Gain Enhancement of CPW Antenna for IoT Applications using FSS with Miniaturize Unit Cell

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Abstract. Wireless connectivity is a critical enabler for many IoT applications. Antennas are often required to be installed inside the device cover, which usually occurs in small sizes with optimal performance. On the other hand, a suitable antenna should also have high efficiency, gain and adequate bandwidth covering the desired frequency range. Here, we proposed new type of Frequency Selective Surface (FSS) with miniaturized resonator element to enhance the gain of an CPW antenna. Furthermore, the miniaturization of the Frequency Selective Surface unit cell is attained by coupling the two meandered wire resonators. The wire resonator is separated by thin and single substrate layer. The structure of the FSS is shown to have a FSS unit cell dimension that is miniaturized to 0.057λ. The CPW antenna size is only 28.8mm x 46.5mm operating at 2.45 GHz frequency. With the additional of the FSS, the antenna’s gain reaches up from 1.8 dBi to 2.6 dBi with omnidirectional radiation pattern.

Keywords: Ultra-wideband (UWB), monopole antenna, slot antenna, IoT, Co-Planar Waveguide (CPW).

1. Introduction

The Internet of Things (IoT) refers to devices that are linked to the internet, gathering, and distributing data all over the world. One of the important devices for IoT application is the antenna. For many IoT applications, wireless connectivity is a critical especially those that need to be portable and mobile, or in a place where the cabled data communication is not cost-effective or practicable. In this situation selecting and integrating a suitable antenna is important where it is dose has a significant impact on the RF system and will affect the system performance such as power consumption, battery life, bandwidth, and communication range.

A lot of techniques have been proposed by the researcher in order to increase the antenna bandwidth. One of them is by combining two different type of antenna [1-2]. By combining the different type of the
antenna, high gain as well as bandwidth can be obtained with more complex geometrical in structure and design. Recently, there is another method that has been use to enhance the bandwidth by using four pairs of parasitic strips and four dipole antenna elements [3]. The antenna produces high bandwidth and small in size. However, the gain of the antenna is low hence it is not suitable for IoT application. In contrast, the dipole antenna presented in [4-6] produces high gain although, the structures are complicated and big.

Currently, FSS has wide applications, which can be applied to stealth technology such as sub-reflector of the Cassegrain Antenna to achieve beam multiplexing and separation [6-7]. It can also be applied to the radar radome and reducing the radar cross section. Current studies have shown many type of multi-layer Frequency Selective Surface designs especially for Ultra-Wideband applications [8-10]. In [11], a double Frequency Selective Surface layer has shown a maximum gain of 8.7 dBi and gain enhancement by 2–4.5 dBi in the antenna bandwidth of 3–14.64 GHz. The design presented in [11] is big while it is not stable in the gain variation through the Ultra-Wideband band. Earlier studies presented multilayer FSS in [12-14]. The multi-layer of the Frequency Selective Surface also deliver Ultra-Wideband response, nonetheless it is having restricted useful use in current communication devices due to their shape, expensive and intricacy.

Here, a CPW fed monopole antenna is presented. This antenna is for IoT communication application. The antenna is not just small but technique for improving the antenna realized gain is also studied. Specifics design of the antenna are introduced, deliberated and discussed.

2. Antenna design and development
Choosing an antenna topology for IoT design, many factors must be considered including physical profile, compatibility, gain, radiation pattern, radiation efficiency, impedance bandwidth and directivity. Specifically, for microwave wireless communications, various design considerations need to be considered especially designed for IoT Antenna systems. In this section, the proposed antenna for IoT is presented in detail. The novelty of this CPW antenna is achieved by using Frequency Selective Surface (FSS) with miniaturized resonator with gain enhancement. The size of the miniature FSS is 7.28mm operating as band stop at 2.45 GHz.

2.1. An equation for the antenna design
For the proposed antenna, patch antenna is choses as it is easy to fabricate. Their low-profile design allows the antennas to be mounted and print on the flat surfaces without a challenge. There are numerous shapes of patch antenna. The most common are rectangular shapes consisting of length, L and Width, W which will determine the size of a rectangle. In order to determine the length and width of the rectangular antenna design, dielectric substrate constant, $\varepsilon_r$ and thickness of the substrate, $h$ are need to be considered. Below is the formula that been used to calculate the parameter of the rectangular CPW fed monopole patch antenna. The initial design of the proposed antenna is based on the equation calculation. Though, in order to obtain a desired result, the optimization is required. The schematic in Figure 1 shows the proposed geometry of the CPW antenna for IoT application.

\[
W = \frac{c}{2f_0\sqrt{\frac{\varepsilon_r+1}{2}}}\]

\[
\varepsilon_{ff} = \frac{\varepsilon_r+1}{2} + \frac{\varepsilon_r-1}{2} \left[ \frac{1}{1+12\left(\frac{h}{w}\right)} \right] \]

\[
L = \frac{c}{2f_0\sqrt{\varepsilon_{ff}}} - 0.824h \left( \frac{\varepsilon_{ff}+0.3\left(\frac{w}{h}+0.264\right)}{\varepsilon_{ff}+0.258\left(\frac{w}{h}+0.8\right)} \right) \]

\[
L_g = 6h + L
\]

\[
W_g = 6h + L
\]
Table-I: CPW fed monopole antenna parameters

| Parameters | $W_s$  | $L_s$  | $W_p$  | $L_p$  | $W_{f1}$ | $W_{f2}$ |
|------------|--------|--------|--------|--------|----------|----------|
| Value (mm) | 28.8   | 46.5   | 26     | 14.4   | 0.28     | 1.3      |

| Parameters | $L_f$  | $G_1$  | $G_2$  | $G_3$  | $G_4$  | $G_5$  |
|------------|--------|--------|--------|--------|--------|--------|
| Value (mm) | 31.2   | 30.25  | 21.6   | 10.8   | 10.8   | 1.5    |

2.2. Antenna design development
Numerous perturbation techniques and design of planar monopole antennas has been used as guidelines in the proposed CPW fed monopole antenna design. Here, the rectangular geometry is chosen as initial geometry to form numerous originalities polygonal. Additionally, rectangular shape is variable to be altered.

To approximate the performance of the proposed antenna, the antenna is designed and simulated using the CST simulator. The effects of adjusting the antenna parameters are investigated to examine the size reduction and gain enhancement of the antenna. Parametric analysis for different parameter values has been carried out as well by varying one parameter and keeping all the other parameters at constant. The main PCB of the antenna is designed on FR4 substrate with permittivity 4.6. The measurement of the substrate is (46.5 x 28.8) mm has been chosen in this study. Initially, the design has a radiator with a rectangular shape with a width (w) of 26 mm and a length (l) of 14.4 mm. The main radiator is fed by 50Ω microstrip feed lines with dimensions of (0.28 x 1.3 x 31.2)mm. The feeding arrangement has additional functionality within the design, and act to generate a proper resonant mode for the 2.45 GHz band. The main objective in this antenna design is to create small antenna with a high gain. Table 1 tabulated the antenna dimension in detail.

Simulated return loss of the proposed antenna is shown in Figure 2. It is shows that the antenna operating from 2.2 GHz – 4.2 GHz. At 2.45 GHz, the antenna has the higher efficiency at 88%. The VSWR result also show a satisfactory result with all above 2.5. At 2.45 GHz, this antenna produces an omni directional radiation pattern with a gain value of 1.865 dBi.
Fig. 2. Simulation result for Co-Planar Waveguide monopole antenna.  
(a) Antenna S11 result, (b) Total efficiency, (c) VSWR value, (d) 3D Radiation Pattern, (e) Far Field cut at Theta=90, (f) Far Field cut at Theta=0.

3. Antenna development and configuration
The frequency response utterly depends on the size of the FSS as well as the the unit cell’s design. The proposed antenna is extended version of [15] which is a micro-wired FSS. The geometry of the Frequency Selective Surface is demonstrated in Figure 3(a). The proposed Frequency Selective Surface is designed on 2.2 dielectric constants of Rogers RT/duroid 5880 substrate with 0.127 mm thick and a loss tangent of 0.0009. The geometry of the low-profile micro-wire resonator, consisting of meandering
printed wires separated by a single substrate layer on the upper and lower of Rogers RT/duroid 5880 substrate. The overall unit cell size are 7.28 mm × 7.28 mm. Detail’s dimension of the proposed FSS can be observed in Figure 3(a).

The capacitance value increasing between the wire elements due to the small separation between the wire. This resulted in a lowering of the resonant frequency value. CST Microwave Studio is a simulator tools that been used in this experiment to perform mathematical evaluation of the micro-wire Frequency Selective Surface unit cell boundary condition as shown in Figure 3(b). The transmission coefficient of the proposed FSS shown in Figure 3(c) which showing a stop band center frequency of 2.45 GHz with -33dB transmission coefficient. The wire resonator antenna shows a superior reduction and miniaturize factor plus be able to generate resonance at 0.057λ.

Apart from S21, another importance criteria for the Frequency Selective Surfaces is the S11 or known as reflection phase. Especially if the FSS is combine with the antenna as gain enhancement in antenna application. To provide in-phase reflection to the antennas, the phase of the Frequency Selective Surface ought to linearly decrease [16]. Here, the Frequency Selective Surface achieves a linearly decreasing phase form 2.3 – 2.5 GHz as presented in Figure 3(d).

Figure 3: (a) Geometry of the proposed FSS in Unit Cell in millimeter(mm) , (b) Simulation of the wire Frequency Selective Surface in CST as periodic unit cell, (c) Simulated (S21) and (S11) results, (d) Simulated reflection phase (S11).
4. CPW antenna with micro-wired Frequency Selective Surface

To test the gain enhancement ability of the CPW Antenna, Frequency Selective Surface is placed at the back of the antenna. Figure 4(a) demonstrates the design of the CPW antenna with the Frequency Selective Surface design array. The Frequency Selective Surface is located underneath the antenna thus it acts as reflection radiations away from the antenna. An array of 18 elements ($3 \times 6$) is created by repetition of the unit cell along $x$-axis and $y$-axis as shown in Figure 4(b). As the frequency increases, the phase of the radiated wave antenna towards the frequency selective surface will increase as well. The reflected wave will be increased as the frequency selective surface is placed on the antenna plane due to the directivity and front-to-back ratio of the Ultra-Wideband antenna is increased. Hence, the phase of the reflected waves must then decrease with the increase in the frequency to ensure constructive interference at the antenna plane.

Shown in Figure 3(d) is the simulated reflection. It is showing reflection phase of the Frequency Selective Surface is linearly decreasing. Based on the result, the proposed Frequency Selective Surface is well paired to influence the phase of the reflected waves, therefore guaranteeing constructive interference at the antenna plane. Furthermore, the gap between the FSS and the antenna is another important factor for determining the condition of constructive interference. The gap it is estimated by calculation using the following equation [17]:

$$\varphi_{\text{FSS}} - 2\beta H = 2n\pi \quad n = \cdots -2, -1, 0, 1, \ldots \quad (6)$$

Where, $\varphi_{\text{FSS}}$ is the reflection phase introduced by the Frequency Selective Surface, $H$ is the height between the Frequency Selective Surface reflector and the antenna and $\beta$ is the propagation constant in free space. Once height, $H$ is set equal to $\lambda/2$. Lambda, $\lambda$ is the wavelength corresponding to the frequency at which the reflected phase $\varphi_{\text{FSS}}$ is zero, then both sides of Eq. (1) become equal. The reflection phase of the FSS crosses zero at 2.45 GHz. Thus, to satisfy Eq. (1), the value of $H$ is calculated to be 60 mm ($\lambda/2$).

![Fig.4. (a) Front view of the CPW antenna, (b) FSS is placed at the back of the CPW Antenna, (c) 3D Radiation Pattern of the CPW antenna with FSS](image-url)
As can be seen in Figure 4(c), the highest gain of CPW antenna with Frequency Selective Surface (in free space), is increased from 1.8 dBi to 2.3. The antenna’s gain is improved 0.5 dBi subsequently when the Frequency Selective Surface is placed beneath the antenna. Furthermore, the antenna gain value increase to 0.8 dBi when the number of FSS’s array is increased as shown in Figure 5(a). Maximum gain improvement occurs around 2.45 GHz, where Frequency Selective Surface improves antenna gain by 0.8 dBi. The peak gain of 2.8 dBi for the antenna composite is achieved at 2.45 GHz with the increment number of the FSS. This is proved that by using the Frequency Selective Surface it is helps to improve the antenna’s gain. Figure 5(b) shows the simulated radiation patterns of the CPW antenna with Frequency Selective Surface at 2.45 GHz. The antenna has omnidirectional pattern in x plane (H-plane) and in y plane (E-plane). It is clearly shows that the radiation patterns become more directional for the Frequency Selective Surface backed CPW antenna.

Fig. 5. (a) CPW antenna with 9 x 9 FSS’s array, (b) 3D Radiation Patter of the CPW antenna with 9 x 9 FSS’s array.

5. Conclusion
The Co-Planar Waveguide (CPW) fed slot antenna with micro-wired Frequency Selective Surface was designed for wireless applications and IoT application. In this paper, A novel Frequency Selective Surface reflector with compact structure is presented. Electrical dimensions of the unit cell are only 0.057 λ × 0.057 λ and corresponding to the operating frequency of 2.45 GHz. This Frequency Selective Surface achieves stopband of 2.45 GHz with an improvement of the antenna gain by using single dielectric layer of the Frequency Selective Surface. The gain improvement ability of the Frequency Selective Surface is demonstrated with an improvement from 1.8 dBi to 2.6 dBi. Furthermore, the Frequency Selective Surface been reported to have a stable incident angle up to 60 degrees [15]. Hence, the antenna with Frequency Selective Surface is suitable for IoT application as well as for ground penetrating radar, wireless communication and medical imagining.

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