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A Composite Heterostructure Mesh-shaped Patch Antenna Based on Left Handed Material

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Abstract

In this paper, a composite heterostructure mesh-shaped patch antenna based on left handed material (LHM) is presented. The method of finite difference time domain (FDTD) is used. The results show that electromagnetic wave resonance occurs near 4.52 GHz, where the equivalent permittivity and permeability of composite material are both negative. The composite antenna's gain improves 9.047 dB, its return loss reduces 20.26 dB compared to the conventional antenna's ones. The results indicate that this composite patch antenna system can reduce return loss of the antenna and increase the gain obviously.

Index Terms: LHM; Heterostructure; patch antenna; Return loss; Gain.

1. Introduction

Left handed material (LHM) is a novel periodic artificial material with simultaneously negative values of dielectric permittivity and magnetic permeability. As early as 1968, Vselageo investigated the abnormal phenomenon of the LHM in theory [1]. When the electromagnetic (EM) wave propagates through the material, the electric field, magnetic field and wave vector of the electromagnetic wave would form a left-handed triad. In 2000, the first artificial LHM was fabricated by Smith and his co-workers by combining SRRs and continuous wires [2]. The success in fabrication opened up the possibility for applying LHM's abnormal EM characteristics in optical and electromagnetic areas.

The heterostructure is composed of two different photonic crystals. The aberrance in the interface of heterostructure will create localized mode and transmission mode of electromagnetic wave [3-5]. The property of heterostructure can be applied in patch antenna widely.

The paper employs FDTD method to analyze a composite heterostructure mesh-shaped patch antenna based on LHM, and its performance parameters are attained by simulation. The refraction index of the medium is extracted from its S parameters in order to validate availability of the structure. Then, the performance of this composite LHM patch antenna is analyzed by its performance parameters.

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2. FDTD equations

Macroscopic Maxwell equations are a set of basic equations to dominate the electromagnetic phenomena, which can be written in differential form, as well as in integral form. The two curl equations in Maxwell equations is the differential form of Faraday's law of electromagnetic induction and the Ampere's law. FDTD equations use the two curl equations as the starting point; calculate electromagnetic field problems directly in time domain.

Maxwell curl equations:

$$\nabla \times \vec{H} = \vec{J} + \frac{\partial \vec{D}}{\partial t} \tag{1}$$

$$\nabla \times \vec{E} = -\vec{J}_m - \frac{\partial \vec{B}}{\partial t} \tag{2}$$

The relationship between electromagnetic fields and currents as follows:

$$\begin{aligned} &\vec{D} = \varepsilon \vec{E}, \quad \vec{B} = \mu \vec{H} \\ &\vec{J} = \sigma_{\varepsilon} \vec{E}, \quad \vec{J}_m = \sigma_m \vec{H} \end{aligned} \tag{3}$$

where $\vec{H}$, $\vec{E}$, $\vec{D}$ and $\vec{B}$ is the magnetic field, electric field strength, electric displacement vector and magnetic induction, respectively; $\vec{J}$ and $\vec{J}_m$ are the current density and magnetic flux density; ε , μ is the medium permeability and permittivity; σ_e , σ_m is the medium of electrical conductivity and magnetic resistivity, corresponding to power loss and magnetic loss of material.

3. Computing model of the patch antenna

In the simulation of many algorithms of patch antenna, because the FDTD method has many advantages [6-8], it can be used to simulate the complex patch antenna commendably. Maxwell equations can be transformed into scalar field model by calculating in rectangular coordinate system, and then numerical difference coefficient in the second rank precision is employed to replace differential quotient. The differential equations are discreted in space-time using the method proposed by Yee, and the patch antenna is made meshed. We assume Δx, Δy are space steps towards x, y direction, respectively, Δt is time step, then we can get difference equations in scalar field model. In transverse electric (TE) mode, Maxwell equations can be transformed into FDTD equations in iteration formulation:

$$E_x^{n+1}(i,j) = E_x^n(i,j) + \frac{H_z^{n+\frac{1}{2}}(i,j+\frac{1}{2}) - H_z^{n+\frac{1}{2}}(i,j-\frac{1}{2})}{\Delta y} \cdot \frac{\Delta t}{\varepsilon(i,j)} \tag{4}$$

$$E_y^{n+1}(i,j)=E_y^n(i,j)+\frac{H_z^{n+\frac{1}{2}}(i+\frac{1}{2},j)-H_z^{n+\frac{1}{2}}(i-\frac{1}{2},j)}{\Delta x}\cdot\frac{\Delta t}{\varepsilon(i,j)} \tag{5}$$

$$H_z^{n+\frac{1}{2}}(i,j)=H_z^{n-\frac{1}{2}}(i,j)+\frac{E_x^n(i,j+\frac{1}{2})-E_x^n(i,j-\frac{1}{2})}{\Delta y}\cdot\frac{\Delta t}{\mu}-\frac{E_x^n(i+\frac{1}{2},j)-E_x^n(i-\frac{1}{2},j)}{\Delta x}\cdot\frac{\Delta t}{\mu} \tag{6}$$

where, n is refer to cell number, and i, j refer to two-dimensional coordinate. In order to ensure a steady iterative solution, $\Delta x, \Delta y, \Delta t$ must be selected to meet the stability condition necessarily[9]:

$$\Delta t \le \frac{1}{c\sqrt{(\Delta x)^{-2}+(\Delta y)^{-2}}} \tag{7}$$

For the transverse magnetic (TM) mode, it can also get similar formula on Hx, Hy, Ez.

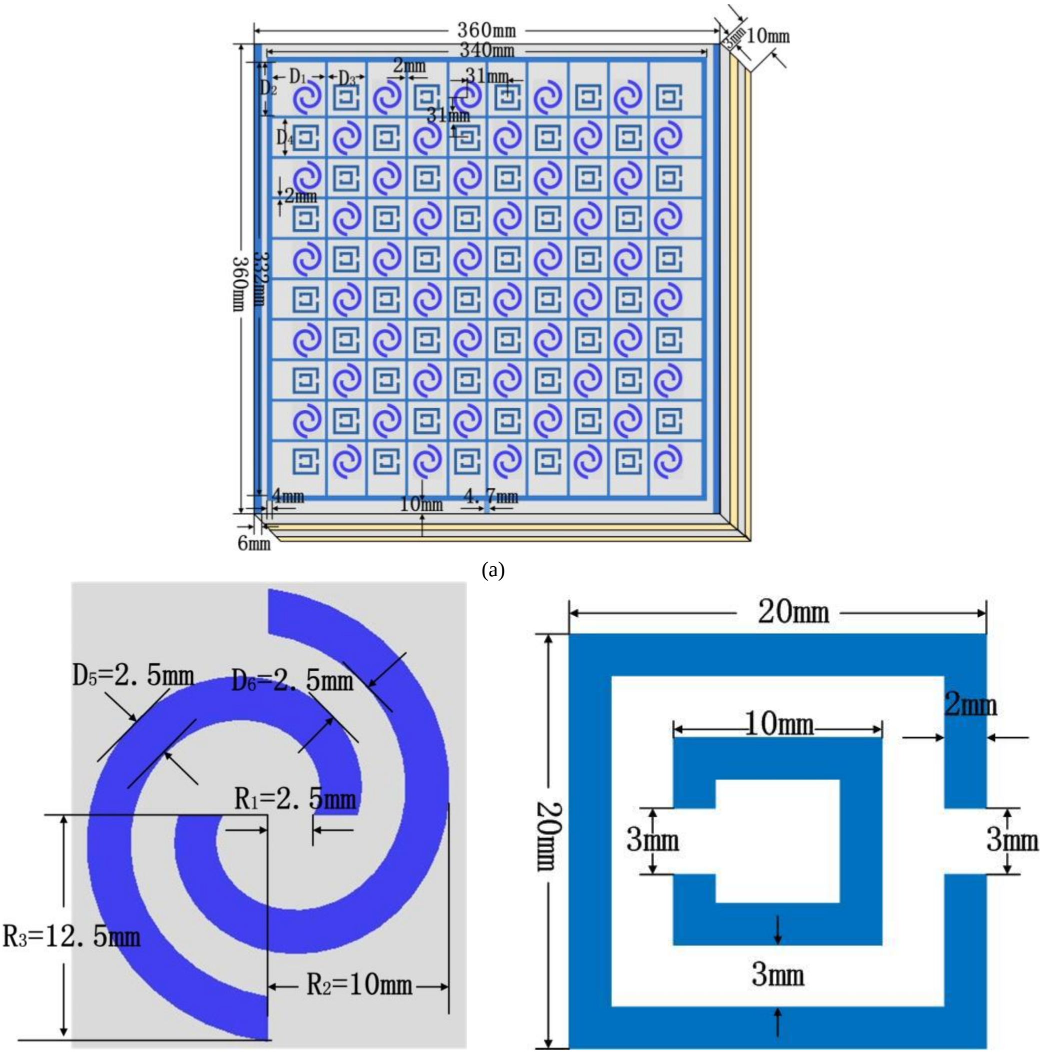
In the calculation procedure, we used perfectly matched layer (PML) boundary conditions in the X, Y direction [8]. Taking the Gauss pulse as the excitation source for its smoothness in the time domain, and the bandwidth is easy to choose. The electric field Ez vector under the micro strip on the excitation plane is:

$$Ez(t)=\exp[-\frac{(t-t_0)^2}{T^2}] \tag{8}$$

The parameters are: $T=40\Delta t$, $t_0=110\Delta t$, where Δt, t_0 and T are time increment step, time delay, and half-width Gauss pulse. Its frequency ranges from 0 to 14.99GHz. 4000 time steps are chosen. The active patch antenna structure is calculated by the FDTD numerical method.

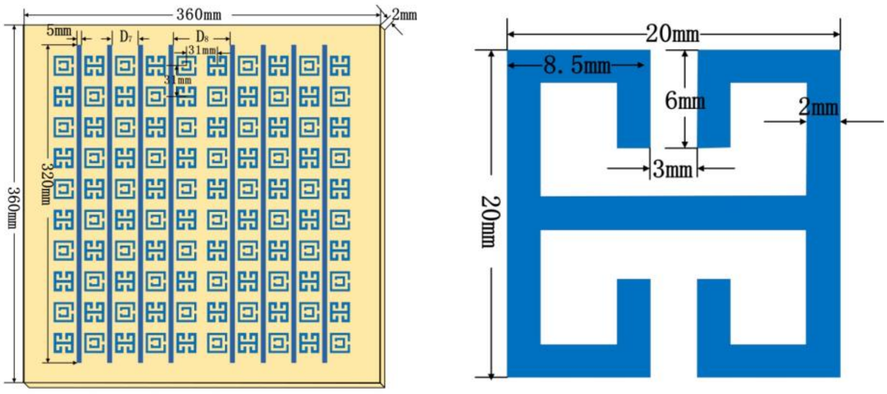
The geometry structure of composite heterostructure mesh-shaped patch antenna based on LHM is shown in Fig. 1 (a): the dimension of the patch antenna is 360 mm×360 mm×10mm, there are four layer substrates with 360 mm long and 360 mm wide, The first and the third layer of the substrate have the same thickness and relative permittivity, which are 3mm and 2. The second and the fourth layer have the same thickness and relative permittivity, which are 2mm and 10. The mesh-shaped radiating patch is etched on the top of the first layer substrate. Outside frame of the mesh-shaped patch is 340 mm long and 4 mm wide, the width of mesh line is 2mm, and their interval D1, D2 are 42mm, D3, D4 are 29mm. Two metal straps with the size 360 mm×6mm are etched outside the mesh-shaped patch. Square SRRs and helices are inset the meshes of mesh-shaped patch alternately, and heterostructure is formed. Fig. 1 (b) shows the view of the helix, the width of helices D1 is 2.5 mm, the distance between edges of two adjacent helices D2 is 2.5mm, the minimum radius R1 is 2.5mm, the radius R2 is 10 mm, and R3 is 12.5 mm. Fig. 1 (c) shows the view of the square SRR, opening of the square SRR is 3mm, the outside side length is 20mm, width is 2mm, the inner side length is 10mm, width is 2mm. The distance between the centers of adjacent helix and square SRR is 31 mm. The second and the forth layer substrates have the same structure, which is shown in Fig. 2 (a). Square SRRs and E-shaped SRRs are etched on the top of the second and the fourth layer substrates alternately. Fig. 2 (b) shows the view of the E-shaped SRR, opening of the E-shaped SRR is 3mm, the outside side length is 20mm, and line width is 2mm. The distance between the centers of adjacent square SRR and E-shaped SRR is 31 mm. Eight thin metal straps with the size 320 mm × 5 mm are etched among square SRRs and E-shaped SRRs with the interval D7 = 28mm, D8 = 59mm. The structure of helices and square SRRs on the third layer substrate is the same as the first layer's ones, which is shown in Fig. 3. Eight thin metal straps of 320 mm × 5 mm are etched among helices and square SRRs, and the interval D9 is 28mm, D10 is 59mm. In the bottom of the fourth layer substrate, there is a metal earth place shown in Fig. 4, which side is 360 mm long and 40 mm wide. Five 260 mm × 40 mm metal straps are distributed symmetrically in the frame of metal earth place, and the interval is 15 mm. The excitation source is Gaussian discrete source, fed by a micro strip whose width is 4.7 mm, length is 10mm. Fig. 5 shows the view of every layer structure combination.

The conventional patch antenna without LHM is shown in figure 6, which dimension is 360 mm × 360 mm × 10mm, and the relative permittivity 10. The mesh-shaped radiating patch is etched on the top of the substrate.



(a) (b) (c)

Fig.1. A top view of: (a) composite heterostructure mesh-shaped patch antenna based on LHM and (b) the helix (c) square SRR



(a) (b)

Fig.2. A top view of: (a) the second and the fourth layer substrates and (b) E-shaped SRR

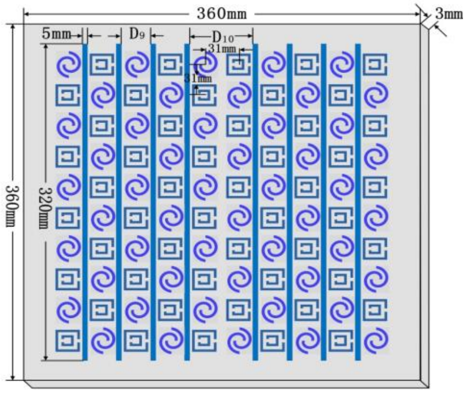


Fig.3. A top view of the third layer substrate

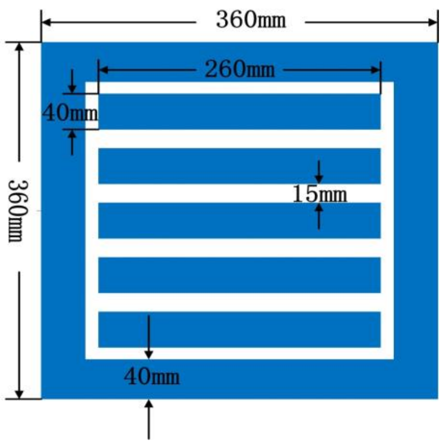


Fig.4. A view of metal earth place

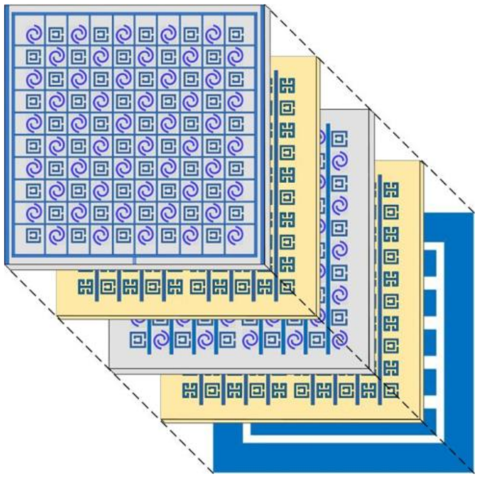


Fig.5. A view of every layer structure combination

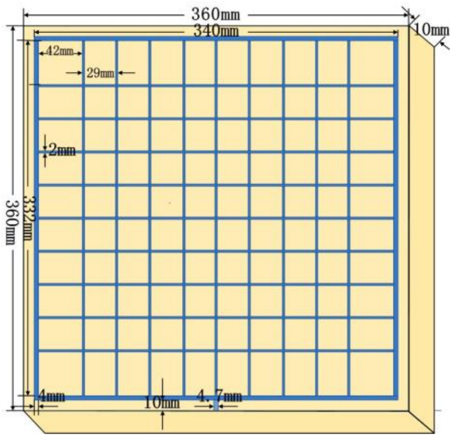


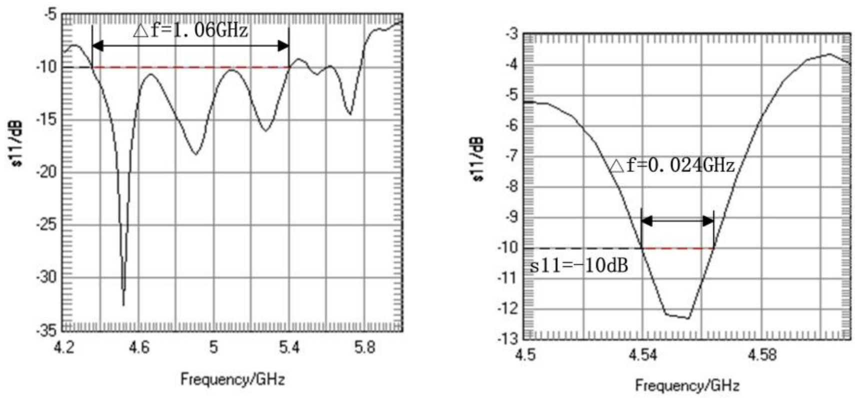
Fig.6. A top view of conventional patch antenna

4. Simulation results and analysis

The FDTD simulator is used to analyze the above composite heterostructure mesh-shaped patch antenna based on LHM and conventional patch antenna. The corresponding return loss (s11) and gain for both composite LHM patch antenna and conventional patch antenna are obtained, which are shown in Fig. 7 and Fig. 8.

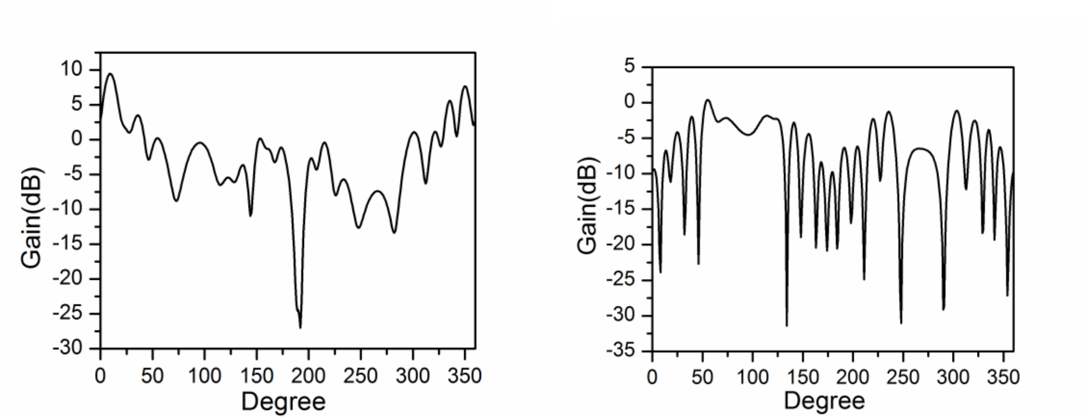
It can be seen from Fig. 7 that the composite LHM patch antenna has a better return loss (s11), that's -32.60 dB at the frequency of 4.52 GHz, compared to the conventional patch antenna, 20.26 dB lower than the conventional one which gets -12.34 dB at 4.55 GHz, so the composite LHM can improve the antenna's matching condition.

Narrow bandwidth is a major disadvantage of microstrip patch antenna. From Fig. 7, it is found that bandwidth of the composite LHM antenna is 1.06 GHZ at 4.52 GHz, and adds 44 times compared to bandwidth of the conventional antenna, 0.024 GHZ at 4.55 GHz. The results indicate that the bandwidth of composite LHM patch antenna is enlarged obviously, which improves patch antenna's property extremely.



(a) (b)

Fig.7. Return loss of: (a) composite heterostructure patch antenna based on LHM and (b) conventional patch antenna



(a) (b)

Fig.8. Gain of: (a) composite heterostructure patch antenna based on LHM and (b) conventional patch antenna

In the Fig. 8, we can find that the conventional antenna's maximum gain is 0.397 dB at 4.55 GHz, while the composite LHM's one is 9.444 dB at 4.52 GHz, which adds 23.8 times compared to the conventional antenna's one, and improves 9.047 dB, showing that the composite LHM can improve patch antennas' gain obviously. The simulated results are listed in Table 1.

Table 1 Parameters of antennas with and without LHM

	Resonant frequency (GHz)	Return loss (dB)	Bandwidth (s11=-10dB)	VSWR	Maximum gain (dB)
composite LHM patch antenna	4.52	-32.60	23.45% (1.06 GHz / 4.52 GHz)	1.048	9.444
conventional patch antenna	4.55	-12.34	0.53% (0.024 GHz / 4.55GHz)	1.637	0.397

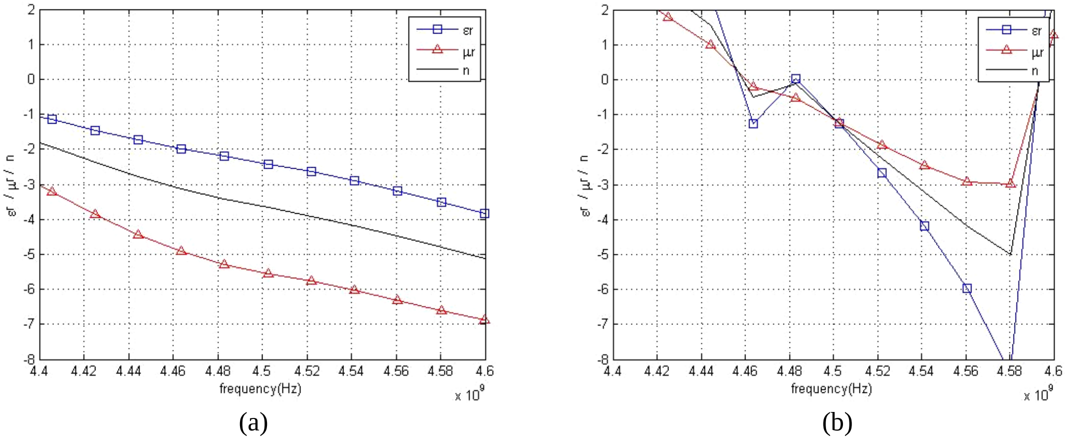


Fig.9. Equivalent permittivity ε_r, permeability μ_r and refraction index n of: (a) the first layer and the third layer substrate based on LHM and (b) the second and fourth layers substrates based on LHM

It can be easily found that the patch antenna presents lower return loss and higher gain by adding the LHM. This is clear from the following theoretical point of view: Because periodic square SRRs, helices, E-shaped SRRs and metals strips are added on the substrates, the negative permittivity and negative permeability can simultaneously appear in a certain frequency range. Thus, on the one hand, this paper proposes that metal straps are etched on the substrate to improve the structure's capacitance, and the added electric field will induce electricity through the patches, so an obvious electric resonance is created. On the other hand, periodic square SRRs, helices or E-shaped SRRs are etched on the substrate's surface so as to improve the structure's inductance, so an obvious magnetic resonance can be attained. When the above two negative parameters' area intersect, a double negative area is formed.

In order to validate the structure, we can use the S parameters, including return loss (or: reflection coefficient) s11 and transmission coefficient s21 to extract the every layer composite structure's equivalent permittivity ε_r and permeability μ_r by Nicolson Ross Weir (NRW) method [9-11]. The extracted results are shown in Fig.9. It can be seen that every layer composite structure's equivalent permittivity ε_r and equivalent permeability μ_r are negative at 4.50GHz - 4.58GHz. According to ε_r, μ_r, the refraction index n is calculated, and they are also negative, those are n1 (refraction index of the first layer composite structure) = n3 (refraction index of the third layer composite structure)= - 3.9, and n2 (refraction index of the second layer composite structure) = n4 (refraction index of the fourth layer composite structure) = - 1.1. These results indicate that the introduction of square SRRs, E-shaped SRRs, helices and metal straps to the patch antenna may result in equivalent negative ε_r and negative μ_r. According to the above characteristics, it is explained that the negative-refraction dielectric can enhance the EM wave's tunnel effect [9], and the boundary plane between the positive refraction and negative refraction dielectric (the plane between the free space and composite structure) accord with the surface wave of the EM wave's tunnel traverse model [12]. These surface waves propagate through the boundary plane according to the evanescent waves' coupling effect. The power density near the boundary plane increase rapidly [10], indicating that the equivalent negative refraction structures have the effect of amplifying evanescent waves, so the transmission of surface waves in these models can be enhanced obviously. This phenomenon can improve the antenna's gain, and improve the system's matching condition.

What's more, after embedding the heterostructure into the antenna, due to the electromagnetic waves' highly localized effect caused by aberrance between two heterostructures, the electromagnetic energy near a frequency range would get a high gain.

5. Conclusion

A composite heterostructure mesh-shaped patch antenna based on left handed material (LHM) is fabricated by assembling helices, square SRRs, E-shaped SRRs and metals strips on the substrates of conventional antennas. According to our simulation and analysis, we find that this composite patch antenna system can improve patch antenna’s property extremely. On the one hand, the electromagnetic wave resonance occurs near f=4.52GHz, and the equivalent permittivity and permeability of every layer composite material are negative. The electromagnetic wave’s tunnel effect and evanescent waves’ enhancing effect are formed, which can improve the localization extent of electromagnetic wave’s energy apparently. Such effects can improve the antenna’s radiation gain and its matching condition. Therefore, the radiation power coupled into the free space can be enhanced. On the other hand, the heterostructure is embedded into the antenna. Due to the electromagnetic waves' highly localized effect caused by aberrance of heterostructure, the electromagnetic energy near a frequency range would get a high gain. So the antenna’s performance can be improved. Due to these advantages, the use of this composite patch antenna can be extended to mobile communication, satellite communication, aviation, etc.

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