

Article

Gain Enhancement of a Dual-Band Antenna with the FSS

Chengming Shi ¹, Jie Zou ², Jing Gao ² and Changjun Liu ^{1,*}¹ School of Electronics and Information Engineering, Sichuan University, Chengdu 610064, China² The Second Research Institute of Civil Aviation Administration of China, Chengdu 611435, China

* Correspondence: cjliu@scu.edu.cn

Abstract: A dual-band directional antenna for Industrial, Scientific, and Medical (ISM) band application is proposed in this article. The antenna consists of two layers of substrates. The first layer contains the square loop loading with a meander stub to realize the dual band. The second layer is a frequency selective surface (FSS) structure, which is a periodic array with square loops. The phase shift from the FSS reflection and the distance between two layers are optimized to realize the field superposition, which could achieve gain enhancement and bandwidth improvement at two operating bands, simultaneously. The measured results indicate that within a 2.3–2.62 GHz range and a 4.9–6.45 GHz range, the $|S_{11}|$ of the antenna is less than -10 dB. The -10 dB impedance bandwidth is 13% and 27%, respectively. The gain of the antenna is 6.8 dB at 2.45 GHz and 9.0 dB at 5.8 GHz. Meanwhile, the antenna gain is over 8.5 dB from 5.0 GHz to 6.0 GHz. The working band of the antenna covers all bands of WLAN. The design has a good application prospect in the future.

Keywords: dual-band; gain enhancement; frequency selective surface



Citation: Shi, C.; Zou, J.; Gao, J.; Liu, C. Gain Enhancement of a Dual-Band Antenna with the FSS. *Electronics* **2022**, *11*, 2882. <https://doi.org/10.3390/electronics11182882>

Academic Editor: Dimitra I. Kaklamani

Received: 31 July 2022

Accepted: 5 September 2022

Published: 12 September 2022

Publisher's Note: MDPI stays neutral with regard to jurisdictional claims in published maps and institutional affiliations.



Copyright: © 2022 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

1. Introduction

Wireless communication systems have developed rapidly in the past few decades, meaning more is required from antennas, such as wideband and multi-band features, high gain, and easy fabrication. Microstrip patch antennas show outstanding advantages for mobile communication devices due to their low profile, easy fabrication, small size, and easy integration with other circuits [1]. Nevertheless, normal microstrip antennas still have many shortcomings which include their narrow- and single-band features, low-radiation efficiency, and so on. In order to improve the performance of a microstrip antenna, many methods have been proposed for various purposes. The use of multi-stubs on a monopole antenna was widely studied in [2–5]. This method easily achieves multi-band performance since it has stubs with different lengths corresponding to various resonant frequencies. However, it is unable to realize a high gain since it is based on a monopole structure. What is more, its radiation pattern could deteriorate, especially in a high frequency band. Multi-mode antennas are a good way to realize dual-band operation as well. In [6], a dual-band folded-end dipole antenna working at an S- and C-band was proposed. The antenna worked in the 6th and 12th mode at 2.5 GHz and 4.7 GHz, respectively. It had a concise structure and a good radiation performance. The use of frequency reconfigurable antennas is another method used to achieve dual-band or multi-band performance [7–9]. However, their complex structures which introduce the DC feed circuit and active components limit their application. The DC feed circuit could cause pattern distortion as well.

In recent years, metamaterial structures have been widely studied because of their excellent improvements of antennas [10–19]. In [10], the authors proposed a printed Yagi antenna loaded with metamaterial-embedded square spiral rings (SSRs) in an array formation to achieve a multi-band and a high gain. The first resonance of the antenna was produced by the Yagi dipole elements, and the other resonances were produced by the parasitic SSR. Thus, by optimizing the dimensions of the parasitic SSR, the antenna working band could be controlled. In [11], an artificial magnetic conductor (AMC) was placed

directly below two orthogonally placed dipoles. Due to the zero-reflection performance of an AMC, the antenna had a low profile with an enhanced gain. Meanwhile, frequency selective surfaces (FSSs) have been used as reflectors to improve the antenna radiation performance. Another article introduced in [12] suggested a comprehensive review focusing on gain enhancement techniques using an FSS as a reflector for UWB antenna applications. According to [11], the main methods of gain enhancement for UWB antennas using FSS reflectors in recent years are classified into two groups: FSS single-layer reflectors and FSS multi-layer reflectors. For FSS single-layer reflectors, some work adopts an FSS unit array on one side of the sheet of substrates as a reflector, though more FSSs are designed based on metallic reflectors to enhance gain, and several pioneering FSS single-layer reflectors are proposed to improve the gain of UWB planar antennas based on the magnitude of their phase reflections. In [13], a wideband microstrip array antenna with an FSS reflector was proposed. The designed FSS had a wide stopband transmission coefficient from 3.3 to 5.6 GHz, which made the antenna obtain a wide bandwidth and a stable high gain. The proposed antenna obtained a high gain of 12.4 dB, and the radiation efficiency was 77.5% (3.3–5.6 GHz). The bandwidth reached 51.12%, which meant the antenna had a better radiation performance than many relative works. Dual-band FSS reflectors are also a research hotspot; in [14], a stopband FSS operating at 750 MHz and 3.5 GHz for a 5 G application was proposed. The FSS unit cell was a bow tie, which was designed by an iteration and fractal technique. A dual-band FSS reflector working at 2.45 GHz and 5.8 GHz, whose unit cell is two square loops, was placed behind a dual-band antenna to enhance the gain and improve the radiation pattern in [15]. In [16], the authors enhanced the performance of a dual-band monopole antenna operating at 3.0 and 5.5 GHz by using an FSS-based corner reflector. The reflector significantly increased the impedance bandwidth from 20% to 44% and directivity to 5.5 GHz while maintaining omnidirectional radiation at 3 GHz.

In this article, a dual-band antenna operates at the ISM band with an FSS loaded as a band-stop reflector at 5.8 GHz and a Partial Reflection Surface (PRS) at 2.45 GHz, through adjusting the reflection phase shifting from the FSS to achieve the field superposition and the gain enhancement. The antenna gain is significantly improved, as is its bandwidth and front-back ratio. Its gain is enhanced from 2.2 dB to 6.8 dB at 2.45 GHz and from 4.4 dB to 9.0 dB at 5.8 GHz. In addition, the enhancement is achieved with a low-profile structure which is $0.13 \lambda_0$ at 2.45 GHz. The antenna structure in this study is presented after the Introduction in Section 1. The design of the antenna and the FSS is described in detail in Section 2. In Section 3, some key parameters that were studied are presented, and a prototype of the antenna is manufactured and measured. The measurement results are presented and analyzed. Finally, the conclusion is given in Section 4.

The main contributions of this article are listed as follows:

1. A method to achieve the maximum field superposition in two ISM bands simultaneously which is based on the FSS reflection phase shift and adjusting the “air-gap” (the gap between antenna and FSS) length is proposed and validated.
2. Some key parameters in gain enhancement such as the “air-gap” length and the FSS unit amount are investigated to establish their effects on antenna radiation performance.
3. A dual-band antenna is proposed and measured, obtaining a wide bandwidth and high gain with a low profile.

2. Antenna and FSS Design

The configuration of the proposed antenna is shown in Figure 1. Two layers of substrate are parallel to each other and are fixed together with nylon screws. The substrate of the first layer is F4B with a dielectric constant of 2.65, a loss tangent of 0.0015, and a thickness of 1 mm. Figure 1b shows the top view of the original antenna which consists of a square loop loaded with a meander stub. The ground of the antenna with a rectangular opening is shown in Figure 1c. The substrate of the second layer is FR4 with a dielectric constant of 4.3, a loss tangent of 0.02, and a thickness of 1 mm. Figure 1d shows the

second layer of the structure, which is a frequency selective surface (FSS) whose fundamental element is a square loop. The distance between the two layers is 13 mm, which is approximately a quarter-wavelength at 5.8 GHz. In Figure 1, the yellow parts mean a copper cladding and the green and blue parts represent the FR4 and the F4B substrates, respectively. The four gray circles are the nylon screws.

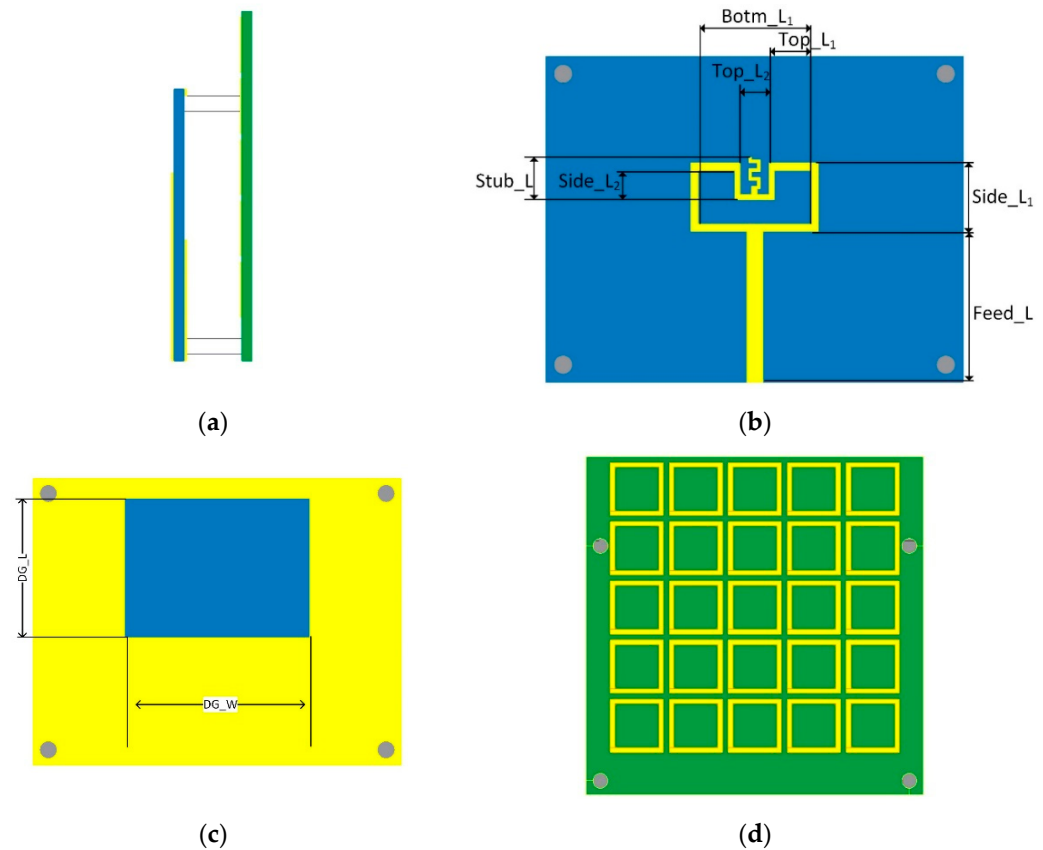


Figure 1. Configuration of antenna: (a) side view, (b) first layer top view, (c) first layer bottom view, (d) second layer.

A dual-band prototype patch antenna is designed to be printed on the first substrate. The main radiating part of the antenna at 2.45 GHz is the square on the first layer. The length of the square is calculated preliminarily by

$$L = \frac{c}{4 \cdot f \cdot \sqrt{\epsilon_r}}, \quad (1)$$

where L , c , f , and ϵ_r are the length of the square, the light speed in vacuum, the operating frequency, and the equivalent dielectric constant of substrate, respectively. Figure 2 is an equivalent circuit model (ECM) of the proposed dual-band prototype antenna. It indicates that the resonance at 2.45 GHz is produced by a “ C_l, L_l, R_l ” series resonant circuit and the resonance at 5.8 GHz is produced by a “ C_h, L_h, R_h ” series resonant circuit. Meanwhile, C_1 and L_1 are the equivalent parasitic parameters.

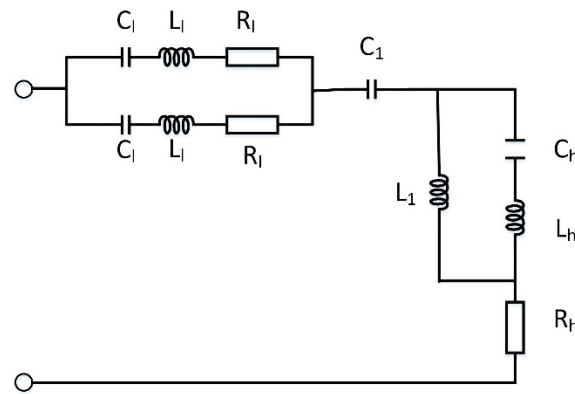


Figure 2. Equivalent circuit model of the original antenna.

The equivalent circuit was designed utilizing the Advanced Design System software (ADS). The input impedance of the proposed antenna and the equations to calculate the equivalent circuit variables are presented as follows [20,21]:

$$Z_{in} = R + jX, \quad (2)$$

$$jX = \frac{\frac{1}{2}C_1(1 - \omega^2 C_l L_l) + C_l}{j\omega C_l C_1} + \frac{(1 - \omega^2 C_h L_h)j\omega L_2}{1 - \omega^2 C_2(L_h + L_2)}, \quad (3)$$

$$C_l = \frac{1}{\omega_{z_1}^2 \cdot L_l}, \quad (4)$$

$$C_h = \frac{1}{\omega_{z_2}^2 \cdot L_h}, \quad (5)$$

$$C_l = \frac{1}{2} \left(\frac{1}{\omega_{z_1}^2} - \frac{1}{\omega^2} \right) \cdot \frac{C_1 \omega_{z_1}^2 (\omega_{p_2}^2 - \omega_{z_1}^2)}{(\omega_{p_2}^2 - \omega_{z_1}^2) - L_1 C_1 \omega_{p_2}^2 \omega_{z_1}^2 \omega_{z_2}^2}, \quad (6)$$

$$C_h = \left(1 - \frac{\omega^2}{\omega_{z_2}^2} \right) \frac{1}{L_1 \omega_{p_2}^2}, \quad (7)$$

$$C_1 = \frac{(\omega_{p_2}^2 - \omega_{z_1}^2)(\omega_{p_2}^2 - \omega_{z_2}^2)}{-L_1 \omega_{p_2}^2 \omega_{z_1}^2 \omega_{z_2}^2}. \quad (8)$$

ω_{z_1} , ω_{z_2} , and ω_{p_2} , respectively, represent two zeros and the second pole of Equation (3), and the value of ω_{p_1} was taken to be zero. When the antenna is working at the resonance frequencies, the imaginary part of input impedance is zero, which means that the ω_{z_1} and ω_{z_2} correspond to 2.45 GHz and 5.8 GHz, respectively. In Equation (2), R represents the radiation resistance. These variables could be calculated using Equations (3)–(8). The lumped RLC values recorded in Table 1 were estimated using the equations mentioned above.

Table 1. Lumped parameters of ECM.

Circuit Parameters	C_l	L_l	C_h	L_h	C_1	L_1
Values	0.745 pF	5.9 nH	0.14 pF	5.4 nH	0.3 pF	9.1 nH

The current distribution at 2.45 GHz is shown in Figure 3a. The current at 2.45 GHz is mainly distributed on the square. However, the bottom side of the square is parallel and close to ground. It could be regarded as a transmission line without radiation. Thus, two sides of the square which are vertical to ground are equivalent to two monopoles. They are in parallel, as shown in Figure 2. The main radiating part of the antenna at 5.8 GHz is

the meander line stub on the U-shaped frame and its length also could be calculated by Equation (1).

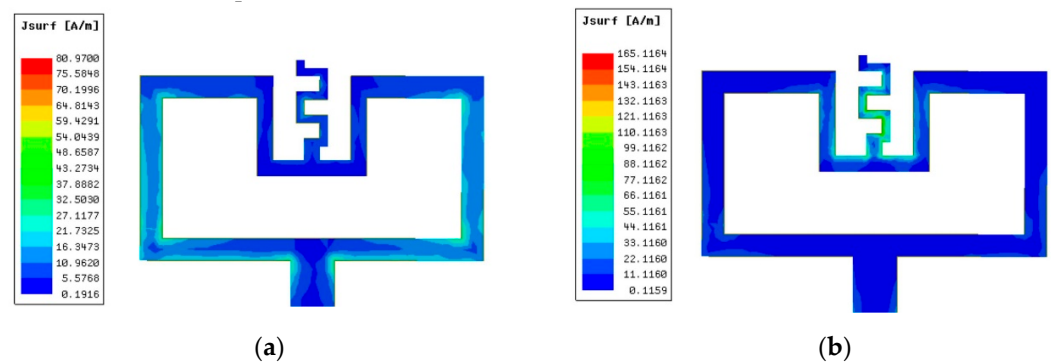


Figure 3. Current distribution of the original antenna at (a) 2.45 GHz and (b) 5.8 GHz.

The meander line stub is adopted since it reduces the size as well as the coupling to the surrounding U-shaped frame. Figure 3b shows the distribution of the current at 5.8 GHz; introducing the stub on the square makes a strong concentration of the current on the stub and a weak concentration of the current on the square, and it indicates that the main radiation part at 5.8 GHz is the meander line stub which is equivalent to a monopole, as shown in Figure 2. A 50Ω microstrip line is used to feed the antenna from the middle of the bottom side.

The bottom substrate is a frequency selective surface (FSS), which is a spatial resonant structure. It has different responses to electromagnetic waves at different frequencies. In this article, a square-loop-based FSS has been designed, which is a band-stop spatial filter as a reflector at 5.8 GHz and as a Partial Reflection Surface (PRS) at 2.45 GHz. The element of the FSS is shown in Figure 4a; it is analyzed as a parallel LC resonant circuit which is equal to an open circuit at the resonant frequency. The equivalent circuit schematic is given in Figure 4b.

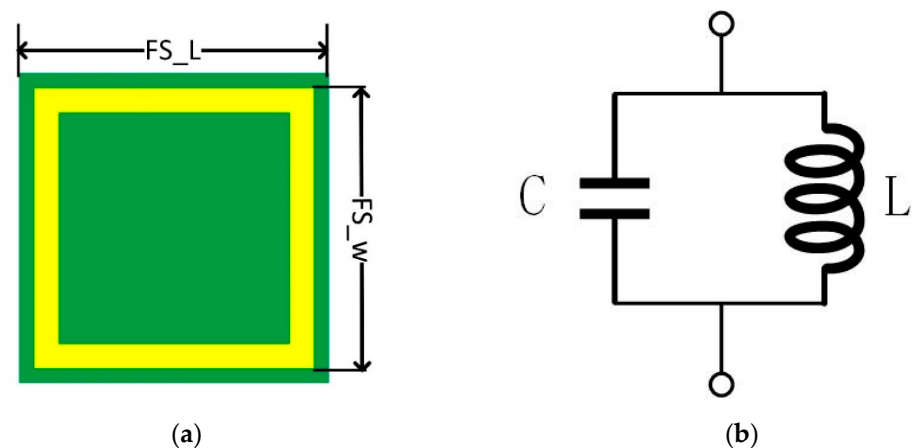


Figure 4. (a) An FSS element and (b) its equivalent schematic.

At the resonant frequency, the phase shift of the reflection of the FSS is about 180°, which is similar to a normal metal reflector. Thus, to achieve the field superposition, the distance between the FSS and the prototype antenna is equal to $\lambda_g/4$, where λ_g is the wavelength. However, for a dual-band antenna, it is hard to realize the field superposition by this method, since the distance between the FSS and the antenna is related to the wavelength. Compared to the normal metal reflector, which has a 180° phase shift for all frequencies, the phase shift of the FSS reflection at the non-resonant frequency varies. Therefore, utilizing the FSS at the non-resonant frequency is a good way to realize the field superposition for a dual-band antenna. At the non-resonant frequencies, some parts of the

incident wave transmitted the FSS and the other parts were reflected by the FSS—the FSS is used as a PRS in this case. For the purpose of gain enhancement, the reflected wave is not expected because the radiation should be mainly towards a single direction. The reflected wave could be eliminated with the original antenna radiation wave if they have a 180° phase difference.

A schematic of the entire structure is shown in Figure 5. Not all the reflected waves are eliminated since the incident angles are different. The remaining reflected waves will be reflected and then reflected again between the antenna ground and the FSS. According to the analysis mentioned above, two conditions are required to realize field superposition at 2.45 GHz:

$$2\pi \frac{2h}{\lambda} + \varphi_r = (2n + 1)\pi, \quad (9)$$

$$\pi + 2\pi \frac{2h}{\lambda} + \varphi_r = 2n\pi \quad (n = 0, 1, 2 \dots), \quad (10)$$

where h is the distance between the FSS and the antenna, φ_r is the reflection phase shift, and λ is the wavelength. Equation (9) is the condition that the reflected wave and the incident wave can be eliminated with each other. Equation (10) is the condition that the final transmitted wave will get the same phase after being reflected between the two substrates many times [22]. The two formulas are equivalent to each other.

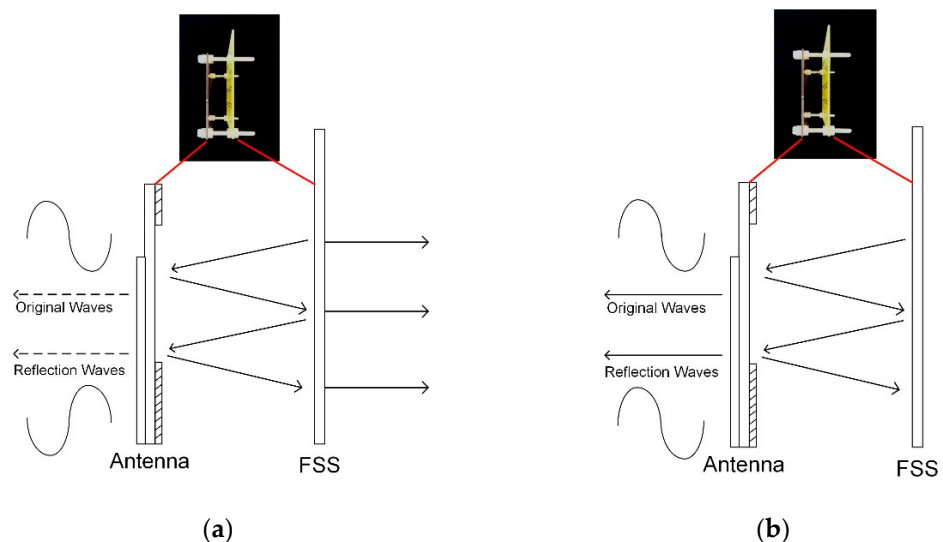


Figure 5. The schematic of the antenna working principle at (a) 2.45 GHz and (b) 5.8 GHz.

In this design, the band-stop FSS is a reflector at 5.8 GHz. Thus, h is about $0.25 \lambda_H$ and $0.1 \lambda_L$, and the value of h is 12.9 mm, where λ_H and λ_L are the wavelengths at 5.8 GHz and 2.45 GHz, respectively. Thus, the designed reflection phase shift φ_r could be calculated at approximately 0.6π .

3. Simulated and Measured Results

The FSS unit is designed and finally optimized by the full wave electromagnetic simulation software. The simulated transmission coefficient ($|S_{21}|$) and the reflection phase shift of the FSS for the normal incidence plane waves are shown in Figure 6. The transmission coefficient is less than -35 dB at 5.8 GHz, which means almost all waves are reflected by the FSS at 5.8 GHz. The transmission coefficient is -3.2 dB at 2.45 GHz, which means that about half the power of the incident waves is reflected. The reflection phase shift is 135° at 2.45 GHz, which is close to the required value in theory.

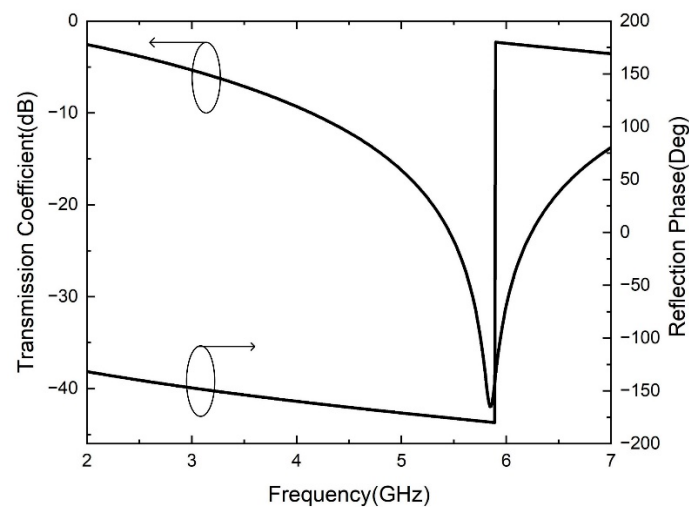


Figure 6. The simulated transmission coefficient and reflection phase of the FSS.

The analysis and simulation of the FSS above are based on an ideal assumption that the FSS is an infinitely large surface. However, the size of antennas is always limited in real antenna design engineering. The effects of the FSS unit cell number on the antenna radiation performance are given in Figure 7a,b, showing $|S_{11}|$ and the gain of the antenna with “2 × 2”, “3 × 3”, “4 × 4”, “5 × 5”, and “6 × 6” FSS unit cell arrays, respectively, when h is 13 mm. The number of FSS unit array dimensions is n , as shown in Figure 7a. When n is increasing, the first resonance frequency is moving to a lower frequency, and the second resonance at the 5.8 GHz band is barely influenced. When $n > 4$, the first resonance frequency is stable at about 2.45 GHz, and the antenna’s bandwidth becomes independent of the FSS size, which illustrates that the FSS is large enough to meet the condition in Section 2. In Figure 7b, it is clear that with the increase in “ n ”, the gain in operating bands is improving, especially at 5.8 GHz band. When $n > 4$, the antenna gain at 2.45 GHz is stable at 7.5 dB. Comparing $n = 5$ with $n = 6$ shows that the gain improvement of the FSS unit cell number increasing is not significant in the two operating bands. Considering the size of antenna, for the number of FSS unit cells, the “5 × 5” array is appropriate.

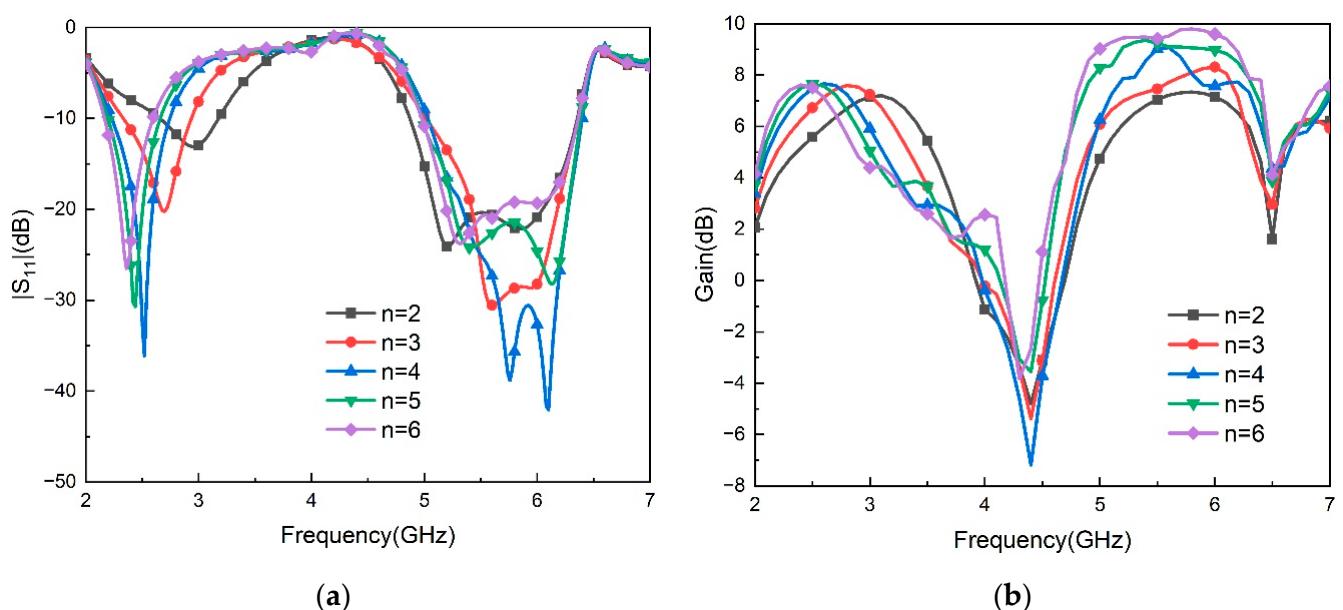


Figure 7. The antenna performance of various FSS unit cell numbers (a) $|S_{11}|$ and (b) gain.

The length of the air-gap between the antenna and the FSS is h , as mentioned above. It plays a crucial role in antenna performance. A parameter study of the air-gap was carried out to explore the influence of the air-gap on the antenna radiating and validating the analysis in Section 2. The results are displayed in Figure 8. Figure 8a shows that the two resonance frequency points vary with the values of the air-gap. The field distribution around the antenna is also changing for the different values of the air-gap and this has an impact on antenna input impedance. As shown in Figure 8b, gain gets a maximum value at 2.45 GHz and 5.8 GHz simultaneously, when the air-gap is 10 mm, and the air-gap is close to a quarter of the wavelength at 5.8 GHz, but is $1/10$ wavelength at 2.45 GHz. What is more, the FSS is a PRS at 2.45 GHz. Hence, even when the air-gap = 30 mm, that is a quarter of the wavelength at 2.45 GHz and the gain is lower than at other values. The simulation results validate the theory analysis in Section 2 that the antenna has a higher gain when meeting Equations (9) and (10).

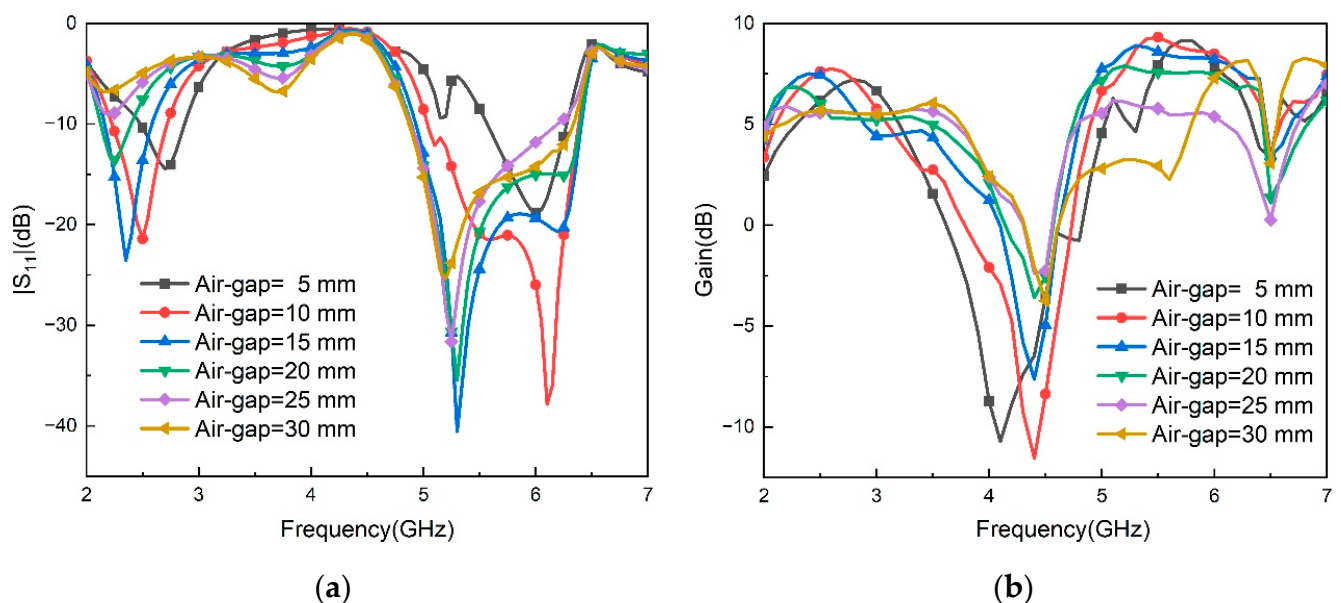


Figure 8. The antenna performance of various values of “air-gap” parameter (a) $|S_{11}|$ and (b) gain.

The antenna and the FSS are simulated and optimized. After combining the two substrates, the input impedance would be influenced especially at 2.45 GHz. In order to realize the impedance matching again, many parameters of the antenna are analyzed. The antenna impedance is sensitive to a key parameter $Botm_L_1$, which is shown in Figure 9. In Figure 9, impedance curve fluctuation is relatively large in the low operating bands, but it stays relatively flat when the resistance is about 50 Ohm and the reactance is 0 Ohm in the high operating bands. Thus, adjusting $Botm_L_1$ may affect the antenna impedance at 2.45 GHz, but has little influence on the antenna impedance at 5.8 GHz. The parameters of the final optimization results are given in Table 2.

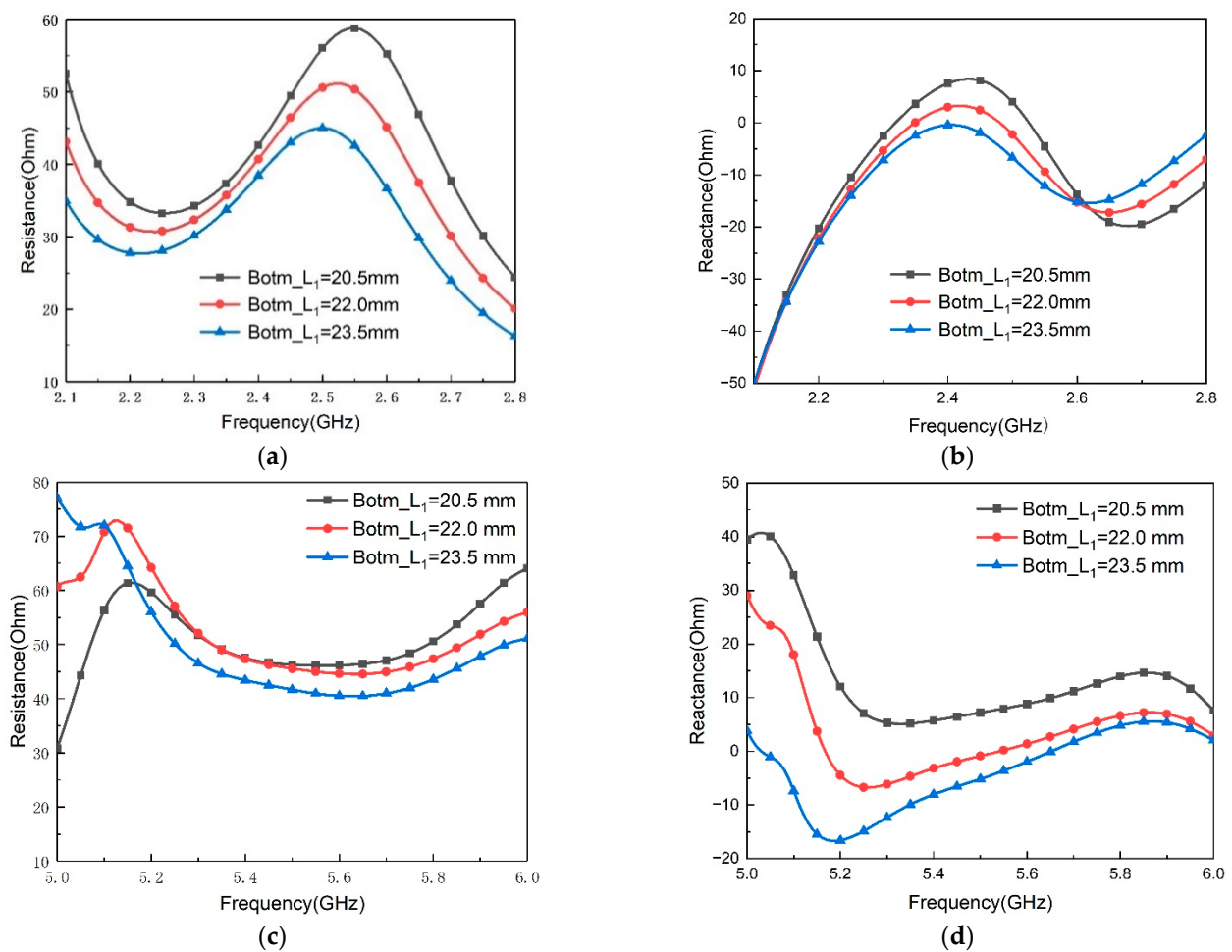


Figure 9. The input impedance of the antenna at various values of the Botm_L₁ parameter. (a) Resistance, (b) reactance at 2.45 GHz, and (c) resistance and (d) reactance at 5.8 GHz.

Table 2. Design parameter values of proposed antenna.

Parameters	Top_L ₁	Top_L ₂	Stub_L	Side_L ₁	Side_L ₂	Botm_L ₁
Value(mm)	8.5	5	6.4	11.8	4	22
Parameters	Feed_L	DG_L	DG_W	FS_L	FS_W	Air-gap
Value(mm)	25.9	27	36	13	10.8	13

A prototype has been manufactured and measured. Two layers were combined using the nylon screws, as shown in Figure 10. Figure 11 shows the antenna measurement environment in an anechoic chamber. The generator produced a signal which was transmitted by the standard horn antenna. The signal was received by the antenna under test (AUT). A spectrum analyzer measured the magnitude of signals from the AUT when the AUT was rotating around two axes to measure the E and the H plane pattern. Another standard horn antenna whose gain was known repeated the steps mentioned above as the receiving antenna. Finally, all values were normalized by the maximum value to draw the patterns and the gain of the AUT from the received signal magnitude difference between the standard horn antenna and the AUT. The radiation pattern and the gain were measured in the anechoic chamber, and the $|S_{11}|$ was measured by a Vector Network Analyzer (VNA). The measured $|S_{11}|$ together with the simulated values are shown in Figure 12a, in which there is an agreement between the simulated and the measured results. The two operating bands of the proposed antenna ($|S_{11}| < -10$ dB) were 2.3–2.62 GHz and 4.9–6.42 GHz, respectively. The relative bandwidths were 13% and 27%, respectively. Moreover, the single

original antenna was measured as well. A comparison between the original antenna and the proposed antenna with the FSS is shown in Figure 12b. The original antenna without the FSS had poor impedance matching at 2.45 GHz and the voltage reflection coefficient was about -5 dB. While loaded with the FSS, the proposed antenna had a resonance of 2.45 GHz and a good bandwidth. The bandwidth at the high frequency band was also expanded. Thus, it can be seen that the FSS improved the antenna bandwidth.

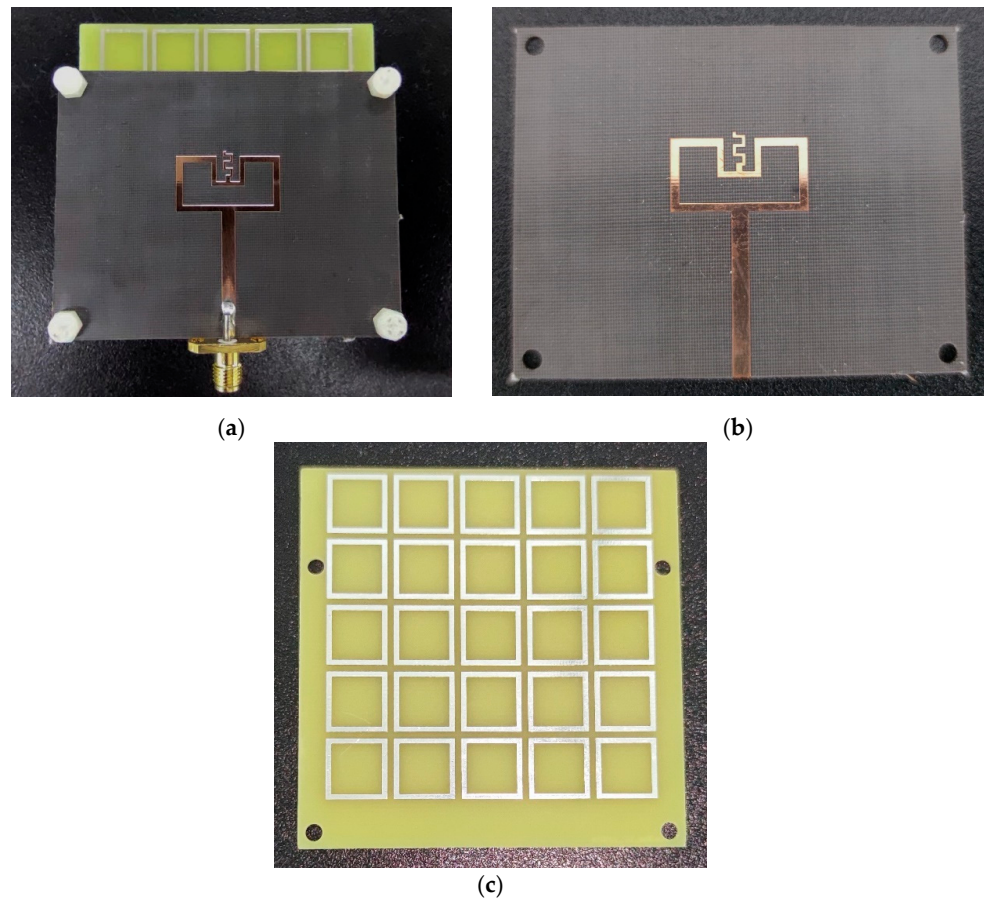


Figure 10. Photographs of the proposed antenna. (a) The integration of the prototype antenna and the FSS, (b) the prototype antenna, (c) the prototype of the 5×5 FSS.

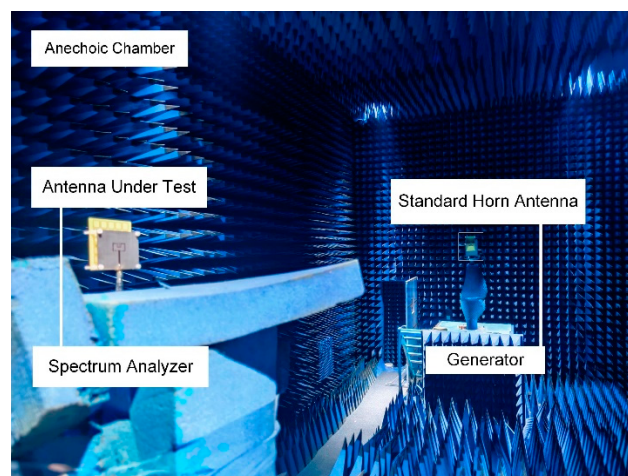


Figure 11. The antenna measurement environment in the anechoic chamber.

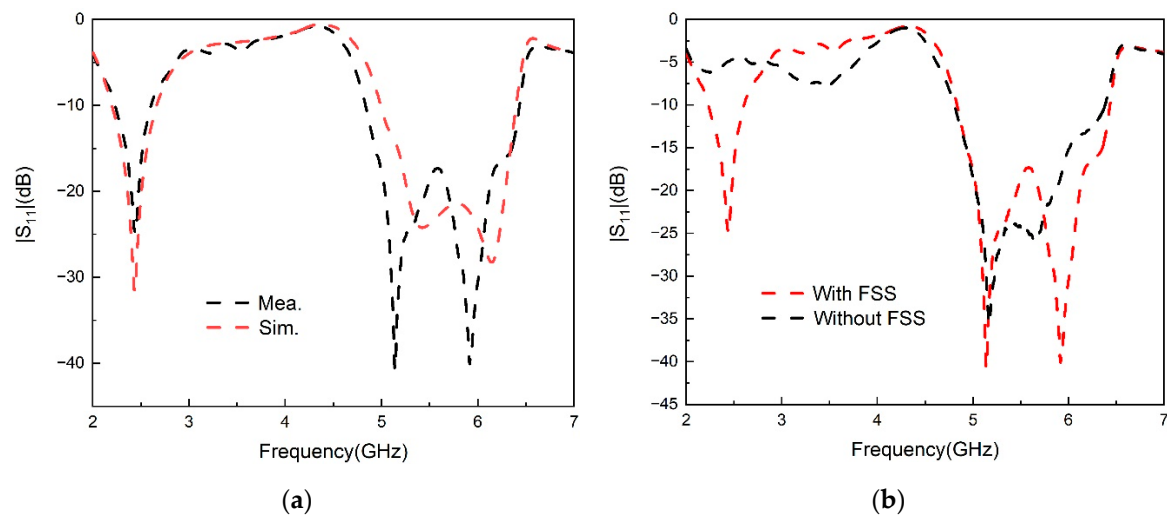


Figure 12. (a) The simulated and measured $|S_{11}|$ of the antenna and (b) the comparison of the measured $|S_{11}|$ of the antenna with and without the FSS.

The simulated and measured radiation patterns of the proposed antenna are shown in Figure 13. Figure 13a contains the E-plane pattern and the H-plane pattern at 2.45 GHz. The maximum gain is 6.8 dB, and the front-back ratio is 8.2 dB. The simulated and measured results are in good agreement. Figure 13b shows the simulated and measured radiation patterns at 5.8 GHz. Meanwhile, the measured E-plane patterns of the proposed antenna at 5.0 GHz, 5.4 GHz, and 6.0 GHz are shown in Figure 13c.

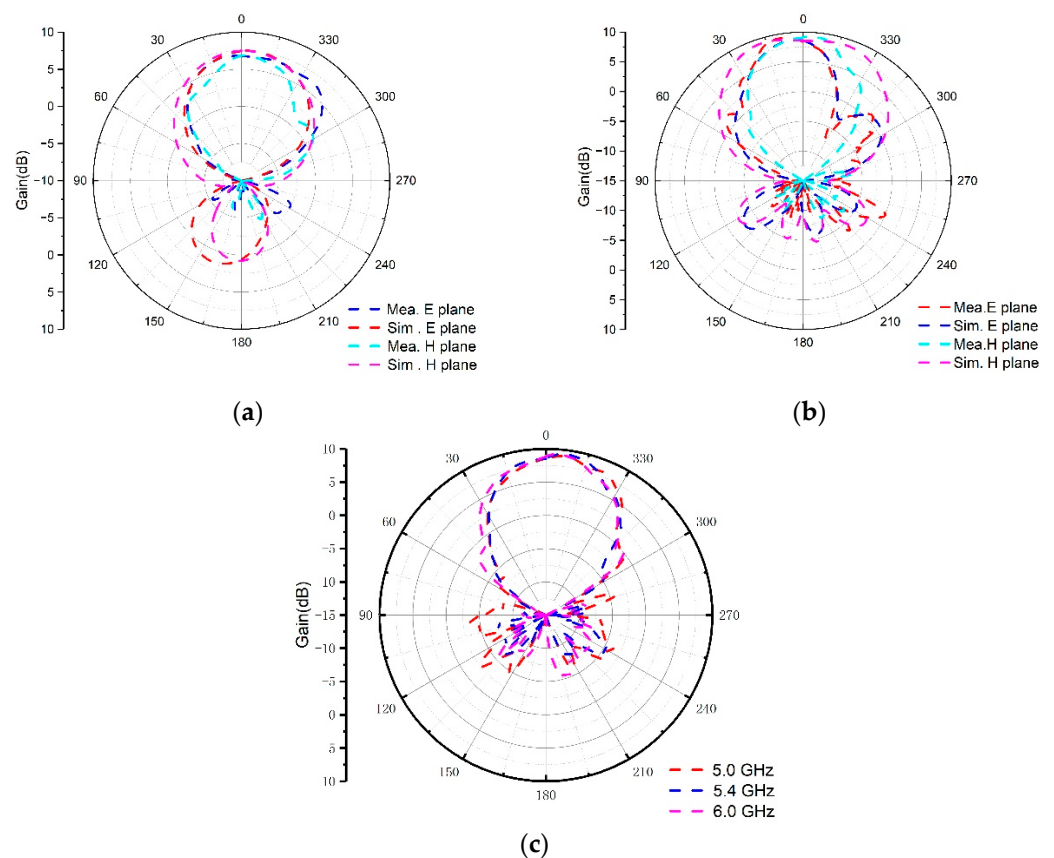


Figure 13. The radiation patterns of the proposed antenna at (a) 2.45 GHz, (b) 5.8 GHz, and (c) 5.0, 5.4, and 6.0 GHz.

The gain measurements of the proposed antenna with and without an FSS are shown in Figure 14. The gains show a significant improvement in the two operating bands compared with the original antenna without an FSS. The measured peak gain reaches 6.8 dB at 2.45 GHz and 9.0 dB at 5.8 GHz, which is a little lower than the simulated value. This reduction may be produced by the fabrication and measurement errors. What is more, the 3 dB gain bandwidth points are marked in Figure 14. The gain is higher than 3.8 dB at 2.0–3.15 GHz and higher than 6 dB at 4.8–6.42 GHz. The 3 dB gain bandwidth is 1.15 GHz and 1.62 GHz at 2.45 GHz and 5.8 GHz, respectively, which illustrates that the antenna has a wide gain bandwidth through integration with the FSS. Figure 15 is the simulated radiation efficiency of the proposed antenna with and without the FSS; it shows that the antenna with the FSS achieved a maximum radiation efficiency of 94.3% and 95.7% at 2.45 GHz and 5.8 GHz, respectively. A significant improvement of efficiency from 66.2% to 94.3% at 2.45 GHz occurs when the antenna is integrated with the FSS. However, this improvement in efficiency at the 5.8 GHz band is not obvious since it is already high without the FSS. The proposed antenna has a high efficiency in the range of 85–95.7% in the two operating bands.

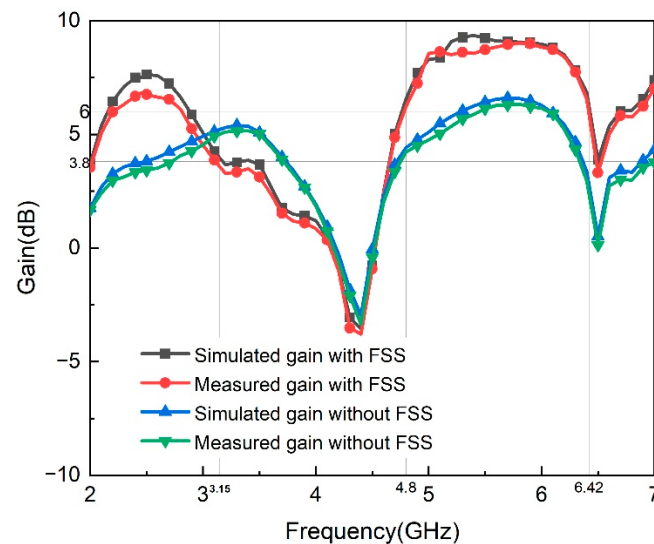


Figure 14. The comparison of the simulated and measured gain of the proposed antenna with and without an FSS.

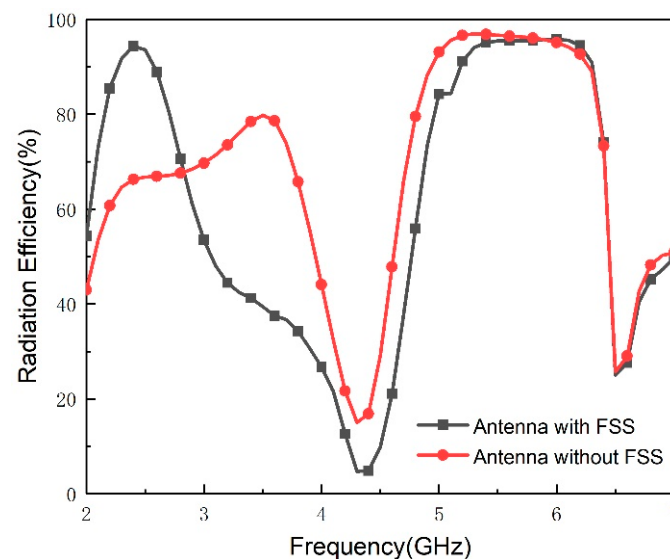


Figure 15. The simulated radiation efficiency of the antenna with and without an FSS.

Analyzing the current distribution of the antenna is a direct way to figure out the operating principle of the antennas. The current distribution of the antenna with the FSS is displayed in Figure 16. As shown in Figure 16a, a strong current is distributed by the central 3×3 FSS unit cells, and a relatively weaker current comes from the outer FSS unit cells, which explains the reason for the increased number of the FSS unit cells no longer improving gain significantly when the number is already high enough, as mentioned above. Figure 16b,c show the current distribution of the antenna integrating with the FSS. It can be observed here that the current on the antenna and the FSS are strong and saturated. The antenna has a larger equivalent aperture compared with Figure 3 in Section 2, which is without the FSS.

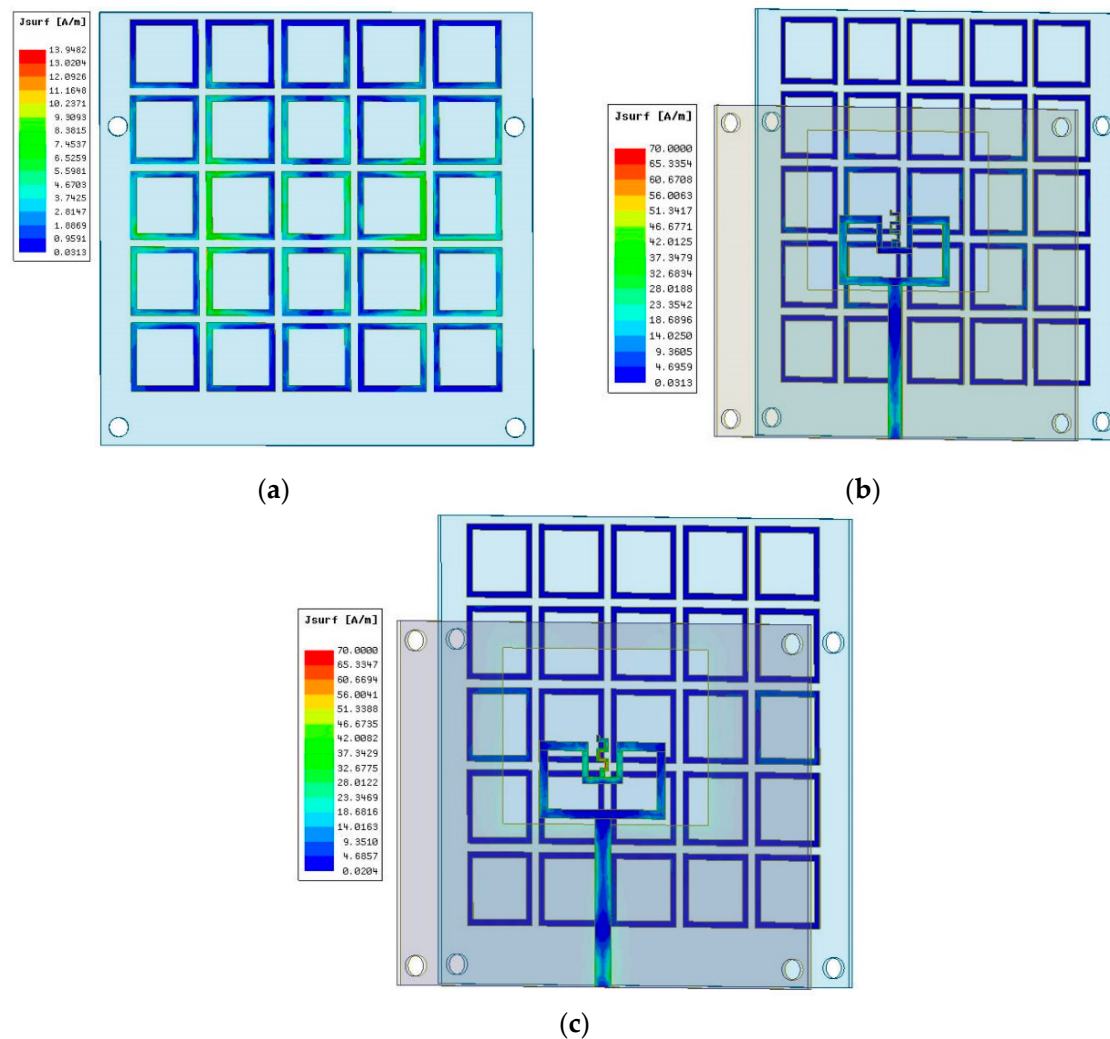


Figure 16. Current distribution of (a) the FSS and the antenna with an FSS at (b) 2.45 GHz and (c) 5.8 GHz.

Previous work related to dual-band, multi-band, broadband, metamaterials, and FSS reflector integration antennas is displayed in Table 3. The antennas are compared in four dimensions which are size, bandwidth, gain, and radiation efficiency. The size is presented as wavelength, with the largest wavelength of operating frequencies being adopted for multi-band antennas. In comparison to other studies using different design methods, it is evident that the proposed antenna has a small size and achieves a wider bandwidth with an appropriate gain and radiation efficiency.

Table 3. Comparison of the proposed antenna with other studies.

Reference	Dimensions (λ_0^3)	Working Bands (GHz)	Bandwidth	Peak Gain (dB)	Radiation Efficiency
[6]	$0.86 \times 0.86 \times 0.04$	2.25–2.75 and 4.6–4.85	20% and 5.3%	7.55 and 4.7	null
[10]	1×1.15	2.38–2.51	5.3%	9.98	null
		2.92–3.36	13%	3.82	
		3.74	null	10.4	
		3.83	null	8.08	
[11]	$0.85 \times 0.85 \times 0.1$	2.36–2.76 and 5.1–6.2	15.6% and 9.3%	7.2 and 7.3	null
[12]	$0.66 \times 0.66 \times 0.31$	2.37–2.56 and 5.15–6.22	7% and 18.8%	7.5 and 6.8	null
[13]	$10.32 \times 4.251 \times 1.295$	3.5–5.8	51.12%	12.4	77.5%
[23]	$0.66 \times 0.66 \times 0.13$	2.3–2.6 and 4.6–5.78	11.8% and 22%	6.4 and 7	null
[24]	$0.62 \times 0.43 \times 0.04$	2.4–2.48 and 5.72–5.83	5.5% and 7.48%	4.9 and 8.3	null
This work	$0.6 \times 0.6 \times 0.13$	2.3–2.65 and 4.9–6.45	13% and 27%	6.8 and 9.0	94.3% and 95.7%

4. Conclusions

In this article, a double-layer dual-band antenna based on the FSS is proposed. A layer of a frequency selective surface is loaded to improve the gain and bandwidth of the antenna at two operating frequencies. The realization of a dual-band operation is through a square loop loading a meander stub and the tuned reflection phase shift of the FSS to achieve field superposition. The equivalent circuit models of the antenna and the FSS unit are given and analyzed. The comprehensive parameters are presented and discussed to reveal the working mechanism of the proposed antennas. The proposed antenna achieves a high gain of 6.8 dB at 2.45 GHz and 9.0 dB at 5.8 GHz with a low profile of $0.13 \lambda_0$ and a structure which is easy to fabricate. Meanwhile, the antenna obtains a wide impedance bandwidth of 13% at 2.45 GHz and 27% at 5.8 GHz. The 3 dB gain bandwidth attains 2–3.1 GHz and 4.8–6.4 GHz in the two operating bands. The results show that the antenna has a good radiation performance in the WLAN bands and is easy to manufacture. It can also be used for ISM communication.

Author Contributions: Conceptualization, C.L. and C.S.; methodology, J.Z.; validation, J.G.; writing—original draft preparation, C.S.; writing—review and editing, C.L.; visualization, J.Z. All authors have read and agreed to the published version of the manuscript.

Funding: This research is supported in part by the National Nature Science Foundation of China 62071316, Sichuan Science and Technology Program 2021YFH0152, and 2020YFH0091.

Data Availability Statement: All relevant data have been presented in article.

Conflicts of Interest: The authors declare that they have no conflicts of interest.

References

- Chen, H.; Tao, Y. Antenna gain and bandwidth enhancement using frequency selective surface with double rectangular ring elements. In Proceedings of the 9th International Symposium on Antennas, Propagation and EM Theory, Guangzhou, China, 29 November–2 December 2010; IEEE: Piscataway, NJ, USA, 2010; pp. 271–274. [\[CrossRef\]](#)
- Ghaffar, A.; Li, X.J.; Seet, B.-C. Compact Dual-Band Broadband Microstrip Antenna at 2.4 GHz and 5.2 GHz for WLAN Applications. In Proceedings of the 2018 IEEE Asia-Pacific Conference on Antennas and Propagation (APCAP), Auckland, New Zealand, 5–8 August 2018; IEEE: Piscataway, NJ, USA, 2018; pp. 198–199. [\[CrossRef\]](#)
- Chen, Y.; Jiao, Y.; Zhao, G.; Zhang, F.; Liao, Z.; Tian, Y. Dual-Band Dual-Sense Circularly Polarized Slot Antenna With a C-Shaped Grounded Strip. In *IEEE Antennas and Wireless Propagation Letters*; IEEE: Piscataway, NJ, USA, 2011; Volume 10, pp. 915–918. [\[CrossRef\]](#)
- Li, X.-P.; Xu, G.; Ma, M.-R.; Duan, C.-J. UWB Dual-Band-Notched Lanky-Leaf-Shaped Antenna with Loaded Half-Square-Like Slots for Communication System. *Electronics* **2021**, *10*, 1991. [\[CrossRef\]](#)
- Przesmycki, R.; Bugaj, M. Crescent Microstrip Antenna for LTE-U and 5G Systems. *Electronics* **2022**, *11*, 1201. [\[CrossRef\]](#)

6. Liu, S.; Raad, R.; Theoharis, P.I.; Tubbal, F. Dual-Band Folded-End Dipole Antenna for Plastic CubeSats. *IEEE J. Miniatur. Air Space Syst.* **2020**, *1*, 172–178. [\[CrossRef\]](#)
7. Li, T.; Zhai, H.; Wang, X.; Li, L.; Liang, C. Frequency-Reconfigurable Bow-Tie Antenna for Bluetooth, WiMAX, and WLAN Applications. *IEEE Antennas Wirel. Propag. Lett.* **2015**, *14*, 171–174. [\[CrossRef\]](#)
8. Ullah, S.; Ullah, S.; Ahmad, I.; Khan, W.U.R.; Ahmad, T.; Habib, U.; Albreem, M.A.; Alsharif, M.H.; Uthansakul, P. Frequency reconfigurable antenna for portable wireless applications. *Comput. Mater. Contin.* **2021**, *68*, 3015–3027. [\[CrossRef\]](#)
9. Dildar, H.; Althobiani, F.; Ahmad, I.; Khan, W.U.R.; Ullah, S.; Mufti, N.; Ullah, S.; Muhammad, F.; Irfan, M.; Glowacz, A. Design and Experimental Analysis of Multiband Frequency Reconfigurable Antenna for 5G and Sub-6 GHz Wireless Communication. *Micromachines* **2021**, *12*, 32. [\[CrossRef\]](#)
10. Khan, O.M.; Islam, Z.U.; Islam, Q.U.; Bhatti, F.A. Multiband High-Gain Printed Yagi Array Using Square Spiral Ring Metamaterial Structures for S-Band Applications. *IEEE Antennas Wirel. Propag. Lett.* **2014**, *13*, 1100–1103. [\[CrossRef\]](#)
11. Zhai, H.; Zhang, K.; Yang, S.; Feng, D. A Low-Profile Dual-Band Dual-Polarized Antenna with an AMC Surface for WLAN Applications. *IEEE Antennas Wirel. Propag. Lett.* **2017**, *16*, 2692–2695. [\[CrossRef\]](#)
12. Al-Gburi, A.J.A.; Ibrahim, I.M.; Zakaria, Z.; Abdulhameed, M.K.; Saeidi, T. Enhancing Gain for UWB Antennas Using FSS: A Systematic Review. *Mathematics* **2021**, *9*, 3301. [\[CrossRef\]](#)
13. Alwareth, H.; Ibrahim, I.M.; Zakaria, Z.; Al-Gburi, A.J.A.; Ahmed, S.; Nasser, Z.A. A Wideband High-Gain Microstrip Array Antenna Integrated with Frequency-Selective Surface for Sub-6 GHz 5G Applications. *Micromachines* **2022**, *13*, 1215. [\[CrossRef\]](#)
14. Decoster, B.; Maes, S.; Cuiñas, I.; García Sánchez, M.; Caldeirinha, R.; Verhaever, J. Dual-Band Single-Layer Fractal Frequency Selective Surface for 5G Applications. *Electronics* **2021**, *10*, 2880. [\[CrossRef\]](#)
15. Fernandes, E.M.F.; da Silva, M.W.B.; da Silva Briggs, L.; de Siqueira Campos, A.L.P.; de Araújo, H.X.; Casella, I.R.S.; Capovilla, C.E.; Souza, V.P.R.M.; de Matos, L.J. 2.4–5.8GHz dual-band patch antenna with FSS reflector for radiation parameters enhancement. *AEU-Int. J. Electron. Commun.* **2019**, *108*, 235–241. [\[CrossRef\]](#)
16. 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*, 2165–2171. [\[CrossRef\]](#)
17. Wang, S.; Gao, H. A Dual-Band Wearable Conformal Antenna Based on Artificial Magnetic Conductor. *Int. J. Antennas Propag.* **2022**, *2022*, 9970477. [\[CrossRef\]](#)
18. Abdelghani, M.L.; Attia, H.; Denidni, T.A. Dual- and Wideband Fabry–Pérot Resonator Antenna for WLAN Applications. *IEEE Antennas Wirel. Propag. Lett.* **2017**, *16*, 473–476. [\[CrossRef\]](#)
19. Yi, X.; Zhou, L.; Hao, S.; Chen, X. Dual-Band High-Gain Shared-Aperture Antenna Integrating Fabry–Perot and Reflect array Mechanisms. *Electronics* **2022**, *11*, 2017. [\[CrossRef\]](#)
20. Al-Gburi, A.J.A.; Ibrahim, I.M.; Abdulhameed, M.K.; Zakaria, Z.; Zeain, M.Y.; Keriee, H.H.; Nayyef, N.A.; Alwareth, H.; Khaleel, A.D. A miniaturised UWB FSS with Stop-band Characteristics for EM Shielding Applications. *Prz. Elektrotechniczny* **2021**, *25*, 142–145. [\[CrossRef\]](#)
21. Costa, F.; Monorchio, A.; Manara, G. Efficient Analysis of Frequency-Selective Surfaces by a Simple Equivalent-Circuit Model. *IEEE Antennas Propag. Mag.* **2012**, *54*, 35–48. [\[CrossRef\]](#)
22. Trentini, G.V. Partially reflecting sheet arrays. *IRE Trans. Antennas Propag.* **1956**, *4*, 666–671. [\[CrossRef\]](#)
23. Varamini, G.; Keshtkar, A.; Naser-Moghadasi, M. Compact and miniaturized microstrip antenna based on fractal and metamaterial loads with reconfigurable qualification. *AEU-Int. J. Electron. Commun.* **2018**, *83*, 213–221. [\[CrossRef\]](#)
24. Chen, H.Y.; Tao, Y. Bandwidth enhancement of a U-slot patch antenna using dual-band frequency-selective surface with double rectangular ring elements. *Microw. Opt. Technol. Lett.* **2011**, *53*, 1547–1553. [\[CrossRef\]](#)