Investigation of Circular Patch Metasurface (MS) on Inverted Suspended Circular Polarized Antenna

H. A. Bakar, M. Z. A. Abd. Aziz, B. H. Ahmad and N. Hassan
Center for Telecommunication Research and Innovation (CeTRI), Faculty of Electronics and Computer Engineering (FKEKK), Universiti Teknikal Malaysia Melaka (UTeM), 76100 Durian Tunggal, Melaka, Malaysia

E-mail: hamizan421@yahoo.com

Abstract. In this paper, an analysis of different stage of circle patch metasurface (MS) on basic structure of inverted suspended circular patch with square slot antenna design is proposed to investigate its effect toward the basic antenna performance. The basic antenna was designed based on inverted suspended circular patch with air gap separation between the patch substrate and copper ground plane at a distance of 10 mm (Basic design). Then, different design of MS structure (Design A, B, C & D) consisting of 5 x 5 unit cell of homogeneous periodic element is place in between the air gap of the basic antenna. All of MS design is located at a fixed position to study the effect of different MS shape to the Basic antenna performance. The proposed antenna and MS structure had been designed and simulated by using Computer Simulation Technology (CST) Software. Target application for this antenna design is for Wireless Local Area Network (WLAN) at operating frequency of 2.4 GHz. Simulation performances in term of return loss, resonant frequency, bandwidth, realized gain, directivity, axial ratio, total efficiency and radiation pattern at the design frequency are investigated and discussed. From observation on simulation result, resonant frequency of Basic design is shifting to a lower frequency from 2.4 GHz to 2.19 GHz (Design C and D) with the integration of the MS structure. Design C obtained the widest axial ratio bandwidth among all of other design with 1380 MHz covered from 1.31 GHz to 2.69 GHz. Directivity for Basic designs at 2.4 GHz increases from 7.94 dBi to 8.17 dBi, 8.16 dBi, 8.15 dBi and 8.06 dBi (Design A, B, C and D) respectively.

1. Introduction
Antenna is one of the most important equipment in a wireless communication system which enables the transmission and reception of signals through air as medium. Nowadays, with the great requirement for compact wireless devices, a small effective antenna with common structures continues to be a subject of great attraction [1-3]. Other than that, antenna with circularly polarized (CP) [4-6] also get more attention because they offer flexibility in the orientation angle between the transmitter and receiver. In recent year, a lot of efforts have been made by researchers to study and modified simple antenna design to be integrated with MS structure in order to represent as circular polarization antenna [7,8], compact [9,10] the structure and miniaturize [11,12] the size of planar antenna for wireless communication system application. Metasurface (MS) is a 2-D planar equivalent of metamaterial structure and has receiving researchers interest in the last few years for planar antenna performance enhancement such as wide bandwidth and high gain [13-17]. Other than that, as in
[18,19] it demonstrate that the performances of patch antenna can be enhanced simultaneously by the addition of MS at the top of the antenna design.

In this work, it is proposed to use different stage of circle patch unit cell of MS to study the effect of MS structure on Basic antenna behaviour in term of return loss, resonant frequency, bandwidth, return loss bandwidth (RLBW), realized gain, directivity, axial ratio, axial ratio bandwidth (ARBW), total efficiency and radiation pattern. A Basic design of inverted suspended circular patch with square slot (Basic) is proposed to be integrated with the MS structure. All of MS design consist 5 x 5 unit cell of homogeneous periodic element. Design A consist of unit cell of one circle patch, Design B and C consist two combination of circle patch and Design D consist of three combination of circle patch. The configuration of Basic design and design with integration of MS structure is demonstrated as in Figures 1.

**2. Antenna Design**

In this paper, the basic antenna and the MS structure was designed by using FR4 substrate with thickness, $h = 1.6 \text{ mm}$, dielectric constant, $\varepsilon_r$ of the substrate $= 4.4$, tangent loss and $\tan \delta = 0.019$. Thickness of copper, $t = 0.035 \text{ mm}$ is used for the ground plane and as the conductive material printed antenna and MS. The basic circular polarized antenna is an inverted suspended circular patch with square slot as shown in Figure 1 (a). Where the antenna feedline and circular patch with square slot are printed at the bottom sided (back) of the antenna substrate as shown in Figure 1 (c) without any copper patch at other sided (front) of the substrate as shown in Figure 1 (b). The inverted suspended circular patch antenna and its ground are separated by 10 mm air gap as illustrated in Figure 1 (a) side view. The feedline was fed by using 50 Ohm SMA coaxial probe connector thus represent as an inverted suspended L-probe technique for the antenna input port.

Figure 1 (d) side view shows the configuration of basic antenna with the integration of MS in between the antenna air gap. From the perspective view illustrated three different layer of the antenna design where layer 1 consisting of inverted suspended circular patch with square slot and feedline, layer 2 consisting of inverted 5 x 5 unit cell of different MS structure design (Design A, B, C & D) and layer 3 consisting of copper ground plane. The width and length of layer 1, layer 2 and layer 3 is equal that is 80 x 80 mm respectively. The MS position of Design A, B, C and D is fixed as shown in side view of Figure 1 (d) where Air gap 1 = 3 mm and Air gap 2 = 5.4 mm. All of MS design has the same gap (g) that separating the unit cell element of MS between each other centre with 16 mm distance as shown in Figure 1 (e), (f), (g) and (h). The radius (r) of all circle patch MS design is the same that is 5 mm respectively as shown in Figure 1 (i), (j), (k) and (l).
The MS is designed as inverted facing toward copper ground plane where the 5 x 5 element unit cell is printed only at the bottom (back) of a single-sided substrate. All of MS design consists of x 5 homogeneous pattern of circle patch MS where each of the unit cells are printed periodically along the x-axis and y-axis. Unit cell of Design A MS has only one circle patch while Design B and Design C has 2 combination of unit circle Design A that periodically in horizontal and vertical position as can be seen in Figure 1 (j) and (k). Design D MS is a combination of 3 unit circle of Design A MS with respect to the radius of circle patch as in Figure 1 (l). The optimize dimension of basic antenna at the frequency of 2.4 GHz and basic antenna with integration of MS are tabulated as in Table 1.
### Table 1. Optimize dimension of Basic antenna with and without MS

| Design Parameter | Dimension (mm) | Description                        |
|------------------|----------------|------------------------------------|
| Air gap          | 10             | Air gap basic antenna              |
| Air gap 1        | 3              | Air gap MS                         |
| Air gap 2        | 5.4            | Air gap MS                         |
| \(h\)            | 1.6            | Thickness of substrate             |
| \(t\)            | 0.035          | Thickness of copper                |
| \(L_s\)          | 80             | Length of substrate                |
| \(L_f\)          | 13             | Length of feedline                 |
| \(W_s\)          | 80             | Width of substrate                 |
| \(W_f\)          | 3.1            | Width of feed                       |
| \(R\)            | 25             | Radius of basic antenna circle patch |
| \(r\)            | 5              | Radius of metasurface circle patch |
| \(g\)            | 16             | Gap between metasurface            |

### 3. Result and discussion

In this section, simulation antenna parameter which comprised of return loss (RL), resonant frequency \((f_r)\), bandwidth (BW), return loss bandwidth (RLBW), realized gain, total efficiency, directivity, axial ratio, axial ratio bandwidth (ARBW) and radiation pattern are analysed and discussed at 2.4 GHz frequency. The antenna performance results of Basic design, Design A, Design B, Design C and Design D from frequency range of 1.2 GHz to 3.5 GHz are compared and demonstrated as in Figure 2 (a) and (b), 3 (a) and (b) and 4. The comparison antenna parameters at 2.4 GHz of all design are tabulated as in Table 2.

#### 3.1. Return loss (RL), Resonant frequency \((f_r)\), bandwidth (BW) and Realized gain

The comparison of simulation S11 and realized gain for Basic design, Design A, B, C and D are illustrated as in Figure 2 (a) and (b). Based on Figure 2 (a), the resonant frequency of Basic design is at 2.398 GHz with -35.64 dB. With the addition of MS, resonant frequency clearly can be observed shifted to a lower frequency at 2.26 GHz (Design A), 2.24 GHz (Design B) and 2.19 GHz (Design C & D). Design A has the most lower resonant frequency with return loss of -39.80 dB compared with other antenna design, while Design D has only -23.16 dB at its resonant frequency. The bandwidth of Basic design is 556 MHz covering from 2.21 GHz to 2.76 GHz. With the addition of MS structure Design A, B, C and D, the bandwidth decreases to 424 MHz, 340 MHz, 334 MHz and 324 MHz respectively.

According to Figure 2 (b), the realized gain of Basic design, Design A, B, C and D at 2.4 GHz are 7.76 dB, 7.74 dB, 7.54 dB, 7.35 dB and 7.15 dB respectively. Even though the resonant frequency are shifting with the addition of MS, the gain of all MS design still more than 7 dB at 2.4 GHz. Maximum gain of Basic design is at 2.5 GHz with 7.96 dB, while maximum gain with the addition of all MS design are at the same frequency which is at 2.3 GHz. All of gain results at 2.3 GHz for MS design are more than 7.7 dB. For a comparison of gain for MS design at 2.3 GHz, Design B has the highest gain with 7.87 dB.
3.2. Total efficiency and directivity

Figure 3 (a) and (b) illustrated the simulation view of the comparison result of MS Design A, B, C and D with Basic antenna design for total efficiency and directivity versus frequency. Based on Figure 3 (a), maximum total efficiency of Basic design is at 2.4 GHz frequency which achieved -0.18 dB. With addition of MS Design A, maximum efficiency is shifted to 2.3 GHz with -0.25 dB. Design B, C and D has the same maximum total efficiency frequency, which is shifted 100 MHz from Design A maximum efficiency at 2.2 GHz with -0.26 dB, -0.23 dB and -0.24 dB respectively. Total efficiency above 50 % of Basic design covering frequency range of 2 GHz to 3.3 GHz. While, total efficiency above -3 dB with addition of MS design ranging around 1.85 GHz to 2.98 GHz respectively. Total efficiency of all design at 2.4 GHz is less than -1 dB.

Figure 2. Comparison simulation result of Basic design, Design A, Design B, Design C and Design D
(a) return loss (b) realized gain
According to Figure 3 (b), the simulation result of directivity for Basic designs at 2.4 GHz increases from 7.94 dBi to 8.17 dBi, 8.16 dBi, 8.15 dBi and 8.06 dBi (Design A, B, C and D). With the addition of MS, maximum directivity of Basic design shift from 2.5 GHz (8.19 dBi) to 2.4 GHz (Design A and B) and 2.3 GHz (Design C and D). The maximum directivity for Design C and D are 8.26 dBi and 8.29 dBi respectively. For a comparison of maximum directivity of all design, Design D obtained the highest directivity. From observation, even though using different MS designs, the performance result between each MS design is quite similar in term of realized gain, total efficiency and directivity.

![Figure 3](image)

**Figure 3.** Comparison simulation result of Basic design, Design A, Design B, Design C and Design D  
(a) total efficiency (b) directivity

### 3.3. Axial ratio, Axial ratio Bandwidth (ARBW)

As demonstrated in Figure 4 is the simulation of axial ratio for Basic design and design with the addition of all different MS structure. Based on Figure 4, the minimum axial ratio for Basic design is at 2.1 GHz with 0.07 dB. While at 2.4 GHz, the axial ratio is 0.62 dB. With addition of all MS design, the axial ratio found to be more than 1 dB at 2.4 GHz. Where Design A has 3.13 dB (linear
polarization), Design B, C and D remain below 3 dB which is 2.94 dB, 1.98 dB and 2.29 dB respectively. Axial ratio bandwidth (ARBW) of Basic design is 1120 MHz which covered from frequency range of 1.37 GHz to 2.49 GHz. While Design A and Design B only covered from 1.29 GHz to 2.40 GHz with 1110 MHz and 1.31 GHz to 2.41 GHz with 1103 MHz. However, Design D covered frequency range of Design A and B which is from 1.29 GHz to 2.45 GHz respectively. In comparison of ARBW for all design, Design C and Design D obtained a wider ARBW. Where, Design C obtained the widest axial ratio bandwidth among all of other design with 1380 MHz covered from 1.31 GHz to 2.69 GHz.

Figure 4. Comparison axial ratio simulation result of Basic design, Design A, Design B, Design C and Design D

3.4. Radiation pattern
Comparison of simulated radiation pattern for phi = 0°, phi = 90° and theta = 90° of Basic design, Design A, B, C and D at 2.4 GHz frequency are demonstrated as in Figure 5. The shapes of radiation pattern of all design are quite similar to each other. As demonstrated in Figure 5, at phi = 0° and phi = 90°, the orientation of main lobe direction are toward 2° and 0°. While at theta = 90°, main lobe direction change toward 129° respectively. Phi = 0° have one back lobe, phi = 90° have two back lobe while theta = 90° has omnidirectional lobe of radiation pattern. From observation, Design D has the biggest lobe of radiation pattern and Basic design has the smallest lobe of radiation pattern in comparison with other design.
Figure 5. Comparison simulation result of radiation pattern for Basic design, Design A, Design B, Design C and Design D (a) $\phi = 0°$ (b) $\phi = 90°$ (c) $\theta = 90°$

The comparison simulation antenna parameter result of Basic design, Design A, Design B, Design C and Design D at 2.4 GHz are tabulated as in Table 2. Based on Table 2, the result of return loss (RL), realized gain, axial ratio (AR), total efficiency and directivity are demonstrated.

| Antenna parameter | Basic | Design A | Design B | Design C | Design D |
|-------------------|-------|----------|----------|----------|----------|
| Return loss (dB)  | -35.64| -14.62   | -11.12   | -9.44    | -8.72    |
| Realized gain (dB)| 7.76  | 7.74     | 7.54     | 7.35     | 7.15     |
| Axial ratio (dB)  | 0.62  | 3.13     | 2.94     | 1.99     | 2.29     |
| Total efficiency (dB) | -0.18 | -0.44    | -0.63    | -0.79    | -0.91    |
| Directivity (dBi) | 7.94  | 8.18     | 8.16     | 8.15     | 8.06     |

4. Conclusion
In this paper, using four different MS design (Design A, B, C & D) to investigate its effect on inverted suspended circular polarized antenna (Basic) has been proposed in this study. The MS which consisting of 5 x 5 unit cell is located in between the basic antenna air gap at a fixed position. Based on the results, it shown with the integration of MS, the basic antenna resonant frequency shifted to a lower frequency from 2.4 GHz to 2.19 GHz (using Design C and D). Other than that, antenna bandwidth and gain (at 2.4 GHz) also decreases gradually with the addition of MS Design A, B, C and D to basic antenna. Total efficiency of all design at 2.4 GHz is less than -1 dB. Directivity for Basic designs at 2.4 GHz increases from 7.94 dBi to 8.17 dBi, 8.16 dBi, 8.15 dBi and 8.06 dBi (Design A, B, C and D). Moreover, Design C obtained the widest axial ratio bandwidth among all of other design
with 1380 MHz covered from 1.31 GHz to 2.69 GHz. At 2.4 GHz, only Design A axial ratio is more than 3 dB which is 3.13 dB. Radiation pattern of all design at 2.4 GHz are quite similar. With the integration of MS structure to the basic antenna, size reduction can be achieved by reducing the radius of circular patch. In order to assemble as more compact and smaller sized antenna, for the next step that may be taken is miniaturizing the antenna substrate size while maintaining a similar antenna performance. Antenna with compact in size, large return loss bandwidth (RLBW) and axial ratio bandwidth (ARBW) and can operate as circular polarization can represent as a good candidate for compact and broadband circular polarization antenna for WLAN application at targeted frequency of 2.4 GHz.

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