Performance improvement of a slotted square patch antenna using FSS superstrate for wireless application

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Abstract. This paper presents a wideband planar antenna integrated with a frequency selective surface (FSS). Initially, the FSS array screen is investigated using a basic square ring to construct a unit cell of the FSS periodical structure with a (12x12) array. FR4 with a permittivity of 4.7 and a thickness of 1.6 mm is used as the substrate material for both FSS structure and antenna. Then, the antenna is placed closely parallel over the FSS configuration at a distance of 28 mm. After analyzing the performance of the antenna in terms of return loss, directivity and antenna gain, the design is integrated with the FSS structure in order to achieve a stable frequency response. Directivity and gain improvement of 6.5 dB and 5.1 dB respectively are observed along broadside direction.

1. Introduction
Frequency selective surfaces (FSS) are resonant structures having either low-pass, band-pass, band-stop and high-pass performance depending on shapes [1]. Due to its unique electromagnetic properties, they are used as radomes, spatial band stop or bandpass filters, electromagnetic absorbers, and shielding structures for wireless signal [2]-[4]. They are also used to form cavity antenna to improve the gain, bandwidth, directivity, front to back ratio and also beam switching control [5]-[8].

Transmission/reflective property of these materials can be used to improve the performance of conventional antennas. Applying FSS structures as a superstrate to modify the performance of planar antenna become a trend nowadays and have been investigated by many authors [9]-[12]. In [9] a reflective surface having square metallic patches on a superstrate is proposed where the gain is improved up to 12.5 dB at the resonant frequency. To improve the radiation efficiency, a CPW-fed antenna is integrated with FSS surface reflector in [10], but no remarkable improvement in gain is obtained. In [11], double layers AMC configuration based on square split ring resonator unit cells was proposed. The proposed design increases the gain (5 dB) with stronger directive radiation.

In [12], a UWB monopole antenna is also designed and integrated with the FSS. Ultra-wide stopband single layer FSS converts the omnidirectional pattern of the monopole antenna into a unidirectional one leading to a significant increase in its gain.
Among those, single layer transmission (passband) type FSS is proposed, in [13]-[15] with the ability to control the radiation antenna. However, the unit cell dimensions of these materials in [13]-[15] are quite large at their operating frequency which lead to the increase of the size of the combined cavity antenna.

In this work, a new transmission (passband) FSS unit cell formed of a double square ring resonator is proposed, aimed to improve the gain, directivity and radiation pattern of the planar wideband antenna. The bandwidth of this antenna covers between 2 and 4.5 GHz for S band applications. A parametric study for the FSS distance above the antenna is observed using CST software to identify the optimum configuration. The size of a unit cell proposed in this work is only 0.086 λ₀ which is smaller than the design reported in [13]-[15].

2. Methodology

The design process starts with the calculation of the proper dimensions at the desired frequency planar for the antenna and FSS structure. Computer Simulation Technology (CST) is used to simulate the design. Antenna characteristics such as resonance frequency, return loss, gain and directivity are considered to optimize the design.

2.1. The design of FSS

The evolution of the double square ring resonator starts with implementing outer square shape rings after the inner square ring is introduced with a spacing (s) = 0.3 mm from the outer ring to decrease the resonant frequency, this is because the capacitance increases as the coupling between the rings are initiated. A gap (g) of 1 mm wide, was introduced in the inner square ring where capacitances caused by reduced effective capacitance. Two parallel dipoles with the same width are combined with an inner ring for miniaturization purpose of the unit cell size. The resonant frequency is calculated to be 2.4 GHz. The FSS unit cell is designed by using FR4 material with a thickness of 1.6 mm, which the dielectric constant is 4.7 and the optimal value of parameters are $p = 10.8$ mm, $w_1 = 0.3$ mm, $w_2 = 0.55$ mm, $w_3 = 0.3$ mm, $g = 1$ mm, $s = 0.3$ mm.

In optimizing the onsets of resonant frequencies at 2.4 GHz the change of geometrical parameters; $p$, $g$, and $s$ can be used to find the best result. The simulated reflection response is shown in Figure 3.

![Figure 1. A unit cell dimensions of 2.4GHz FSS](image1)

![Figure 2. 12*12 array structure](image2)
2.2. Design of the planar antenna

The proposed microstrip patch antenna is shown in Figure 4, and it is built on FR4 material with a dielectric constant \( \varepsilon_r = 4.7 \) and \( \tan \delta = 0.019 \) which is similar for FSS unit cell. The antenna dimensions (in mm) are: the substrate width \( w = 47 \) mm, length \( l = 47 \) mm and thickness \( h = 1.6 \) mm, the square patch has width \( l_p = 16 \) mm and length \( w_p = 16 \) mm, the microstrip feed line has \( w_f = 3 \) mm and \( l_f = 17.5 \) mm, the partial ground plane has width \( w_g = 47 \) mm and length \( l_g = 16.5 \) mm.

The antenna dimensions in [16] are used as a baseline design and modified appropriately in this work to enhance the performance of the slotted square patch antenna.

To improve the antenna bandwidth (BW) and matching, steps are added to the corners of the patch; it also increases the distance between the patch and the ground plane, which tunes the capacitive coupling between them.

![Figure 4. Geometries of the proposed antenna (a) top view showing radiating patch and (b) back view showing ground plane of the antenna](image)

![Figure 5. Front view of the proposed integrated antenna in FSS structure (12x12 array)](image)
The FSS structure is placed above the antenna, as shown in Figure 5. The distance between the antenna and the FSS surface are tested at different height and the corresponding results are illustrated in Figure 6. It is found that the optimum return loss is obtained at $h = 28$ mm.

![Figure 6](image-url) Side view of the proposed integrated antenna in FSS structure (12x12 array).

### 3. Simulation results, analysis and discussion

The results of the simulated return loss for the antenna is shown in Figure 7. As shown in the figure, the antenna resonates at 3.3 GHz with a bandwidth of 2.4 GHz (2.1 - 4.5 GHz), but the frequency of interest is 2.5 GHz. When the FSS structure is placed over the antenna, frequency shifts downward due to the coupling capacitive effects created between the antenna and the FSS surface, as shown in Figure 8. The significant decrease in the return loss achieved from combining FSS superstrate and antenna is notable. In planar antenna, the maximum value of return loss is about -30 dB whereas with antenna FSS superstrate is about -52 dB.

In Figure 9, the simulated gain is presented. The highest gain is about 8.1 dB which is better than wideband antenna without FSS where the gain is only 2.70 dB. The radiation characteristics are improved by the FSS surface due to the control of the current distribution which reduces energy leakage near the antenna edges. The gain of the proposed antenna with and without FSS surface are presented in Figure 9. By applying the FSS screen, the gain of the planar antenna is enhanced almost 5 dB and the antenna became more directive with lesser interference to adjacent microwave components. It was approximately 2.78 dB in the usual case whereas it increases to about 5 - 8.1 dB in the final design. The augmentation of planar antenna performance proves the effectiveness of using FSS structure as a double layer in such applications. Figure 10 shows the directivity for the integrated structure with FSS placed at different heights above the antenna. It is seen that the antenna with FSS layer is more directive with a lower interference where the directivity is enlarged about 6.5 dB where the optimum result is obtained at a distance 14.5 mm from the antenna.

In Figure 11 and 12, the simulated radiation pattern for the proposed design before and after placing the FSS surface at 0° and 90° are shown. As mentioned previously, the FSS surface focused the radiations to the broadside direction and reduced it at the back. It is noticed that the integrated design is more directive compared to antenna only design. In addition, surface waves are also reduced and the power of the boreside is also increased. This shows that the use of FSS enhances the radiation characteristics, gain and directivity. The near-field performance demonstrated that the antenna becomes unidirectional by applying FSS structure where the main lobes direction is fixed to the broadside leading to the improvement of E and H- radiations by maximizing along with broadside radiations.
Figure 7. Simulated return loss for the proposed antenna.

Figure 8. Simulated return loss for the integrated structure at different heights.

Figure 9. Simulated gain for the antenna with and without FSS.

Figure 10. Simulated directivity of the antenna with and without FSS.
Figure 11. 3D radiation pattern of xz plane

Figure 12. 3D radiation pattern of yz plane

Figure 13. E-Plane @ 2.4 GHz.

Figure 14. H-Plane @ 2.4 GHz.

Table 1. Performance comparison with previous works.

| Ref. | Size of Unit Cell | Operating Band (GHz) of antenna | Type of FSS | Gain /Directivity Improvement (dB) |
|------|-------------------|---------------------------------|-------------|-----------------------------------|
| 14   | 0.135 λ₀          | 1.90-2.10                       | Band-pass   | 3                                  |
| 15   | 0.126 λ₀          | 9.0-11.0                        | Band-pass   | 6.9                                |
| 16   | 0.118 λ₀          | 4.80-5.50                       | Band-pass   | 5.1                                |
| 17   | 0.185 λ₀          | 2.20-4.80                       | Band-stop   | 4                                  |
| 18   | 0.165 λ₀          | 4.50-6.50                       | Band-stop   | 10                                 |
| 19   | 0.09 λ₀           | 3.50-10.60                      | Band-stop   | 6.5                                |
| This work | 0.086 λ₀     | 2.0-4.50                        | Band-pass   | 6.5                                |
4. Conclusion
This paper proposed a planar antenna integrated with a pass-band FSS structure for wireless communication. Both antenna and FSS structures used FR4 as the substrate. It is observed that by applying the FSS as a superstrate, the directivity and gain of the antenna can be improved by approximately 6.5 dB and 5.1 dB respectively along broadside direction.

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References
[1] Munk BA. Frequency-selective surfaces: Theory and design. John Wiley & Sons; 2000.
[2] Syed IS, Ranga Y, Matekovits L, Esselle KP, Hay SG. A single-layer frequency selective surface for ultra-wideband electromagnetic shielding. IEEE Trans Electromagn Compat. 2014; 56(6):1404–1411.
[3] M. Li, S. Xiao, Y.-Y. Bai, B.-Z. Wang, "An ultrathin and broadband radar absorber using resistive FSS", IEEE Antennas Wirel. Propag. Lett. 2012; vol. 11, pp. 748-751.
[4] Kesavan A, Mantash M, Zaid J, Denidni TA. A dual-plane beam-sweeping millimeter-wave antenna using reconfigurable frequency selective surfaces. IEEE Antennas Wireless Propagation Letter 2018; 17(10):1832–6.
[5] Chatterjee A, Parui SK. Performance enhancement of a dual-band monopole antenna by using frequency-selective surface-based corner reflector. IEEE Trans Antennas Propag 2016; 64(6):2165–71.
[6] Das P, Mandal K. Modelling of ultra-wide stop-band frequency-selective surface to enhance the gain of a UWB antenna. IET Microwaves Antennas Propag 2019; 13(3):269–77.
[7] Rishishwar D, Shrivastava L. Rectangular microstrip patch antenna with FSS and slotted patch to enhance bandwidth at 2.4 GHz for WLAN applications. Int J Technol Enhance Emerg Eng Res 2014; 2(4):59–62.
[8] A, Foroozesh L, Shafai L. Investigation into the effects of the patch- type FSS superstrate on the high-gain cavity resonance antenna design. IEEE Trans Antennas Propag 2010; 58(2):258 – 269.
[9] Vaidya AR, Gupta RK, Mishra SK, Mukherjee J. Right hand/lefthand field circularly polarized high gain antennas using partially reflective surfaces. IEEE Antennas Wireless Propag Lett. 2014; 13: 431434.
[10] M. Alam, M. T. Islam, and N. Misran, "Inverse triangular-shape CPW-fed antenna loaded with EBG reflector," Electronics Letters, 2013, vol. 49, pp. 86-88.
[11] M. Z. Mahmud, M. T. Islam, N. Misran, S. Kibria, M. Samsuzzaman, "Microwave imaging for breast tumor detection using uniplanar AMC based CPW-fed microstrip antenna", IEEE Access, 2018, vol. 6, pp. 44763-44775.
[12] M. Z. Mahmud, M. T. Islam, N. Misran, S. Kibria, M. Samsuzzaman, "Microwave imaging for breast tumor detection using uniplanar AMC based CPW-fed microstrip antenna", IEEE Access, 2018, vol. 6, pp. 44763-44775.
[13] Das P, Mandal K. Modelling of ultra-wide stop-band frequency-selective surface to enhance the gain of a UWB antenna. IET Microwaves Antennas Propag 2019; 13(3):269–77.
[14] Y.-J. Kim, S.-S. Nam, and H.-M. Lee, Frequency selective surface superstrate for wideband code division multiple access system, in European Wireless Technology Conference (EuWIT), 2009, pp. 33–36.

[15] L. Kurra, M.P. Abegaonkar, A. Basu, S.K. Koul, "FSS properties of a uniplanar EBG and its application in directivity enhancement of a microstrip antenna", IEEE Antennas Wireless Propag. Lett. 2016, vol. 15, pp. 1606-1609.

[16] N. M. Awad, M. K. Abdelazeez, "Multislot microstrip antenna for ultra-wide band applications", J. King Saud Univ.—Eng. Sci, 2015, pp. 11962.

[17] Kushwaha N, Kumar R. Design of a wideband high gain antenna using FSS for circularly polarized applications. Int J Electron Commun (AEÜ) 2016; 70:1156–1163.

[18] Chatterjee, A., Parui, S.K.: ‘Performance enhancement of a dual-band monopole antenna by using a frequency selective surface-based corner reflector’, IEEE Trans Antennas Propag., 2016, 64, pp. 2165-2171.

[19] Yahya, R., Nakamura, A., Itami, M.: ‘Low profile UWB frequency selective surface based antenna’, ITE Trans. on MTA, 2016, 4(4), pp. 369-374.