Performance Enhancement of Inverted Suspended Circular Polarized Antenna with the Integration of Metasurfaces (MS) Structure Technique

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Abstract. In this paper, it is proposed to use metasurface (MS) structure for the miniaturization and antenna performance enhancement of inverted suspended circular patch with square slot. The antenna was designed based on inverted suspended circular patch with air gap between the patch substrate and copper ground plane is separated with distance of 10 mm (Design A). L-probe technique is used for the antenna design and by using Design A the MS structure is put at the top of the antenna with air gap separation of 1 mm (Design B). The proposed antenna 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 and measurement antenna 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. Based on the result, with the integration of MS, Design B antenna substrate size can be reduced by 23.45 %, yet maintaining the similar performance. Other than that, axial ratio bandwidth (ARBW) for Design B also increases up to 68.8 % from 58.4% (Design A) with impedance bandwidth 627 MHz which is 71 MHz wider than Design A.

1. Introduction
Nowadays, with the great requirement for compact wireless devices, a small effective antenna with common structures continues to be a subject of great attraction [1-4]. According to the characteristics of low profile and simple structure, planar antenna appears to be a great choice for numerous portable wireless devices. However, patch antenna restricted with narrow bandwidth, poor gain and antenna size is in general contrarily proportional to the frequency of operation. The size of radiator for patch antenna is generally 0.5 \( \lambda_o \times 0.4 \lambda_o \), whereas \( \lambda_o \) is the wavelength of the frequency operation [5]. Thus the size will be larger and not suitable to fit to a small wireless device.

In recent year, a lot of efforts have been made by researchers to compact [6,7] the structure and miniaturize [8,9] the size of planar antenna using metasurface structure 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 [10-18]. Other than that, as in [19,20] 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 MS to miniaturize and enhanced antenna performance in term of return loss bandwidth (RLBW) and axial ratio bandwidth (ARBW). A simple design of inverted suspended circular patch with square slot (Design A) is proposed to be integrated with the MS structure. Design A is designed as circular polarization with operated frequency at 2.4 GHz which is for WLAN application. Design B antenna was designed to have a similar design as Design A (antenna without MS) for a comparison purpose. The Design B antenna consists of 8 x 5 pine tree look like MS which is placed on top of the inverted circular patch with 1 mm separation of air gap. With the integration of MS, the patch antenna substrate size can be reduced which is up to 23.45 % of size reduction, yet maintaining quite similar performances in term of axial ratio, realized gain, total efficiency and directivity.

2. Antenna design
The antenna and the MS structure was designed by using FR4 substrate with thickness, h = 1.6 mm, dielectric constant, \( \varepsilon_r \) of the substrate = 4.4, tangent loss and \( \tan \delta = 0.019 \). Thickness of copper, t = 0.035 mm is used for the ground plane and as the conductive material printed antenna. The basic circular polarized antenna (Design A) is an inverted suspended circular patch with square slot where both feedline and circular patch are printed at the bottom sided of the antenna substrate without any copper patch at other sided of the substrate. The inverted suspended circular patch antenna and its ground are separated by 10 mm air gap as illustrated in Figure 1 (a). The feedline was fed by using 50 Ohm SMA coaxial probe connector and represent as an L-probe technique for the antenna input port.

![Figure 1. Design A and B configuration and fabricated prototype (a) Design A vertical view (b) prototype Design A (c) prototype Design B (d) Design B vertical view (e) 8 x 5 pine tree metasurfaces top view (f) single unit MS design process view.](image-url)
The MS (Design B) is adding at the top of the antenna with separation of 1 mm air gap from the inverted suspended antenna substrate as in Figure 1 (d). The MS is designed on the front of a single-sided substrate. This MS consists of 8 x 5 homogeneous pattern of pine tree look like MS where each of the MS is separated by 8.7 mm gap between each other centre as demonstrated in Figure 1 (e). Each of the unit cells are printed periodically along the x-axis and y-axis with having a width of \( N \) and length of \( M \). The width (\( W_s \)) and length (\( L_s \)) of substrate for the inverted suspended antenna, copper ground plane and proposed MS substrate are all equal which is 80 x 80 mm for Design A and 70 x 70 mm for Design B. The design is illustrated as in Figure 1. Optimization on the dimension of the design has been made in order to get the best performance result for both antenna designs. Both antennas are designed to operate at the frequency of 2.4 GHz. The optimize dimension for Design A and Design B antenna are tabulated as in Table 1.

### Table 1. Optimize dimension of design A and B.

| Design Parameter | Dimension (mm) | Description            |
|------------------|----------------|------------------------|
| Air gap 1        | 10             | Air gap                |
| Air gap 2        | 1              | Air gap                |
| \( h \)          | 1.6            | Thickness of substrate |
| \( t \)          | 0.035          | Thickness of copper    |
| \( R_1 \)        | 25             | Design A Circle patch radius |
| \( R_2 \)        | 18             | Design B circle patch radius |
| \( L_{s1} \)     | 80             | Length of substrate    |
| \( L_{s2} \)     | 70             | Length of MS substrate |
| \( L_{f1} \)     | 13             | Length of feedline     |
| \( L_{f2} \)     | 12             | Length of MS feedline  |
| \( W_{s1} \)     | 80             | Width of substrate     |
| \( W_{s2} \)     | 70             | Width of MS substrate  |
| \( W_f \)        | 3.1            | Width of feed          |
| \( M \)          | 13             | Length of metasurface  |
| \( N \)          | 8.7            | Width of metasurface   |
| \( P \)          | 1.75           | Width of rectangular slot |
| \( \text{GapMS} \) | 8.7          | Gap between metasurface |

### 3. Result and discussion

In this section, simulation and measurement 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 for Design A and Design B are compared and demonstrated as in Figure 2, 3, 4, 5, 6 and tabulated as in Table 2.

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

The comparison of simulation and measurement result for Design A and Design B are shown as in Figure 2. At 2.4 GHz frequency, the simulation return loss for Design A is -35.64 dB while its measurement result reduced to -20.28 dB. While for Design B, the simulation result is -31.94 dB and it is clearly observe that the measurement result shifted to a higher frequency resulting -11.78 dB return loss at 2.4 GHz. Simulation and measurement resonant frequency for Design A is at 2.398 GHz and
2.42 GHz with return loss -35.77 dB and -21.47 dB respectively. For Design B, the simulation resonant frequency is at 2.41 GHz with -32.11 dB. However the measurement result is shifted to a higher frequency at 2.56 GHz with -31.54 dB. According to Figure 2, it clearly shows that both measurement bandwidth for Design A and Design B is smaller compared to its simulation bandwidth. From observation, simulation of Design B bandwidth is the largest following by Design A. The simulation bandwidth for Design A is 556 MHz from frequency range of 2.21 GHz to 2.77 GHz. While its measurement bandwidth covering in between the frequency ranges of simulation which is from 2.28 GHz to 2.65 GHz with 362 MHz respectively. For a comparison, Design B has 71 MHz wider simulation bandwidth than Design A which ranging from 2.11 GHz to 2.74 GHz. However, the measurement bandwidth for Design B only 386 MHz covered 2.37 GHz to 2.76 GHz frequency.

![Figure 2. Comparison result of simulation and measurement return loss for Design A and B](image)

3.2. Total efficiency and directivity

Figure 3 and Figure 4 are illustrated the simulation view of the comparison Design A and Design B antenna design for total efficiency and directivity versus frequency. The total efficiency and directivity for both design show good response at 2.4 GHz frequency. Based on Figure 3, maximum total efficiency for both designs is at 2.4 GHz frequency which achieved above -0.5 dB. Design A maximum efficiency is -0.18 dB and the total efficiency covering above 50% ranging from 2 GHz to 3.3 GHz and 3.9 GHz to 4.34 GHz. While Design B maximum efficiency is -0.23 dB with total efficiency above 50 % ranging from 1.89 GHz to 3.18 GHz and 3.54 GHz to 3.93 GHz respectively. According to Figure 4, the maximum directivity for both designs is at 2.5 GHz. The maximum directivity for Design A is 8.18 dBi while at 2.4 GHz the directivity is 7.94 dBi. Directivity for Design B at 2.4 GHz slightly decreases to 7.59 dBi with its maximum directivity is 7.73 dBi respectively. For a comparison of Design A and Design B, directivity for Design B at 2.4 GHz slightly dropped around 0.35 dBi. However, both antennas obtained more than 7 dBi directivity at that frequency and maintaining quite similar performance result.
3.3. Axial ratio
Figure 5 illustrated the simulation axial ratio for Design A and Design B. Based on Figure 5, the minimum axial ratio for Design A is at 2.1 GHz with 0.07 dB. While at 2.4 GHz, the axial ratio is 0.62 dB. Design B has a minimum axial ratio at 1.7 GHz frequency with 0.29 dB and 0.58 dB at 2.4 GHz respectively. Axial ratio bandwidth (ARBW) for Design A is 1127 MHz which covered from frequency range of 1.37 GHz to 2.50 GHz. While Design B covered from 1.44 GHz to 2.95 GHz with 1511 MHz ARBW. In comparison of ARBW for both design, Design B obtained a wider ARBW by 384 MHz. However, both design obtained axial ratio below than 1 dB at 2.4 GHz. It was indicated that both design can represent as a good circular polarization antenna at that frequency.

Figure 3. Comparison of simulation total efficiency for Design A and B.

Figure 4. Comparison of simulation directivity for Design A and B.
3.4. Radiation pattern
The radiation pattern of the antenna is measured in far field region at 2.4 GHz frequency for phi = 0°, phi = 90° and theta = 90°. Comparison of simulated and measured radiation pattern for Design A and Design B at 2.4 GHz frequency are demonstrated as in Figure 6.

Figure 5. Comparison of simulation axial ratio for Design A and B.

Figure 6. Comparison of simulation and measured radiation pattern for Design A (a) phi = 0° (b) phi = 90° (c) theta = 90° and Design B (c) phi = 0° (d) phi = 90° (f) theta = 90°.
The simulation and measurement result for Design A and Design B 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. The realized gain of Design A and Design B are quite similar which are 7.76 dB and 7.36 dB. However, the calculated realized gain based on data taken from measurement in far field result a decrease in gain performance to 5.32 dB and 3.47 dB.

Table 2. Comparison of simulation and measurement result performance for Design A and Design B at 2.4 GHz.

| Antenna parameter | Design A (80 x 80 mm) | Design B (70 x 70 mm) |
|-------------------|-----------------------|-----------------------|
|                   | Sim. | Meas. | Sim. | Meas. |
| Return loss       | -35.64 | -20.28 | -31.94 | -11.78 |
| Realized gain     | 7.76  | 5.32  | 7.36  | 3.47  |
| Axial ratio       | 0.62  | -     | 0.58  | -     |
| Total efficiency  | -0.18 | -     | -0.23 | -     |
| Directivity       | 7.94  | -     | 7.59  | -     |

4. Conclusion
In this paper, using MS to miniaturize the size of inverted suspended circular patch antenna (Design A) and widen the impedance bandwidth and axial ratio bandwidth of the antenna has been proposed in this study. The MS (Design B) which consisting of 8 x 5 pine tree look like element is put atop of the Design A antenna with 1 mm air gap separation. Based on the results, it shown with the integration of MS, the inverted circular patch antenna substrate size can be reduced which is up to 23.45 % of size reduction from 80 x 80 mm to 70 x 70 mm. Other than that, Design B also have a wider antenna bandwidth up to 627 MHz compared to Design A which is 556 MHz, yet maintaining a quite similar performances in terms of realized gain, axial ratio, total efficiency and directivity at the same operating frequency of 2.4 GHz. Moreover, the axial ratio bandwidth (ARBW) for Design B also increases up to 68.8 % from 58.4% (Design A). Overall, with the integration of MS structure, the antenna (Design B) performance was enhanced simultaneously. The Design B antenna can represent as a good candidate for broadband circular polarization antenna for WLAN application at 2.4 GHz frequency.

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