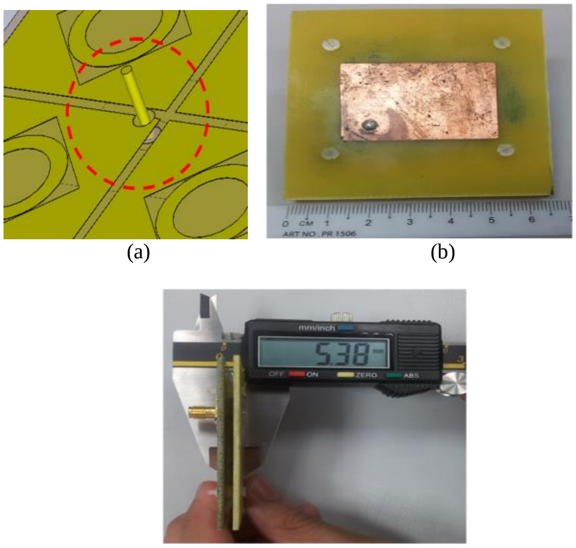



(a) (b)

**Figure 3** (a) Three dimensional exploded view and (b) side view of the simulated AAMC

The measurement of the overall structure dimension is crucial since the performance of AAMC is sensitive to the air gap between the radiating element and the ground plane. The influence of air gap will be discussed in the subsequent sections. The substrate layer in Figure 3(a) exhibits as a transparent rectangular layer, which gives better view of the overall antenna structure, the position of AMC unit cell as well as the core feeding from the coaxial connector to the radiating patch. The core of the coaxial connector was not connected to the AMC patches, otherwise; electromagnetic wave will be shorted and not propagate to the radiating patch.

Thus, a semi circular edge was introduced to the AMC patch in close vicinity to the core of coaxial connector as shown in Figure 4(a). Figure 4(b) shows the fabricated prototype while Figure 4(c) shows the measurement via Vernier Caliper of the overall thickness of AAMC. Table 1 shows the design dimensions of AAMC in comparison with the standalone antenna.



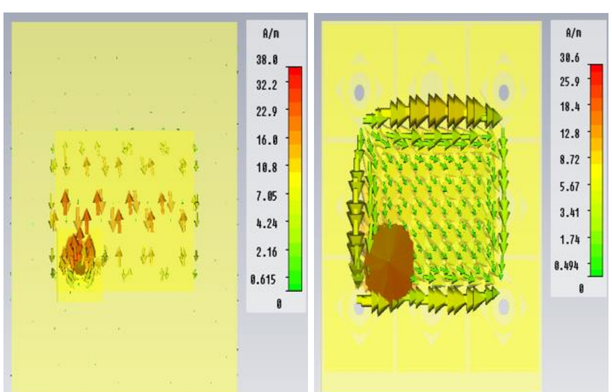
(a) (b)

(c)

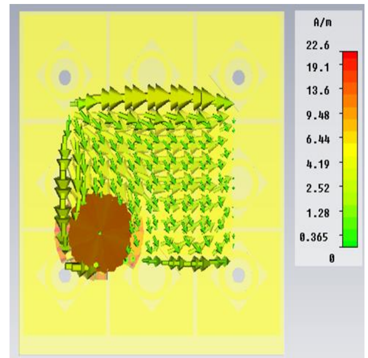
**Figure 4** (a) the semi-circular edge of AMC patched around coaxial feeding, while (b) shows the fabricated prototype and (c) the measurement of the overall thickness of the structure via Vernier caliper

## ■4.0 SURFACE CURRENT DISTRIBUTION

The integration of the AMC ground plane significantly influences the surface current concentration flowing on the radiating patch. The comparisons of the surface current were conducted for both standalone patch antenna and patch antenna with AMC ground plane. The red and light green in the colour indicator accompanying Figure 5(a)-(c) shows the highest and lowest magnitude of surface current respectively, which represented in terms of ampere/meter. Quantitatively, greater number of arrow revolving around the radiating patch shows greater concentration of the surface current although the magnitude of surface current varies in the three scenarios of simulation.




(a) (b)




(c)

**Figure 5** The surface current distribution of the standalone antenna at (a) 2.3 GHz; and AAMC at (b) 2.3 GHz and (c) 2.4 GHz

Based from Figure 5(b)-(c), the implementation of AMC ground plane successfully increases the concentration of the surface current of the antenna at both bands of 2.3 GHz and 2.45 GH as compared to the concentration of surface current in standalone antenna which is shown in Figure 5(a). Due to the bandwidth widening effect of AMC ground plane to the antenna (which will be discussed in the following section), so the antenna performs at 2.3 GHz and 2.45 GHz band. It can be observed that AMC ground plane improves the flow of surface current revolving around the radiating patch.

## ■5.0 RESULT AND DISCUSSION

To fully analyze the performance made by embedding AMC to the patch antenna, the behaviour of the standalone patch antenna which acts as a reference antenna is initially studied. Figure 6 shows the parametric study of *Lp* with respect to return loss. It is observed that the value of *Lp* is not significantly affect the antenna in terms of return loss as the three parameter variation of 39 mm, 40 mm and 41 mm show similar curve characteristics. However, value of 40 mm is chosen as it obtains better $S_{11}$ at 2.3 GHz.

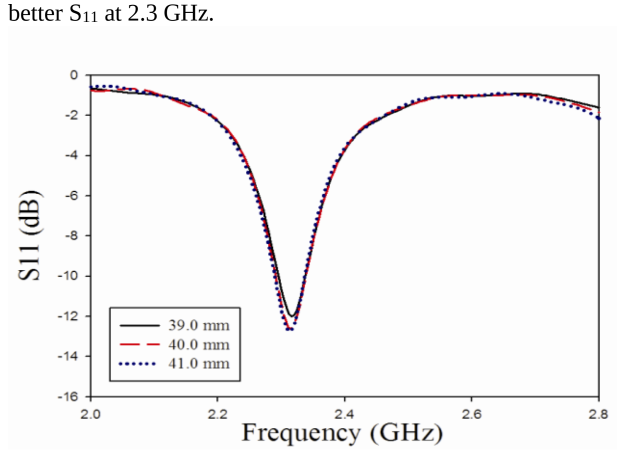



**Figure 6** The simulated variation of *Lp* with respect to return loss

Referring to Figure 7, it is observed that the return loss curve is shifted to the left when *Wp* is varied from 28.77 mm to 27.77 mm and vice versa. Nevertheless, the 10 dB bandwidth of the return loss curve approximately similar for all parameter variation of *Wp*. The simulated return loss of the standalone antenna is shown in Figure 8. The return loss covers from 2.29 GHz to 2.34 GHz, which correspond to a simulated bandwidth of 0.05 GHz.

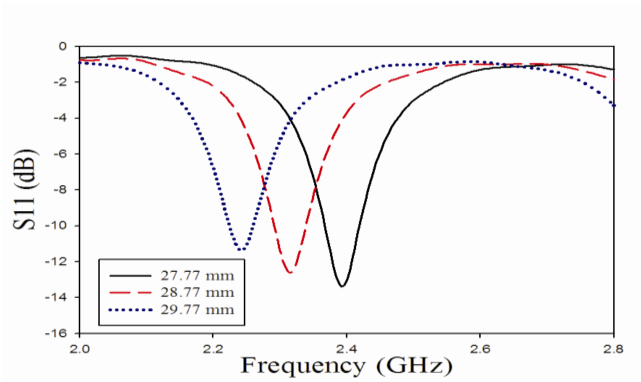



**Figure 7** The simulated variation of *Wp* with respect to return loss

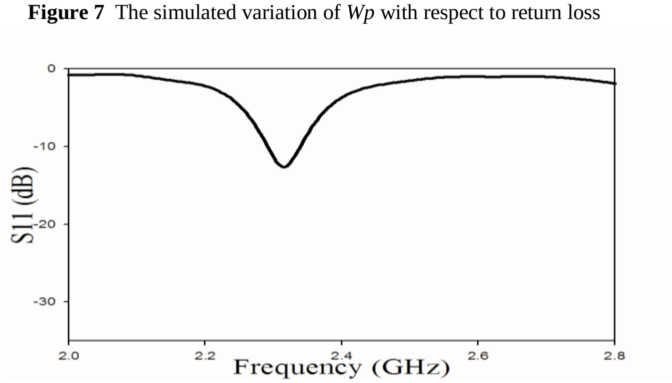
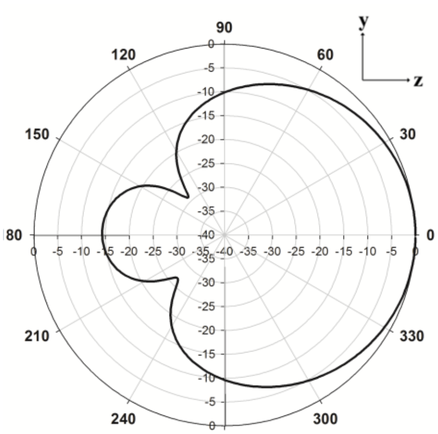
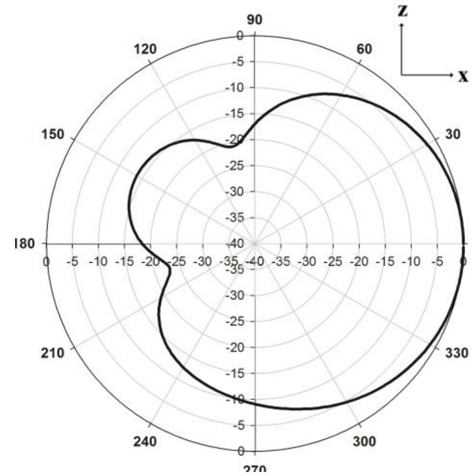



**Figure 8** The simulated return loss of the standalone antenna

Figure 9(a) and Figure 9(b) shows the simulated radiation patterns of the standalone antenna for E-field and H-field, respectively. The standalone antenna exhibits a simulated maximum gain of 4.59 dBi in the direction of 0º with half power beam widths (HPBW) of 92.1º.




(a)




(b)

**Figure 9** The simulated radiation patterns of the standalone antenna at 2.3 GHz for (a) E-field and (b) H-field

Subsequently, the performance of the AAMC is analyzed. Figure 10 shows the parametric result of air gap versus return loss. Based on the simulation results for the case of $g$ = 0 mm, no bandwidth enhancement was achieved, a lower gain of 2.63 dBi (at 2.3 GHz) and a relatively lower efficiency (15.53 %) as compared to the reference antenna. Air gap, $g$ of 2 mm was selected as the optimized value, as it gives wider bandwidth.

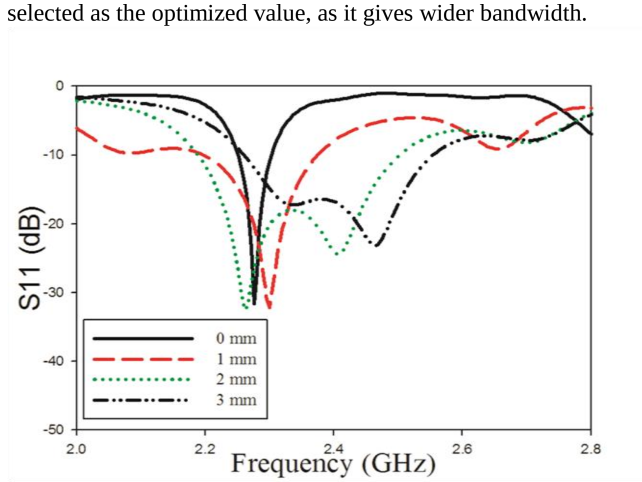



**Figure 10** The simulated variation of $g$ with respect to return loss

As depicted in Figure 11, a parametric study was also performed to analyze the variation of air gap to the gain of the AAMC at 2.3 GHz. It is observed that the gain is at its lowest when the air gap is not introduced to the AAMC ($g$ = 0 mm). Subsequently, the gain is slowly increased as the value of $g$ increase from 0 mm to 2 mm. Gain is barely increased further for any value of $g$ greater than 2 mm. 2 mm was chosen as the optimum value of $g$ to achieve minimum thickness of overall structure.

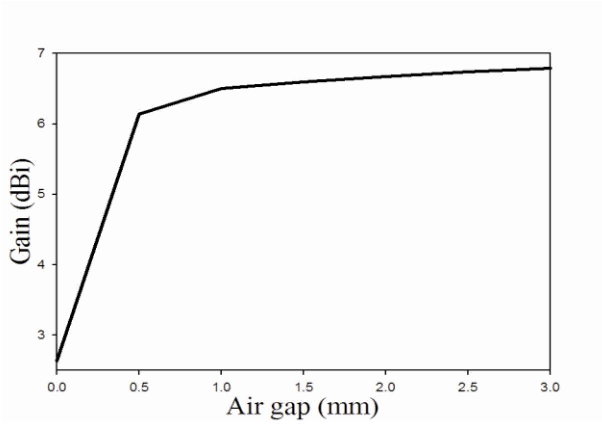



**Figure 11** The simulated variation of *g* with respect to antenna gain

Figure 12 shows the simulated and measured return loss of AAMC. The frequency covered by AAMC was from 2.19 GHz to 2.50 GHz which corresponds to bandwidth of 0.31 GHz. From the simulation result, it is observed that the integration of AMC ground plane enhances the antenna bandwidth by 520 %, as compared to the standalone antenna. Equation (1) was used to calculate the bandwidth enhancement whereby the reference bandwidth was based on the simulated bandwidth of the standalone antenna [22]. The measured return loss of the fabricated prototype is shifted to the right, while covering the commercial wireless application at 2.3 GHz and 2.45 GHz bands. The shifted in return loss is due to the misalignment of the antenna and AMC which located on different substrates and the soldering at the feeding point at the radiating patch of the antenna. Furthermore, a precise air gap is difficult to attain at any point located between the bottom and top substrate.

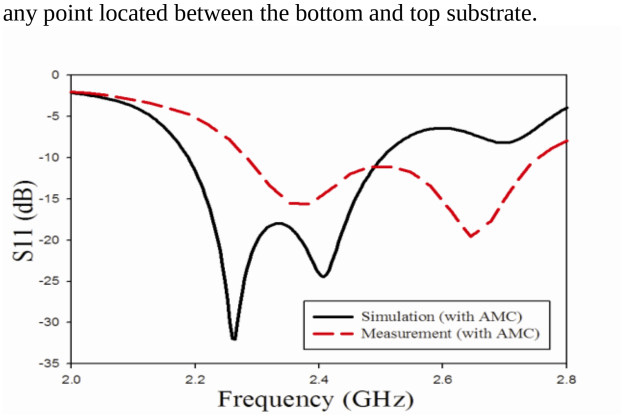



**Figure 12** The simulated and measured return loss of AAMC

$$\%\text{Bandwidth Improvement} = \frac{\text{New Bandwidth} - \text{Reference bandwidth}}{\text{Reference bandwidth}}(100\%) \quad (1)$$

The incorporation of AMC to the antenna successfully widens the bandwidth of the antenna which initially operated at narrowband of 2.3 GHz. Figure 13(a) and Figure 13(b) show the radiation pattern at the lower band while higher band radiation pattern were shown in subsequent of Figure 13(c) and Figure 13(d). At 2.3 GHz, The AAMC exhibits a simulated maximum gain of 6.67 dBi in the direction of -3$^o$ with a HPBW of 85.10$^o$. Additionally, for 2.45 GHz, it is observed that the AAMC shows a maximum gain of 6.70 dBi in the direction of 0$^o$ with a HPBW of 82.50$^o$. It is observed that all the measured radiation patterns satisfactorily agreed with the simulated results.

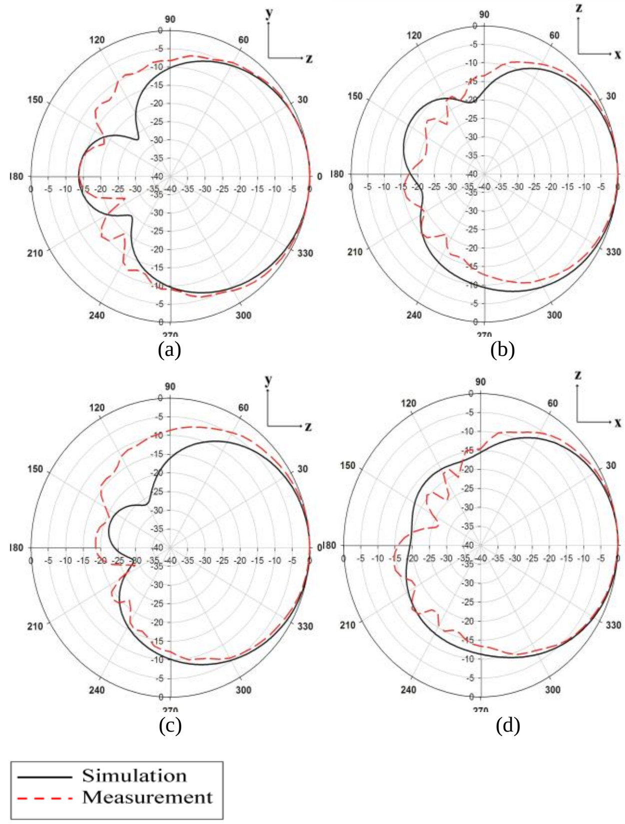



**Figure 13** The radiation patterns of (a) E-field and (b) H-field at 2.3 GHz while (c) E-field and (d) H-field of radiation patterns at 2.45 GHz

Table 2 shows the parameter performance comparison of the standalone antenna and AAMC. The integration of AMC as an AMC ground plane to the antenna, reducing the HPBW of the standalone antenna by 7$^o$. Subsequently, the directivity of the antenna of the AAMC was increased by 0.6 dBi. It is observed that, the efficiency and gain of typically low microstrip antenna were increase up 30% and 2.1 dBi, respectively. The measured gain of AAMC was in good agreement with the simulated ones.

**Table 2** Antenna parameter of performance

| **Parameter** | **Standalone Antenna** | **AAMC** |
|---|---|---|
| Area of Radiating Patch ($cm^2$) | 11.52 | 11.12 |
| Percentage bandwidth (%) | 2.16 | 14.50 |
| Simulated Gain (dBi) | 4.59 | 6.67 |
| Measured gain (dBi) | - | 6.24 |
| Simulated directivity (dBi) | 6.61 | 7.20 |
| Efficiency (%) | 58.17 | 87.74 |

## 6.0 CONCLUSION

Patch antennas with artificial magnetic conductor ground plane is proposed in this paper. Performance comparison has been made between the standalone antenna which uses a conventional ground plane and an AAMC. It is discovered that the integration of AMC in to the antenna successfully enhanced the bandwidth by 520% and increase the gain up to 2 dBi. It is also observed that the efficiency increases up to 30% as well as improves the directivity of the antenna. The AAMC ground plane covers bandwidth from 2.19 GHz to 2.50 GHz band suitable for WLAN, WiMAX and RFID applications; which is in contrast with the standalone antenna which only operates at 2.3 GHz band.

## References


[1] Kumar, A., and D. Kumar V. 2013. High-performance Metamaterial Patch Antenna. *Microwave and Optical Technology Letters.* 55: 409–413.

[2] Wenquan, Cao, Bangning Zhang, Aijun Liu, Tongbon Yu, Daosheng Guo, and Yi Wei. 2012. Gain Enhancement for Broadband Periodic Endfire Antenna by Using Split-Ring Resonator Structures. *IEEE Transactions on Antennas and Propagation.* 60: 3513–3516.

[3] Steven Yang, S.-L. 2008. The Forbidden Bandgap Characteristic of EBG Structures. *Microwave and Optical Technology Letters.* 50: 2965–2967.

[4] Khaleel, H. R., Al-Rizzo, M. Hussain, and Rucker, G. Daniel. 2012. On the Bending Effects on Artificial Magnetic Conductors. *Microwave and Optical Technology Letters.* 54: 2503–2505.

[5] Tao, H., Padilla, J. Willie, Xin Zhang, R.D. Averitt. 2011. Recent Progress in Electromagnetic Metamaterial Devices for Terahertz Applications. *IEEE Journal of Selected Topics in Quantum Electronics.*17: 92–101.

[6] Boney, M., S. K. A. Rahim, R. Dewan, and B. M. Saad. 2014. Dual band Trapezoidal antenna with Partial Ground and Meander line feed for GPS and WiMAX applications. *Microwave and Optical Technology Letters.* 56: 497–502.

[7] Emadian, S. R., C. Ghobadi, J. Nourinia, M.H. Mirmozafari, and J. Pourahmadazar. 2012. Bandwidth Enhancement of CPW-Fed Circle-Like Slot Antenna With Dual Band-Notched Characteristic. *IEEE Antennas and Wireless Propagation Letters.* 11: 543–546.

[8] Dewan, R., S. K. A. Rahim, S. F. Ausordin, H. U. Iddi, and M. Z. A. A. Aziz. 2011. X-Polarization Array Antenna with Parallel Feeding for WiMAX 3.55 GHz Application. *IEEE RF and Microwave Conference.* 368–372.

[9] A. Foroozesh and L. Shafai. 2008. Application of Combined Electric- and Magnetic-conductor Ground Planes for Antenna Performance Enhancement. *Electrical and Computer Engineering, Canadian Journal of.* 33: 87–98.

[10] Bo, L., Wang Xinho, Zheng Chuan, Jiangtao Huangfu, Li Changzhi, and Lixin Ran. 2012. Radiation Enhancement for Standard Patch Antennas Using a Loosely Grooved Ground Plane. *IEEE Antennas and Wireless Propagation Letters.* 11: 604–607.

[11] De Cos, M. E., Y. Alvarez, and Las-Heras. 2011. Enhancing Patch Antenna Bandwidth by Means of Uniplanar EBG-AMC. *Microwave and Optical Technology Letters.* 53: 1372–1377.

[12] Yim, T. L., S. K. A. Rahim, and R. Dewan. 2012. Reconfigurable Wideband and Narrowband Tapered Slot Vivaldi Antenna with Ring Slot Pairs. *Journal of Electromagnetic Waves and Applications.* 27: 276–287.

[13] Dewan, R., S. K. A. Rahim, S. F. Ausordin, and H. U. Iddi. 2012. Improved Design of Tapering and Through Element Series Antenna. *IEEE Symposium on Wireless Technology and Applications (ISWTA).* 202–205.

[14] Zhuo, Y., L. Yan, X. Zhao, and K. Huang.2011. A Compact Dual-band Patch Antenna for Wlan Applications. *Progress In Electromagnetics Research Letters.* 26: 153–160.

[15] Li, X., X. Ren, Y. Yin, L. Chen, and Z. Wang. 2013. A Wideband Twin-diamond-shaped Circularly Polarized Patch Antenna with Gap-coupled Feed. *Progress in Electromagnetics Research.* 139: 15–24.

[16] Deng, Z., W. Jiang, S. Gong, Y. Xu, and Y. Zhang. 2013. A New Method for Broadening Bandwidths of Circular Polarized Microstrip Antennas by using DGS & Parasitic Split-ring Resonators. *Progress in Electromagnetics Research.* 136: 739–751.

[17] Krishna, D. D., M. Gopikrishna, C. K. Aanandan, P. Mohanan, and K. Vasudevan. 2008. Compact Dual Band Slot Loaded Circular Microstrip Antenna with A Superstrate. *Progress in Electromagnetics Research.* 83: 245–255.

[18] Hadarig, R. C., M. E. De Cos, and F. Las-heras. 2012. Microstrip patch Antenna Bandwidth Enhancement using AMC/EBG Structures. *International Journal of Antennas and Propagation.* 2012: 2012.

[19] Foroozesh A. and L. Shafai. 2011. Investigation Into the Application of Artificial Magnetic Conductors to Bandwidth Broadening, Gain Enhancement and Beam Shaping of Low Profile and Conventional Monopole Antennas. *IEEE Transactions on Antennas and Propagation.* 59: 4–20.

[20] Wei, K. P., Z. J. Zhang and Z. H. Feng. 2012. Design of a Dualband Omnidirectional Planar Microstrip Antenna Array. *Progress in Electromagnetics Research.* 126: 101–120.

[21] Dewan, R., S. K. A. Rahim, S. F. Ausordin, H. U. Iddi. 2012. Design of Triple Band Artificial Magnetic Conductor. *IEEE Asia-Pacific Conference on Applied Electromagnetics*. 253–256.

[22] Dewan, R., S. K. B. A. Rahim, S. F. Ausordin and T. Purnamirza. 2013. The Improvement of Array Antenna Performance with the Implementation of an Artificial Magnetic Conductor (AMC) Ground Plane and In-Phase Superstrate. *Progress in Electromagnetics Research.* 140: 147–167.