Research Article

Improved Microstrip Antenna with HIS Elements and FSS Superstrate for 2.4 GHz Band Applications

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This research presents a microstrip antenna integrated with the high-impedance surface (HIS) elements and the modified frequency selective surface (FSS) superstrate for 2.4 GHz band applications. The electromagnetic band gap (EBG) structure was utilized in the fabrication of both the HIS and FSS structures. An FR-4 substrate with $120\text{ mm} \times 120\text{ mm} \times 0.8\text{ mm}$ in dimension ($W \times L \times T$) and a dielectric constant of 4.3 was used in the antenna design. In the antenna development, the HIS elemental structure was mounted onto the antenna substrate around the radiation patch to suppress the surface wave, and the modified FSS superstrate was suspended 20 mm above the radiating patch to improve the directivity. Simulations were carried out to determine the optimal dimensions of the components and the antenna prototype subsequently fabricated and tested. The simulation and measured results were agreeable. The experimental results revealed that the proposed integrated antenna (i.e., the microstrip antenna with the HIS and FSS structures) outperformed the conventional microstrip antenna with regard to reflection coefficient, the radiation pattern, gain, and radiation efficiency. Specifically, the proposed antenna could achieve the measured antenna gain of 10.14 dBi at 2.45 GHz and the reflection coefficient of less than -10 dB and was operable in the 2.39–2.51 GHz frequency range.

1. Introduction

Microstrip antennas are commonly used in wireless communications devices for their low-profile, low-cost, and lightweight characteristics. Despite the benefits, this antenna type does suffer from the electromagnetic (EM) surface wave that occurs on the substrate. Specifically, the surface wave could induce the minor lobes and the EM wave to radiate in directions different from the radiation source. In addition, the surface wave contributes to the degradation of the antenna performance and gain. Likewise, the surface wave increases the cross-polarization of the antenna, thereby restricting the antenna's usefulness [1].

To address these issues, a metamaterial could be integrated into the microstrip antenna [2]. The metamaterial refers to an engineered material whose behaviors or properties are naturally nonexistent, for example, a double-negative material, a left-handed material, or a zero refractive index material [3]. Another metamaterial suitable for the

electromagnetic applications is the electromagnetic band gap (EBG) structure [4]. Typically, the EBG structures are constructed by a periodic arrangement of dielectric materials and metallic conductors and can be categorized into three groups according to their geometrical configurations: the 3D volumetric structure, the 2D planar surface, and the 1D transmission line. Most suitable for integration with the microstrip antenna is the 2D planar surface EBG structure, which is typically fabricated on a printed circuit board (PCB). A typical 2D EBG structure consists of the upper periodic sheet metallic conductors parallel to the lower sheet metallic conductor with the dielectric substrate in the middle. In this research, the 2D EBG structures were of two configurations: the structures with and without a vertical via, which were, respectively, referred to as the mushroom-like EBG (or HIS) and the uniplanar EBG (or FSS superstrate). Despite the ease of fabrication associated with the uniplanar EBG, given the same frequency, the mushroom-like EBG is smaller in size than the uniplanar EBG, and the bandwidth of the

FIGURE 1: The schematic diagrams of (a) the FSS superstrate layer with the antenna ground plane acting as the lower plane of the EBG structure and (b) the top view of the FSS superstrate.

former is wider than that of the latter [5]. The design of the mushroom-like EBG structure was based on the high-impedance surface (HIS) principle [6] and subsequently incorporated onto the antenna substrate for suppressing the surface wave [7]. Meanwhile, the design of the uniplanar EBG structure was based on the frequency selective surface (FSS) technology [8] and utilized as the superstrate layer suspended above the radiating microstrip patch antenna. The FSS structure was for enhancing the radiation aperture of the original radiating source to achieve the improved directivity.

The HIS structure of the uniplanar EBG structure is presented in [9]. Normally, the microstrip antenna suspended with the artificial magnetic conductor (AMC) suffers from fabrication. In [10, 11], the AMC was mounted around the radiation source and FSS superstrate can easily fabricate. However, these structures have bulky size. In [12], the microstrip antenna (MA) with interdigital capacitance FSS superstrate achieved a high directivity and compactness of FSS size. However, the interdigital capacitance FSS superstrate must be additional designed. The dielectric resonator antenna (DRA) with superstrate and reflector plane is presented in [13]. This structure has low back lobe and high copolarization to cross-polarization ratio in E and H planes. The antenna structure is not low profile. In this research, the mushroom-like EBG structure was mounted around the radiation source to suppress the surface wave together with increasing the directivity at the resonant frequency. Meanwhile, the FSS superstrate-layer structure was compact and easy to fabricate. Moreover, the low-profile antenna can be achieved by using FSS resulting in cost minimization. In addition, its refractive index should be zero or close to zero [14, 15]. The refractive index of the radiation source of an interior medium is close to zero. The angle of incident waves from an interior medium to an exterior medium is perpendicular to the medium surface, according to Snell's law [16]. Specifically, while the EM wave travels through the superstrate layer, the waves will be deliberately directed by the superstrate, causing the waves to travel in parallel to free space, thereby achieving the high-directivity antenna [17]. In [18], the woodpile EBG structure was used as the superstrate layer in place of the conventional dielectric layer. The woodpile EBG structure has a complete band gap. In addition, the

woodpile EBG structure helps direct the radiation in the desired direction and lessen the EM wave propagation to other directions. Nonetheless, the woodpile EBG is afflicted with the fabrication challenges and its specific dielectric constant, rendering the FSS technology a good candidate as the superstrate since it could be fabricated on a PCB and thereby the low-profile antenna structure.

In this research, the design and incorporation of the HIS and FSS structures is to achieve a compact and high-directivity antenna. In general, the conventional FSS superstrate [19] requires multilayer to achieve the resonant frequency for a high-directivity antenna, resulting in the relatively bulky antenna structure. In contrast, this research has deployed a *single-layer* superstrate based on the optimally designed HIS and FSS structures, in which the HIS structure serves as the artificial ground plane and thus reduces the distance between the FSS superstrate and the radiation source, subsequently resulting in the low-profile antenna.

This research is organized as follows: antenna with FSS and HIS is presented in Section 2. In Section 2, the directive wave direction from radiation source and "how does HIS work?" are described. Section 3 shows the design of FSS and HIS. In this section, the modified FSS cell is presented to reduce the cells size at the resonant frequency. In addition, the design of HIS works as an artificial ground plane is described in this section. In Section 4, the effects of FSS and HIS on a radiation pattern and gain of a microstrip antenna are described and the measured results are presented.

2. Microstrip Antenna with HIS and FSS

In this research, a probe-fed microstrip antenna (PFMA) was utilized as the radiation source due to its ease of integration with the mushroom-like EBG structure (i.e., HIS structure) on the same layer of substrate. In Figure 1(a), the ground plane of the PFMA acts as the lower plane of the 2D superstrate-layer EBG structure. Figure 1(b) depicts the top view of the FSS superstrate suspended above the antenna ground plane with a distance of h .

To achieve the low-profile structure, the superstrate layer should be thin and thus of a *single* layer. In this research, the superstrate layer was thus redesigned using the transmission matrix in (1).

FIGURE 2: The schematic diagram of a microstrip antenna with HIS structures.

$$T_1 = \begin{bmatrix} \frac{1}{t} & -\frac{r}{t} \\ \frac{r}{t} & \frac{t^2 - r^2}{t} \end{bmatrix}, \quad (1)$$

where r and t are, respectively, the reflection and transmission coefficients of the single-layer superstrate.

The phase change of the wave propagation from the antenna to the superstrate layer can be determined by (2).

$$T_2 = \begin{bmatrix} e^{j\varphi} & 0 \\ 0 & e^{-j\varphi} \end{bmatrix}. \quad (2)$$

The total transmission matrix is thus

$$T_{\text{total}} = T_1 \times T_2 \times T_1 = \begin{bmatrix} \frac{1}{T} & -\frac{R}{T} \\ \frac{R}{T} & \frac{T^2 - R^2}{T} \end{bmatrix}, \quad (3)$$

where

$$T = \frac{t^2 e^{-j\varphi}}{1 - r^2 e^{-2j\varphi}} \quad (4)$$

and

$$R = \frac{r(1 + (t^2 - r^2)e^{-2j\varphi})}{1 - r^2 e^{-2j\varphi}}, \quad (5)$$

where $\varphi = k_0(2h)$. In general, the distance (space) between the antenna and the superstrate is approximately one-half wavelength ($h \approx \Delta\lambda/2$), where $\Delta\lambda = c/\Delta f_r$, where Δf_r is the difference between adjacent resonant frequencies.

Figure 2 illustrates a microstrip antenna with HIS structures. The HIS elemental structure acted as the LC parallel equivalent circuit [20, 21]. The surface impedance (Z_s) can be, respectively, calculated using (6).

$$Z_s = \frac{j\omega L}{1 - \omega^2 LC} \quad (6)$$

At the resonant frequency ($\omega_0 = 1/\sqrt{LC}$), the surface impedance (Z_s) is very high, rising to infinity. The surface wave can thus no longer propagate along the substrate. The reflection phase (ψ) of HIS is calculated by (7).

$$\psi_r = \text{Im} \left[\ln \left(\frac{Z_s - \eta_0}{Z_s + \eta_0} \right) \right] \quad (7)$$

In this research, the frequency bandwidth of interest was between 90° and -90° of the reflection phase. At the resonant frequency, the reflection phase becomes 0° . The

FIGURE 3: The simulated magnitude and phase of the reflection coefficient of the square-loop FSS cell for various d_1 ($d_1 = d_2$).

bandwidth (BW) of the antenna with the HIS elements can be calculated by

$$BW = \frac{Z_0}{\eta_0}, \quad (8)$$

where $Z_0 = \sqrt{L/C}$ and $\eta_0 = \sqrt{\mu_0/\epsilon_0} \approx 377 \Omega$.

Meanwhile, for the antenna integrated with both the HIS and FSS structures, their respective parameters can be calculated by [11].

$$D_{\text{max}} = \frac{1 + r}{1 - r} \quad (9)$$

$$\varphi_r + \psi_r - \left(2\frac{\pi}{\lambda}\right)2h = 2m\pi, \quad m = 0, 1, 2, \dots \quad (10)$$

where φ_r and ψ_r are, respectively, the reflection phases of the FSS superstrate and the HIS structure. In (9), given the reflection coefficient of 1, the antenna would achieve a very high directivity (D_{max}). In addition, the appropriate distance between the antenna and the FSS superstrate layer is governed by φ_r and ψ_r , as expressed in (10).

3. Design of the FSS Superstrate and HIS Elements

3.1. The FSS Superstrate Layer. The proposed superstrate layer is of the 2D periodic FSS structure with loop elements. Unlike other elemental types, for example, the strip and patch elements, the loop elements offer the symmetry shape and ease of design. The loop-element FSS is typically of square shape with concentric elemental loops. In addition, the fabrication of the superstrate layer is straightforward with the loop-element FSS structure, given the target reflection coefficient for the desirable frequency range. In this research, individual FSS unit cells were simulated using CST microwave studio [22] to determine their optimal parameters that achieve the target reflection coefficient and total transmission coefficient for the FSS superstrate structure.

Figure 3 illustrates the simulated magnitude and phase of the reflection coefficient of a square-loop FSS element for

FIGURE 4: The simulated magnitude and phase of the reflection coefficient of the modified FSS cell for various w_1 .

FIGURE 5: The simulated magnitude of the total transmission coefficient of the modified FSS for various w_1 .

various loop lengths ($d_1 = d_2$). The simulations revealed that the magnitude and phase were governed by the loop lengths. Specifically, at the center frequency of 2.45 GHz and the loop length (d_1, d_2) of 20 mm, the magnitude and phase were -0.42 dB and 166° , respectively.

Notwithstanding, the square-shaped loop element suffers from the frequency tuning and large size limitations. In this research, the FSS cells were thus further modified using the fractal technique [23] and simulations carried out. Figure 4 illustrates the schematic of the modified FSS cell and, as an example, its simulated magnitude and phase of the reflection coefficient under various w_1 , where w_1 is the fractal width, w_2 is the edge width, d_1 is the modified loop length, d_2 is the concentric loop length, and d_3 is the load.

The simulations indicated that the optimal dimensions of the modified FSS cells were 15.25 mm for d_1 , 5.75 mm for d_2 , 5.5 mm for d_3 , 5 mm for w_1 , and 2 mm for w_2 . Given the optimal dimensions, the magnitude and phase of the reflection

FIGURE 6: The simulated magnitude of the transmission coefficient of the modified FSS with and without load (d_3).

coefficient of the modified FSS cells, at the center frequency of 2.45 GHz, were respectively -0.0057 dB and 157.63° . By comparison, the modified FSS cells were smaller in size than the square-loop FSS cell, while the reflection coefficient magnitude of the modified FSS cells (-0.0057 dB) was larger than the square-loop FSS's (-0.42 dB); the microstrip antenna integrated with the modified FSS superstrate layer could thus achieve the higher directivity with a narrower distance between the antenna and the superstrate.

Figure 5 depicts, as an example, the magnitude of the total transmission coefficient of the modified FSS superstrate layer for various w_1 . As the total transmission coefficient approaches 1 (i.e., 0 dB), the propagation of EM waves from the antenna becomes perpendicular to the superstrate layer. Since the waves traveling through the superstrate layer become parallel to free space, the higher directivity could thus be realized.

Meanwhile, Figure 6 compares the magnitude and phase of the transmission coefficient of the modified FSS

FIGURE 7: The simulated reflection phase of the HIS elemental structure.

in the presence and absence of load (d_3). It is clear that the load could significantly enhance the capacitance inside the FSS loop, and a strong resonance could thus be achieved at a lower frequency. In addition, the modified FSS structure exhibited no loss, giving rise to a mere small mismatch [24].

3.2. The HIS Elemental Structure. In this research, the HIS elemental structure was fabricated from the EBG square cells with a vertical via and thereby resembles the mushroom. The reflection phase of interest was between -90° and 90° at the center frequency of 2.45 GHz.

Figure 7 illustrates, as an example, the reflection phase of the HIS element under various w_3 , where w_3 is the HIS cell width and g is the gap distance since the fringe capacitance associated with the LC parallel equivalent circuit of the HIS structure minimally varies with the variation in the gap distance (g) and the subsequent resonant frequency. The gap distance (g) of 1.5 mm was deliberately selected due to the ease of actual fabrication and eventual compactness. The findings revealed that the reflection phase decreased with the increase in w_3 since the size of HIS unit cell was increased. Given the center frequency of 2.45 GHz, the simulated optimal HIS cell width (w_3) was 15 mm.

4. Effects of FSS and HIS on the Microstrip Antenna Performance

This section discusses the design of the HIS-FSS-integrated microstrip antenna fabricated on an FR-4 substrate with a dielectric constant of 4.3 ($\epsilon_r = 4.3$), given the center (target) frequency of 2.45 GHz. In addition, the effects of the integration of HIS and FSS on the antenna performance, with regard to $|S_{11}|$, the radiation pattern, gain, and radiation efficiency, were determined.

Figures 8(a) and 8(b), respectively, illustrate the microstrip antennas with only the FSS superstrate and with both the FSS and HIS structures. The incorporation of the HIS elemental structure resulted in a more compact antenna

structure (Figure 8(b)), vis-à-vis that in the absence of HIS (Figure 8(a)). According to (10) and Figures 4 and 7, the phases of the reflection coefficient at the 2.45 GHz frequency for the modified FSS and HIS were 157.63° and 0.53° , respectively. In addition, the resulting distance between the antenna and the superstrate was $h = 0.22 \lambda_{2.45 \text{ GHz}}$ or 26 mm.

In this research, the HIS structure was introduced to suppress the surface wave of the microstrip antenna whereby the HIS elements were mounted around the radiating patch of the antenna. The antenna evolution is illustrated in Figures 9(a)–9(c), beginning with the radiating patch (Figure 9(a)), the radiating patch enclosed by the HIS elements (Figure 9(b)), and the modified FSS superstrate structure (Figure 9(c)). Specifically, the size of the antenna (L), given the 2.45 GHz operating frequency, was $120 \times 120 \text{ mm}$ and that of the radiating patch (W) was $29 \times 29 \text{ mm}$ (Figure 9(a)).

4.1. The Optimal High-Directivity Antenna with the FSS Superstrate Layer. In this step, the modified FSS parameters were varied for the optimal FSS cell dimensions with the resulting high-directivity antenna. Figure 10 illustrates, as an example, the simulation results with regard to the directivity and $|S_{11}|$ under various fractal widths (w_1).

In Figure 10, given w_1 of 5.62 mm, the antenna exhibited the lowest $|S_{11}|$, whereas the antenna directivity was highest under w_1 of 4.75 mm. In addition, given the initial distance between the antenna and the superstrate of 26 mm, the distance (h) was further varied for the highest antenna directivity, given the target operating frequency of 2.45 GHz. In Figure 11, the highest antenna directivity of 11.10 dBi could be achieved at the distance between the antenna and the superstrate (h) of 20 mm.

Figures 12(a) and 12(b), respectively, illustrate the simulated electric field distribution of the conventional microstrip antenna and the proposed microstrip antenna with HIS elements and modified FSS superstrate. The electric field distribution of the conventional microstrip antenna behaves like a hemispherical shape above the radiator. The extension region of the proposed microstrip antenna with HIS and FSS is larger than the conventional microstrip antenna. This region is enlarged by FSS cell of the superstrate layer. Meanwhile, the electric field distribution through the superstrate layer becomes almost parallel to free space. The transmission coefficient of the superstrate layer is approached to 0 dB, resulting in higher directivity. Moreover, as shown in Figure 4, the reflection coefficient of the modified FSS was -0.0057 dB (greatly high reflection). The modified FSS superstrate placed parallel with the antenna with HIS elements at the distance of 20 mm. As the result, it causes resonant from the multiple reflection between the superstrate layer and the antenna [25]. The very high directivity of the antenna was achieved, according to (9). Table 1 tabulates the optimal dimensions of the proposed microstrip antenna with the HIS and FSS structures.

4.2. Measurements of the HIS-FSS-Integrated Microstrip Antenna. Figures 13(a)–13(c) are the photograph images of

FIGURE 8: The schematic diagrams of the microstrip antenna with (a) the FSS superstrate and (b) the FSS and HIS.

FIGURE 9: The antenna structure. (a) The initial antenna. (b) The antenna with HIS. (c) The modified FSS structure. (d) FSS unit cell. (e) Side view.

the prototype microstrip antenna with the HIS elemental structure and the modified FSS superstrate layer. The proposed antenna was fabricated on an FR-4 substrate with

0.8 mm in thickness, while the FSS superstrate layer was suspended 20 mm above the microstrip antenna (Figure 13(c)). Meanwhile, Figures 14, 15, 16, and 17 compare the

FIGURE 10: The simulated antenna directivity and $|S_{11}|$ of the modified FSS under various w_1 .

FIGURE 11: The simulated antenna directivity under various distances between the antenna and the superstrate.

simulation and experimental (measured) results with regard to $|S_{11}|$, the radiation pattern, gain, and radiation efficiency, respectively, under various antenna schemes (i.e., the conventional microstrip antenna, the microstrip antenna with HIS, and the microstrip antenna with both HIS and FSS).

In Figure 14, the bandwidth of the proposed antenna (i.e., the microstrip antenna with HIS and FSS) was noticeably wider than that of the conventional microstrip antenna. This phenomenon could be attributed to the high-impedance surface of the HIS elemental structure at the resonant frequency and thereby the wider bandwidth of the proposed antenna ((8)). Moreover, the measured $|S_{11}|$ indicated that the proposed antenna was operable in the 2.39–2.51 GHz frequency range.

Figures 15(a) and 15(b), respectively, illustrate the XZ- and YZ-plane radiation patterns at 2.45 GHz. The half-power beam widths (HPBW) of the initial antenna in the XZ- and YZ-planes were, respectively, 95° and 105° , and its front-to-back (F/B) ratio was 13.967 dB. Meanwhile, the HPBW of the proposed antenna in the XZ- and YZ-planes were, respectively, 45° and 50° , and its F/B ratio was 26.96 dB. By comparison, the HPBW associated with the

FIGURE 12: Simulated electric field distribution (a) conventional microstrip antenna and (b) proposed microstrip antenna with HIS elements and modified FSS superstrate.

TABLE 1: The optimal dimensions of the microstrip antenna with the HIS elements and FSS superstrate.

Symbols	Parameters	Size (mm)
L	Antenna size	120
W	Antenna patch size	29
h	Distance between antenna and FSS	20
d_1	Modified FSS loop length	15.25
d_2	Concentric loop length	5.75
d_3	Load size	5.5
w_1	Fractal width	4.75
w_2	Edge width	2
w_3	HIS cell size	15
g	Gap distance	1.5

proposed antenna was narrower than the conventional microstrip antennas. In addition, the XZ- and YZ-plane cross-polarization levels of the proposed antenna were lower than the corresponding cross-polarization levels of the

FIGURE 13: Photograph images of (a) the prototype microstrip antenna with HIS, (b) the prototype-modified FSS superstrate layer, and (c) the side view of the HIS-FSS integrated microstrip antenna.

FIGURE 14: The simulated and measured $|S_{11}|$ under various antenna schemes.

conventional microstrip antenna. This could be explained by the fact that the surface wave could no longer propagate and the FSS superstrate layer efficiently directs the EM waves from the microstrip antenna. The proposed antenna could thus achieve the higher directivity, relative to the conventional microstrip antenna.

Figure 16 compares the simulated and measured antenna gains at 2.45 GHz under the various antenna schemes. The findings showed a significant increase in the antenna gain (10.14 dBi) under the proposed antenna scheme (i.e., the microstrip antenna with HIS and FSS) vis-à-vis that of the conventional microstrip antenna (2.28 dBi).

Figure 17 compares the radiation efficiencies under the various antenna schemes. The radiation efficiency is enhanced with the incorporation of both the HIS and FSS structures into the microstrip antenna. Specifically, at the

2.45 GHz frequency, the simulated and measured radiation efficiencies of the proposed antenna are 82% and 77%, respectively. The measured radiation efficiency of the proposed antenna is enhanced by 35.6% comparing with the conventional microstrip antenna.

Table 2 tabulates the comparative performances of the existing metamaterial-integrated antennas and the proposed antenna. Specifically, in [26], the PFMA with spiral-like EBG achieved a gain of 5.6 dBi, suffered from the design and fabrication challenge due to the spiral-like EBG structures, while in [27], the aperture-coupled microstrip antenna (ACMA) with FSS superstrate achieved a gain of 15 dBi at 9.5 GHz. However, this structure has high back lobe. Interestingly, the EBG resonator antenna (ERA) with phase-correcting structures (PCS) superstrate in [28] achieved the highest gain (21.2 dBi), suffered from the fabrication challenge due to the PCS design. All in all, the proposed antenna (i.e., the microstrip antenna with HIS and FSS) could achieve a relatively high gain (10.14 dBi), given its compact size and low profile.

5. Conclusions

This research has proposed the microstrip antenna integrated with the high-impedance surface (HIS) elements and the modified frequency selective surface (FSS) superstrate for 2.4 GHz band applications. The electromagnetic band gap (EBG) structure was adopted in the fabrication of both the HIS and FSS structures. In the antenna design, the HIS elemental structure was mounted onto the antenna substrate around the radiation patch to suppress the surface wave, and the modified FSS superstrate was suspended 20 mm above the radiating patch to improve the directivity. Simulations were carried out to determine the optimal dimensions of the constituent components and the antenna prototype subsequently fabricated and experimented. The

FIGURE 15: The simulated and measured radiation patterns under various antenna schemes: (a) XZ- and (b) YZ-planes.

FIGURE 16: The simulated and measured antenna gains under various antenna schemes.

simulation and measured results were in good agreement. Specifically, the proposed antenna (i.e., the microstrip antenna with the HIS and FSS structures) could achieve the measured antenna gain of 10.14 dBi at the 2.45 GHz frequency and the < -10 dB reflection coefficient. In addition,

FIGURE 17: The simulated and measured radiation efficiency under various antenna schemes.

the HIS-FSS-integrated antenna was operable in the 2.39–2.51 GHz frequency range. More importantly, the proposed integrated antenna outperformed the conventional microstrip antenna with regard to $|S_{11}|$, the radiation pattern, gain, and radiation efficiency.

TABLE 2: The performance comparison of antennas with metamaterial(s).

Number	Ref.	Antenna structure	Antenna dimension ($W \times L$) (λ)	Distance, superstrate, and antenna (λ)	Antenna material (ϵ_r)	Substrate thickness (mm)	Frequency (GHz)	Antenna gain (dBi)
1	[9]	PFMA suspended on AMC	1.31×1.31	—	FR-4 (4.3)	1.5	2.45	7.087
2	[12]	MA with FSS superstrate	1.58×1.58	0.5	FR-4 (4.3)	1.6	8.12–9.18	14.15 (directivity)
3	[13]	Cylindrical DRA with superstrate and reflector plane	1.35×1.35	0.22	FR-4 (4.4)	1.6	7.4 and 7.9	11.34
4	[26]	PFMA with spiral-like EBG	0.37×0.37	—	FR-4 (4.4)	2.4	2.4	5.6
5	[27]	ACMA with FSS	N/A	0.47	RT-duroid (3.38)	0.782	9.5 (center frequency)	15
6	[28]	ERA with PCS superstrate	6×6	0.53	ERA (PFMA-Rogers UltraLam2000 (2.5), PRS-Roger TMM4 (4.5)) PCS-Rexolite 1422 (2.53)	1.57 (PFMA), 3.17 (PRS)	11.1	21.2
7	Proposed antenna	PFMA with 7×7 square HIS and modified FSS	0.98×0.98	0.16	FR-4 (4.3)	0.8	2.45	10.14

Conflicts of Interest

The authors declare that there is no conflict of interests regarding the publication of this paper.

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