

A Novel Antenna Based on Hexagonal Shaped Left-Handed Materials

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Abstract

In this paper, the design and analysis of a hexagonal left-handed material is presented, which is based on the analysis of the structural parameters. The effective permittivity and the effective permeability of the designed hexagonal left-handed material are simultaneously negative in the range from 7.4GHz to 7.9GHz. According to the empirical formula of the microstrip antenna, a conventional microstrip antenna is designed. The different combinations of the hexagonal left-handed materials and the conventional microstrip antenna are analyzed in HFSS software. The novel antenna is proposed based on the analysis of the combinations. The simulation results show that the gain of the antenna increased by 0.51dB, and the half power beam width decreased by 3°. Besides, the bandwidth of the novel antenna is 140MHz wider than that of the conventional microstrip antenna. It is concluded that the performance of microstrip antenna can be improved by using left-handed materials.

Keywords: left-handed material, microstrip antenna, gain, half power beam width, bandwidth

1. Introduction

The left-handed material (LHM) is a material which the effective permeability and the effective permittivity are simultaneous negative. This characteristic is determined by the structure of the LHM rather than the composition of the LHM. In 1968, the term LHM is theoretical postulated by Veselago. Due to the material with abnormal property do not exist in nature, the LHM left neglected [1]. The interest in Veselago's work was renewed since the split-ring resonators put forward, which exhibited negative permeability. Almost at the same time, the negative permittivity came true with the use of copper wires. Based on these researches, Smith proposed the first LHM [1]. The first LHM consisted of an array of split-ring resonators and copper wires.

The permittivity and the permeability of the traditional medium are positive. When the electromagnetic wave propagating in the traditional medium, the electric field E , the magnetic field H , and the propagation vector k formed "right-handed" (RH) rule based on the individual Maxwell curl equation of the electric field [1]. However, When the electromagnetic wave propagating in the LHM, the vector E , H and k formed a "left-handed" rule. Many attractive characteristics of LHM have been found such as the reversal of Snell's law, reversed Doppler Effect, Vavilov-Cerenkov effect [2-3], etc. Because of these abnormal properties, LHM has been used to design different microwave components like radomes, filters, antennas, phase shifters and so on.

The microstrip patch antennas are widely used due to the advantages like small volume [4-6], low weight and easy to fabricate. Because of these advantages, the microstrip patch antennas play an important role in the modern communication system. With the development of the science and technology, communication equipments have a rapid

development in recent years, and the demand for smaller antenna with higher gain or wider bandwidth has emerged. Therefore, a new technology to improve the performance of the microstrip antenna is badly needed.

Recently, the LHM used in the antenna technology is extensively studied. The LHM are used in the Vivaldi antenna, and the gain of the antenna improved by 1.2dB, the half power beam width (HPBW) decreased by 14° [7]. A mushroom-like LHM was used to reduce the thickness of the antenna, and the bandwidth of the antenna extended with a growing of 150MHz, as well as the gain increased by 1.95dB [8]. Bala proposed a microstrip patch antenna based on the split ring resonators. As a result, the bandwidth of the antenna increased, while the gain decreased [9]. Although many studies are ongoing, how to further improve the radiation characteristics of the antennas and the method to take advantages of the LHM are still the challenges.

This paper is arranged as follows. Section II analyzes the influence of the structure parameters on the effective permittivity and the effective permeability, and a hexagonal shaped LHM is proposed. A conventional microstrip antenna is designed in Section III. As a comparison, a novel antenna is designed in Section IV, and the performance of the proposed antennas constituted by different LHM combinations is also demonstrated in this section. The comparison between the designed novel antenna and the conventional microstrip antenna is done in Section V. Finally, a conclusion is put forward that the radiation characteristics of the microstrip antenna can be improved by using LHM.

2. LHM Design and Analysis

The hexagonal shaped LHM was proposed in 2012 [10], as shown in Figure 1 (a). The strips are made of copper with the thickness of 0.017mm laid out on the face of the substrate which the relative dielectric constant is 4.4, and the thickness of the substrate is $t = 0.8mm$. In the present simulation, the width of the hexagonal strip is $w = 0.33mm$, the length of the strip is $a = 5.7mm$, and the cut of the wire is $g = 0.33mm$. Figure 1 (a) is the front view of the hexagonal LHM, and the angular view of the hexagonal LHM is shown in Figure 1 (b). Figure 1 (a) and Figure 1 (b) illustrates the structural parameters of the hexagonal LHM.

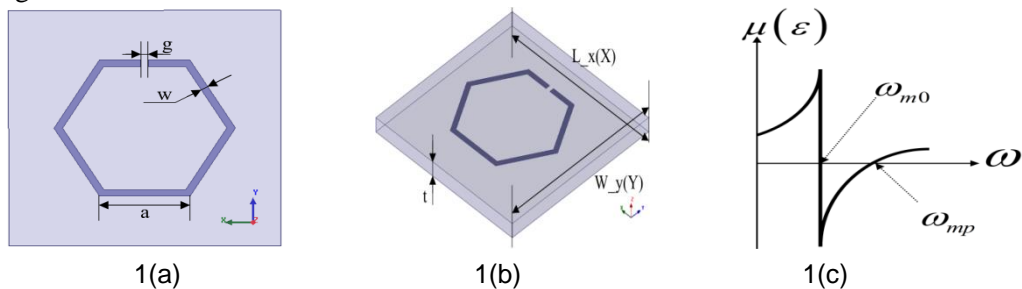


Figure 1. The Schematic of the Hexagonal LHM (a) Front View; (b) Angular View; (c) the Resonance Frequency and the Plasma Frequency

The boundary conditions are set as perfect electric condition (PEC) on y-axis and perfect magnetic condition (PMC) on z-axis while wave ports are constructed in x direction. When the electromagnetic wave propagating through the hexagonal LHM, there is a capacitance and inductance in the equivalent circuit. Thus, the hexagonal LHM can be considered as a LC resonant circuit [10], and there is no doubt that the resonance frequency of the hexagonal shaped LHM only depends on the inductance and capacitance of the hexagonal LHM [10]. When the structural parameters changed, the equivalent circuit will changed either. Besides, the resonance frequency and the plasma frequency will be changed. Within the domain $\omega_{m0} < \omega < \omega_{mp}$ the effective permittivity and the

effective permeability are negative. The ω_{m0} represents for the resonance frequency, and ω_{mp} represents for the plasma frequency, as illustrated in Figure 1(c).

The simulation of the hexagonal LHM structure is executed using HFSS software, and the reflection and transmission data of the hexagonal LHM can be calculated. The retrieval procedure is applied to calculate the effective permittivity and the effective permeability from the simulated reflection and transmission data. The most commonly used retrieval algorithm [2] is

$$n = \frac{1}{kt} \cos^{-1} \left[\frac{1}{2S_{21}} (1 - S_{11}^2 + S_{21}^2) \right] \quad (1)$$

$$z = \sqrt{\frac{(1 + S_{11})^2 - S_{21}^2}{(1 - S_{11})^2 - S_{21}^2}} \quad (2)$$

$$\varepsilon = n/z \quad (3)$$

$$\mu = nz \quad (4)$$

Where the parameter n represents for the refractive index and z represents for the wave impedance, k is the wave number of free space, t is the thickness of the LHM structure.

The parameter X represents for the length of the substrate, and it varied in five steps of 1mm each, that is $X = 8mm$, $X = 9mm$, $X = 10mm$, $X = 11mm$, $X = 12mm$. The effect of the length of the substrate on the effective permittivity and the effective permeability are demonstrated in figure 2(a) and figure 2(b).

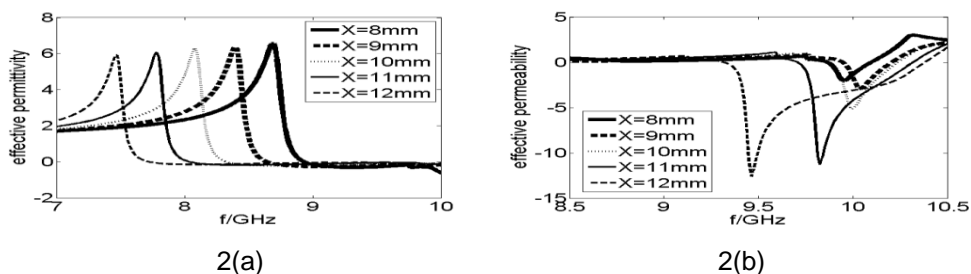


Figure 2. The Retrieved Parameter Versus Frequency Plot (a) Effective Permittivity Versus Frequency Plot; (b) Effective Permeability Versus Frequency Plot

Figure 2(a) shows that the frequency range of the negative effective permittivity is dependent on the length of the substrate. With the length of the substrate increase, the negative frequency band shift from high frequency band to low frequency band. The range of the negative effective permeability shares the same regular with the effective permittivity.

The parameter Y is used to represent for the width of the substrate, and varied in five steps for respectively 8mm, 9mm, 10mm, 11mm, and 12mm. The effect of the width of the substrate on the effective permittivity and the effective permeability are demonstrated in figure 3(a) and figure 3(b).

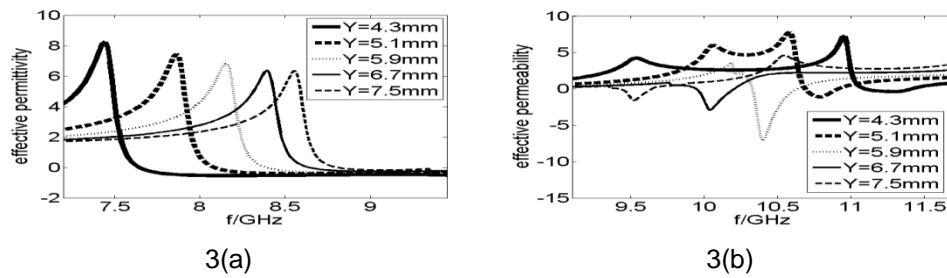


Figure 3. The Retrieved Parameter Versus Frequency Plot (a) Effective Permittivity Versus Frequency Plot; (b) Effective Permeability Versus Frequency Plot

In figure 3(a), It can be found that the range of the negative effective permittivity shift from low frequency band to high frequency band when the width of the substrate increased. On the contrary, the range of the negative effective permeability shifts from high frequency band to low frequency band when the width of the substrate increased, as shown in figure 3(b).

The gap of the copper strip is expressed as the parameter g , and varied in five steps of 0.1mm each, that is $g = 0.13mm$, $g = 0.23mm$, $g = 0.33mm$, $g = 0.43mm$, $g = 0.53mm$. The effect of the gap on the effective permittivity and the effective permeability are exhibited in figure 4(a) and figure 4(b).

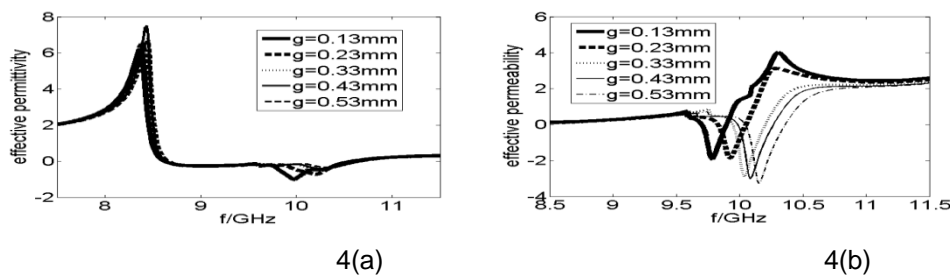


Figure 4. The Retrieved Parameter Versus Frequency Plot (a) Effective Permittivity Versus Frequency Plot; (b) Effective Permeability Versus Frequency Plot

It indicates that the effective permittivity is almost independent of the gap, as shown in figure 4(a). The frequency bands stay the same when the gap changed. While the range of the negative effective permeability shift from low frequency band to high frequency when the width of the substrate increased.

The length of the hexagon is varied in five steps for respectively 2.9mm, 3.6mm, 4.3mm, 5mm, and 5.7mm, and the effect on the effective permittivity and the effective permeability are demonstrated in figure 5(a) and figure 5(b).

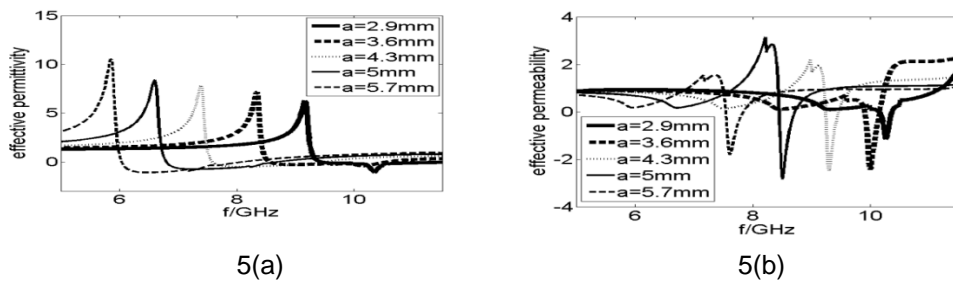


Figure 5. The Retrieved Parameter Versus Frequency Plot (a) Effective Permittivity Versus Frequency Plot; (b) Effective Permeability Versus Frequency Plot

The results show that the effective permittivity and the effective permeability hinge on the length of the hexagon. The negative frequency range of the effective permittivity and the effective permeability shifts from high frequency band to low frequency when the length of the hexagon increased.

The width of the copper strip is represented as the parameter w . The width of the copper strip varied in five steps of 0.1mm each, that is $w=0.13mm$, $w=0.23mm$, $w=0.33mm$, $w=0.43mm$, $w=0.53mm$. The effect on the effective permittivity and the effective permeability are shown in figure 6(a) and figure 6(b).

Figure 6(a) shows that the negative frequency band of the effective permittivity shift from low frequency band to high frequency band as the width of the copper strip increased. Figure 6(b) shows that the effective permeability is almost independent of the width of the copper strip.

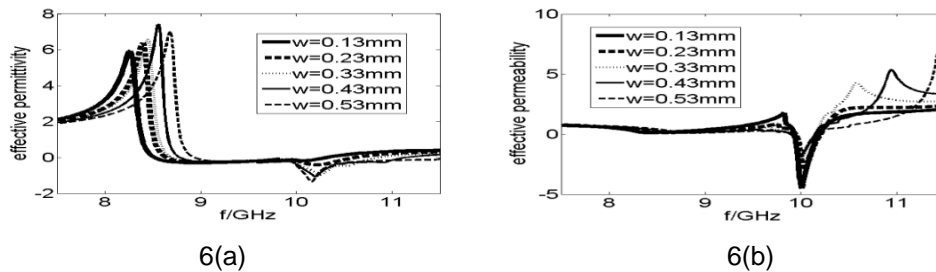


Figure 6. The Retrieved Parameter Versus Frequency Plot (a) Effective Permittivity Versus Frequency Plot; (b) Effective Permeability Versus Frequency Plot

The parameter t is used to represent for the thickness of the hexagonal LHM. The thickness is varied in five steps for respectively 0.72mm, 0.76mm, 0.8mm, 0.84mm, and 0.88mm. The effect on the effective permittivity and the effective permeability are demonstrated in figure 7(a) and figure 7(b).

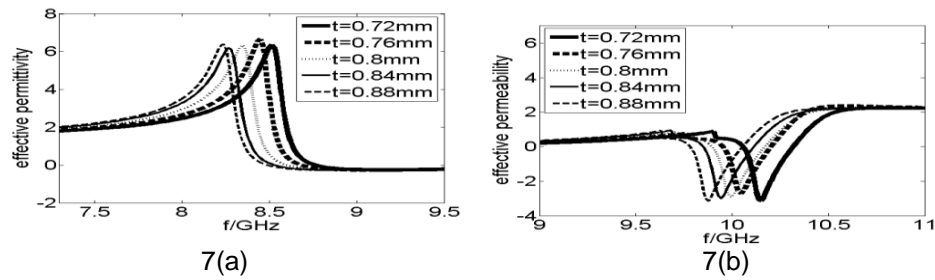


Figure 7. The Retrieved Parameter Versus Frequency Plot (a) Effective Permittivity Versus Frequency Plot; (b) Effective Permeability Versus Frequency Plot

It can be found that the negative frequency band of the effective permittivity shift from high frequency band to low frequency band, and the negative frequency range of the effective permeability share the same regular with the effective permittivity.

After the parametric analysis of the hexagonal LHM structure, the dimensions corresponding to the best results are used to design the hexagonal LHM. The design parameters selected for further study are listed in Table 1.

Table 1. The Parameters of the Designed Hexagonal LHM

Structural parameters	value
$L_x(X)$	12mm
$W_y(Y)$	12mm
g	0.33mm
w	0.33mm
t	0.8mm
a	5.7mm

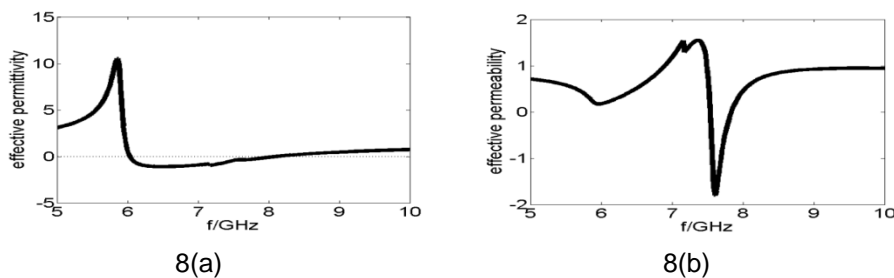


Figure 8. The Retrieved Parameter of the Designed Hexagonal LHM (a) Effective Permittivity; (b) Effective Permeability

Figure 8(a) and Figure 8(b) show that the frequency band of negative permittivity extends from 6GHz to 8GHz, and the permeability is negative from 7.4GHz to 7.9GHz. Therefore, the double negative properties appeared from 7.4GHz to 7.9GHz.

It can be found that the hexagonal LHM reflects the pass-band characteristic from the Figure 9(a) and Figure 9(b), and the pass-band extends from 7.76GHz to 7.87GHz. Besides, the double negative properties appeared from 7.4GHz to 7.9GHz. Therefore, the designed hexagonal LHM has the left-handed pass-band property.

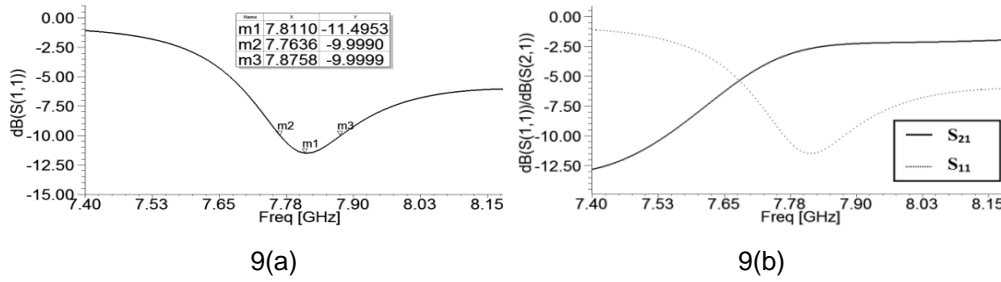


Figure 9. The Performance of the Hexagonal LHM: (a) S_{11} ; (b) S_{21}

3. Microstrip Antenna Design

The microstrip antenna is designed from the following formulas^[8]. The L_e represents for the effective length of the patch, and calculated by

$$L_e = \lambda_g / 2 \quad (5)$$

Where the λ_g represents for the wavelength of the material, and λ_g is calculated by

$$\lambda_g = \lambda_0 / \sqrt{\epsilon_e} \quad (6)$$

In the equation 6, the λ_0 represents for the wavelength of the free space, and the ϵ_e represents for the effective dielectric constant, the ϵ_e is calculated by

$$\epsilon_e = \frac{\epsilon_r + 1}{2} + \frac{\epsilon_r - 1}{2} \left(1 + 12 \frac{h}{W} \right)^{-\frac{1}{2}} \quad (7)$$

Where the ϵ_r represents for the relative dielectric constant of the substrate, the h represents for the height of the substrate, the W represents for the width of the patch. Given that the electromagnetic wave are radiated from a gap in the front of the substrate^[11]. The length of the gap is represented as ΔL , and the ΔL is calculated by

$$\Delta L = 0.412h \frac{(\epsilon_e + 0.3)(W/h + 0.264)}{(\epsilon_e - 0.258)(W/h + 0.8)} \quad (8)$$

The actual length of the patch is calculated by

$$L = L_e - 2\Delta L \quad (9)$$

Where the L represents for the actual length of the patch. Here, inserting the equation (8) into the equation (9), it can be obtained that

$$L = L_e - 2\Delta L = \frac{c}{f_0} \frac{1}{\sqrt{\epsilon_e}} - 2\Delta L \quad (10)$$

The W represents for the width of the patch and it can be calculated by

$$W = \frac{c}{2f_r} \sqrt{\frac{2}{\epsilon_r + 1}} \quad (11)$$

The parametric studies are not written here for brevity. From the parametric studies, the optimal values of each parameter are obtained. The values of the structure parameter are exhibited in table II.

Table 2. The Parameters of the Designed Conventional Microstrip Antenna

Structural parameters	value
W0	36mm
L0	36mm
W1	8.9mm
L1	11.7mm
H	0.8mm

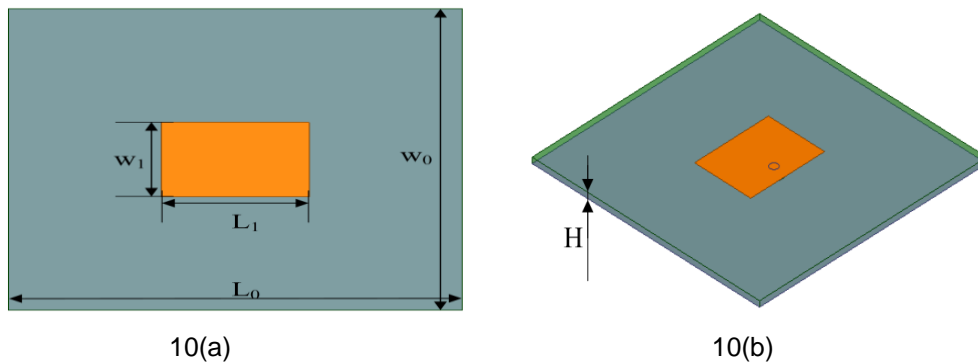


Figure 10. The Sketch Graph of the Conventional Microstrip Antenna: (a) Front View; (b) Side-View

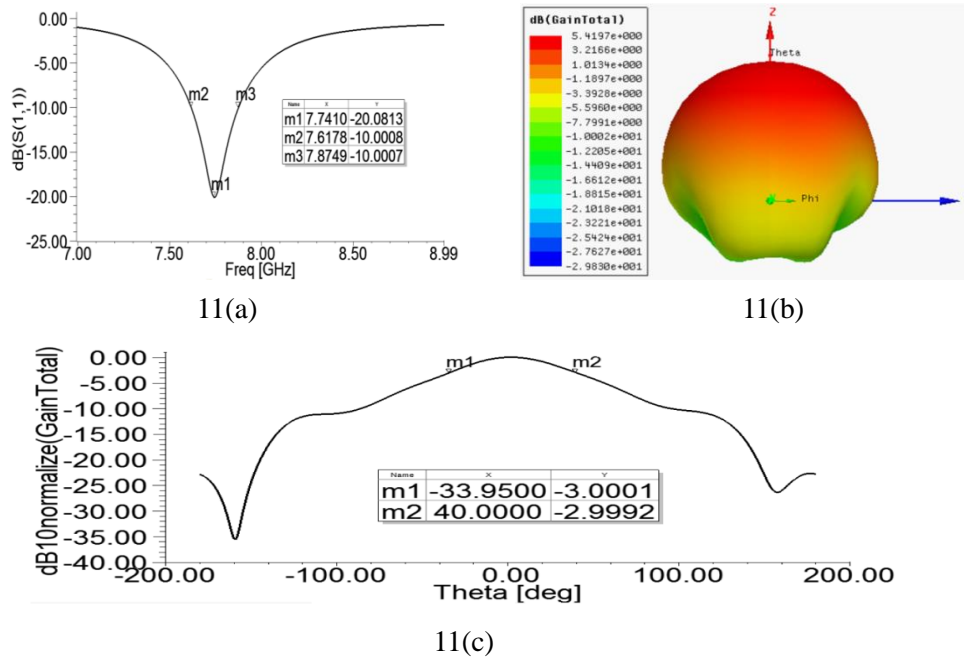


Figure 11. The Performance of the Conventional Microstrip Antenna: (a) Return Loss; (b) Gain; (c) HPBW

The microstrip antenna configuration is exhibited in Figure 10 (a), and the front view of the microstrip antenna is shown in Figure 10(b). The size of the microstrip antenna is $36 \times 36 \text{mm}^2$. The microstrip antenna is designed at 50Ω matching impedance. The relative dielectric constant of the substrate is 4.4 and the thickness of the microstrip antenna is 0.8mm. The inner conductor of the coaxial feed passes through a hole and electrically connected to the patch [10]. The simulation analysis is carried on with the use of the HFSS software.

4. Novel Antenna Based On LHM

The proposed antennas consist of the hexagonal LHMs and the conventional microstrip antenna. From the literature [12], different LHM locations have an impact on the radiation characteristics of the antenna. In this paper, different models are proposed for further study. The structural configurations of the proposed antennas are shown in figure 12.

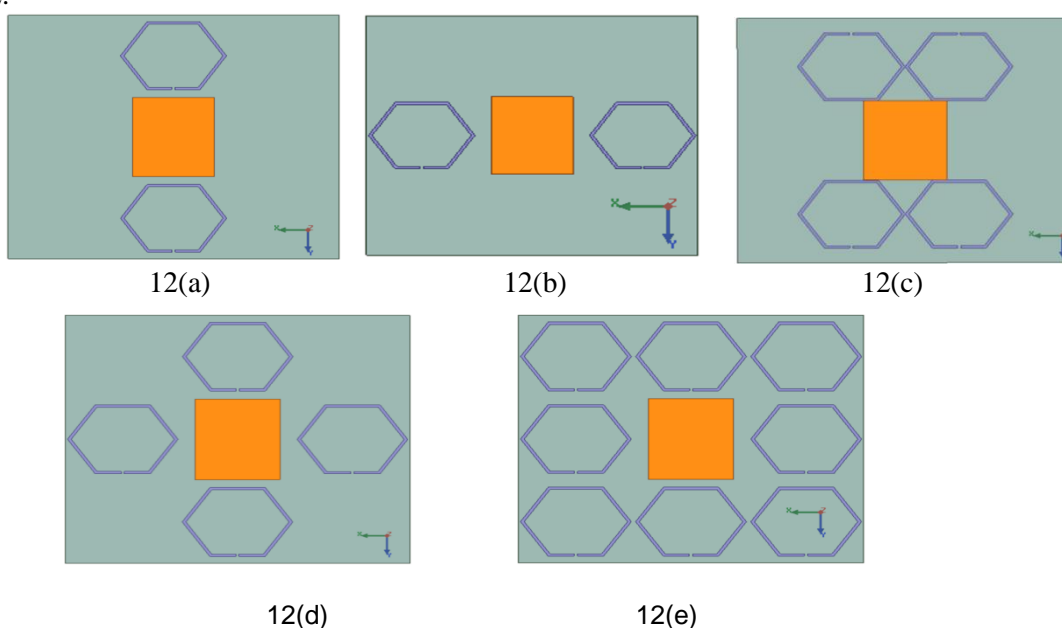


Figure 12. The Combinations of the Conventional Microstrip Antenna and the Hexagonal LHMs: (a) Model 1; (b) Model 2; (c) Model 3; (d) Model 4; (e) Model 5

The analysis of the proposed antennas is not written here for brevity. In order to demonstrate the different radiation characteristics of the proposed antennas, table 3 is constructed. It is easy to contrast the performances of various models with the use of the table.

Table 3. The Performances of Various Models

Model	Working Frequency	Bandwidth	Gain	HPBW
Model 1	7.93GHz	180MHz	2dB	81°
Model 2	7.75GHz	250MHz	5.28dB	75.7°
Model 3	8.43GHz	160MHz	4.67dB	83°
Model 4	7.76GHz	400MHz	5.93dB	71°
Model 5	7.93GHz	160MHz	1.8dB	80°

After the analysis of the proposed antennas, the combination corresponding to the best result is used for the novel antenna. The structural configuration of the novel antenna is demonstrated in figure 13.

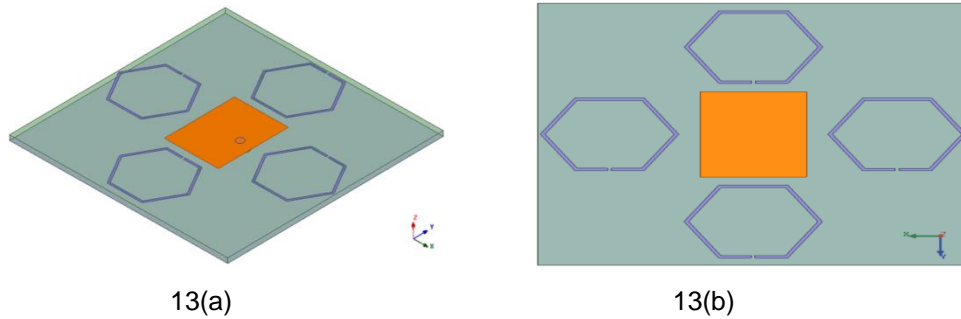


Figure 13. The Sketch Graph of the Novel Antenna: (a) Front View; (b) Side-View

The novel antenna is consists of the conventional microstrip antenna and four hexagonal LHMs. The four hexagonal LHMs located in four direction of the patch, and the hexagonal LHMs placed at the top of the substrate. The novel antenna is designed to resonate within the double negative frequency region of the hexagonal LHM.

Figure 14(a) shows the return loss of the novel antenna. It can be observed that the resonating frequency of the novel antenna is 7.76GHz, and the bandwidth is 400MHz. Because of the introduction of the hexagonal LHMs, the second resonating point produced at the frequency of 7.88GHz.

Figure 14(b) illustrates the gain of the novel antenna is 5.93dB. The HPBW of the novel antenna is shown in figure 14(c). It can be seen that the HPBW is about 71° for the novel antenna, slightly larger than that of the conventional microstrip antenna.

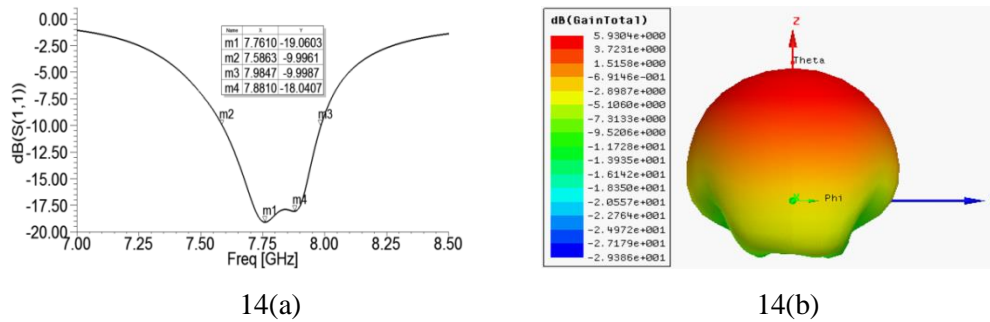


Figure 14. The Performance of the Novel Antenna: (a) Return Loss; (b) Gain; (C) HPBW

5. Conclusion

In this paper, a hexagonal LHM is proposed. The effect of the structural parameters on the electromagnetic properties is analyzed, and the hexagonal LHM is designed based on the analysis. In the range of 7.4GHz to 7.9GHz, the effective permittivity and the effective permeability of the hexagonal LHM are negative. Besides, the pass-band of the hexagonal LHM extends from 7.76GHz to 7.87GHz. Therefore, the range of 7.76GHz to 7.87GHz is a pass band with double negative property. In order to have an accurate comparison, the conventional microstrip antenna is designed at first. Then the antennas based on the hexagonal LHMs are proposed. The different combinations of the hexagonal LHMs and the conventional microstrip antenna are proposed. After the analysis of the different combinations, the novel antenna is put forward. The simulation results show that the conventional microstrip antenna has a bandwidth of 260MHz, and the gain of the microstrip antenna is 5.42dB, the HPBW is 74°. And the novel antenna's maximum gain is 5.93dB at 7.76GHz, improved by 0.51dB. The novel antenna's HPBW is 71° at 7.76GHz, decreased by 3°. Besides, the bandwidth of the novel antenna is 400MHz, 140MHz bigger than that of the conventional microstrip antenna. Therefore, there is an improvement in the antenna characteristics in term of gain, bandwidth, and HPBW. As a consequence, the performance of the microstrip antenna can be improved by using LHM.

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