Study on a Composite Patch Antenna Based on Left Handed Material with Near Zero Index

Jijun Wang, Zhipan Zhu, Yanrong Zhang, Leilei Gong, Yuntuan Fang

Abstract—**In this paper, a composite patch antenna based on left handed material (LHM) with near zero index (NZI) is presented. This composite patch antenna is designed by assembling split resonant rings (SRRs) and metal strips on the substrates. This multilayer composite structure results in a metamaterial with NZI near 13.89 GHz. A method of finite difference time domain (FDTD) is used. The results show that the composite antenna's gain improves 0.61 times, and its bandwidth adds 2.95 times 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*—Near zero index, LHM, Photonic crystals, Return loss, Gain.**

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I. INTRODUCTION

IN the recent years, metamaterials research has received growing attention due to their necessity in developing technologies. Both Left handed material (LHM) and near zero / zero index metamaterials (NZIM / ZIM) have become important, as they are needed for different applications. LHM is an artificially structured material with simultaneously negative permittivity and permeability. As early as 1968, Veselago first analyzed novel physical effects in LHM theoretically [1]. In 2000, the first artificial LHM was fabricated by Smith and his co-workers by combining SRRs and continuous wires [2]. NZIM/ZIM metamaterials are another important branch of metamaterials. According to Snell's law, when the ray is incident from inside the NZIM / ZIM into free space, the angle of refraction will be close to zero, so the refracted rays will be normal to the interface. This property provides a unique method of controlling the direction of emission. In 2002, the group of Enoch experimentally demonstrated for the first time that energy radiated by a source embedded in a slab of ZIM will be concentrated in a narrow cone in the surrounding media, so a great improvement of directivity was potentially obtained [3], after which many groups have realized NZIM/ZIM metamaterials through experiments [4-5].

The concept of photonic crystals is first introduced by E. Yablonovitch [6] and S. John [7] in 1987. Photonic crystals are a periodic arrangement of dielectric materials. Their internal propagating characteristic of electromagnetic waves in the structure is similar to the propagating of the electrons in semiconductor crystals. If we consider the propagation of an electromagnetic wave in photonic crystals, under certain circumstances a "photonic band gap" can be opened up, and EM waves in the photonic band gap will be forbidden to propagate. Due to this property, the photonic crystals were already used in microwave circuits, antennas [8-9], etc.

In this paper, the FDTD method is employed to analyze a composite patch antenna based on LHM with NZI, and its performance parameters are attained by simulation. The refraction index of the medium is extracted from its S parameters in order to validate the structure. Then, the performance of the composite LHM patch antenna is analyzed by its performance parameters.

II. RESEARCHING METHOD OF THE PATCH ANTENNA

A. FDTD equations

To simulate patch antennas, we use the well-known FDTD method [10-12]. The FDTD method is proving useful in many antenna applications, because it facilitates modelling of complex structures and is capable of characterising antenna performance over a wide-frequency band. 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 made discrete 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:

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

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

$$H_z^{n+\frac{1}{2}}(i,j) = H_z^{n-\frac{1}{2}}(i,j) + \frac{E_x^n(i,j+\frac{1}{2}) - E_x^n(i,j-\frac{1}{2})}{\Delta y} \cdot \frac{\Delta t}{\mu} - \frac{E_x^n(i+\frac{1}{2},j) - E_x^n(i-\frac{1}{2},j)}{\Delta x} \cdot \frac{\Delta t}{\mu} \tag{3}$$

Where, n refers 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 [13]:

$$\Delta t \le \frac{1}{c\sqrt{(\Delta x)^{-2} + (\Delta y)^{-2}}} \tag{4}$$

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 [12]. 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:

$$Ez(t) = \exp[-\frac{(t-t_0)^2}{T^2}] \tag{5}$$

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 [13].

B. *Geometric model of the composite patch antenna*

The geometry structure of the composite patch antenna based on LHM with NZI is shown in Fig. 1. There are four layer substrates, the first and the third layer of the substrate have the same thickness and relative permittivity, which are 0.6mm and 3.9, and the second and the fourth layer have the same thickness and relative permittivity, which are 0.4mm and 4.4. The SRRs and metal straps on every layer substrate have the same structure and sizes. The frame-shaped radiating patch composed of square frame-shaped patch and square patch is etched on the top of the first layer substrate. The second and the forth layer substrates have the same structure, which is shown in Fig. 2. Fig. 3 shows the top view of the third layer substrate. Fig. 4 shows the view of every layer structure combination. The conventional patch antenna is shown in Fig. 5, and the relative permittivity of substrate is 3.9. The frame-shaped radiating patch is etched on the top of the substrate. Geometrical dimensions of the composite patch antenna based on LHM with NZI and the conventional patch antenna in the below figures are: $L_1 = W_1 = 44.6$ mm, D = 2 mm, $D_1 = D_3 = 0.6$ mm, $D_2 = D_4 = 0.4$ mm, $L_2 = W_2 = 36.6$ mm, $T_1 = 1$ mm, $L_3 = 1.8$ mm, $W_3 = 16$ mm, $L_4 = 13$ mm, $W_4 = 1$ mm, H = 30 mm, $T_3 = 1$ mm, $T_2 = 0.6$ mm, $T_4 = 4$ mm, $D_5 = D_6 = D_7 = 3$ mm, $a_1 = b_1 = a_2 = b_2 = 4.2$ mm, c1 = c2 = c3 = c4 = c5 = c6 = c7 = c8 = 0.6 mm.

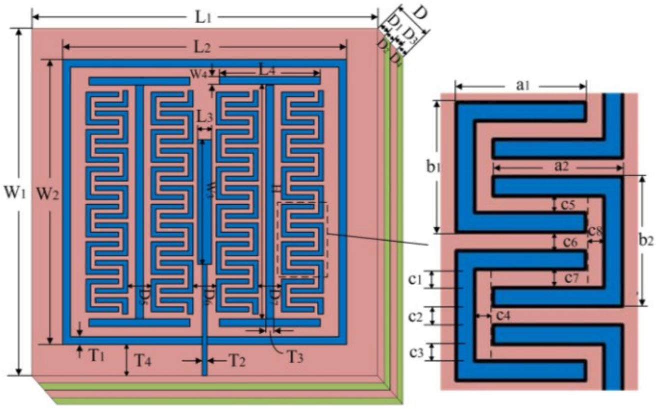


Fig.1. A top view of the composite patch antenna based on LHM with NZI.

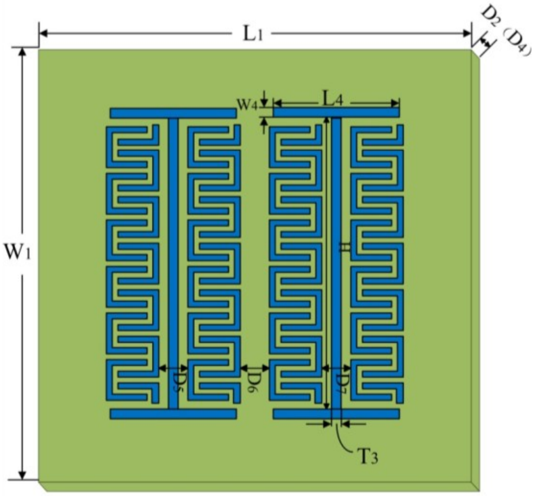


Fig.2. A top view of the second and the fourth layer substrates.

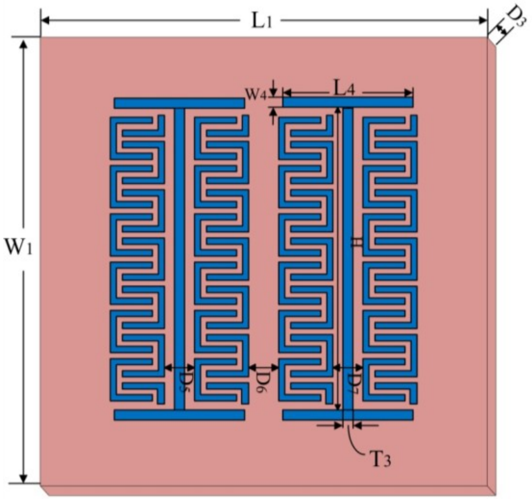


Fig.3. A top view of the third layer substrate.

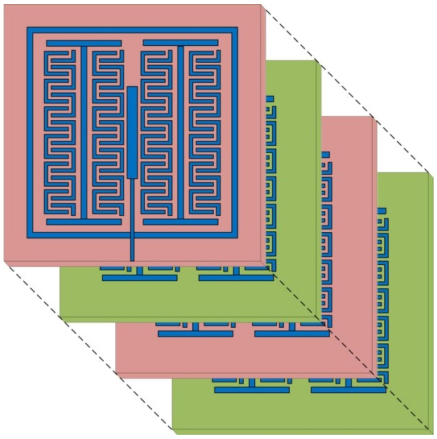


Fig.4. A view of every layer structure combination.

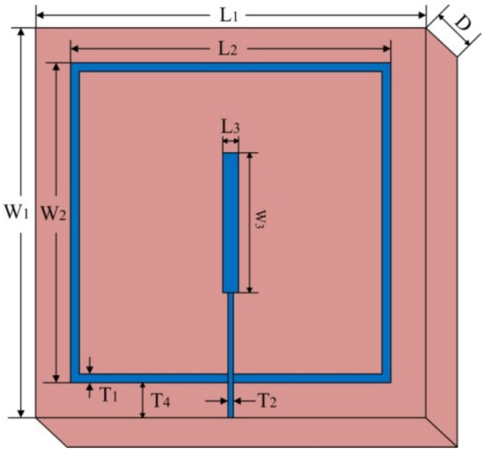


Fig.5. A top view of conventional patch antenna.

III. SIMULATION RESULTS AND ANALYSIS

The above composite patch antenna based on LHM with NZI and conventional patch antenna are analyzed by XFDTD, which is a three-dimensional full wave electromagnetic solver based on the FDTD method. In order to validate the structure, we can use the S parameters, including return loss (or: reflection coefficient) S_{11} and transmission coefficient S_{21} to extract the every layer composite structure's equivalent permittivity ε_r and permeability μ_r by Nicolson Ross Weir (NRW) method [14-16]. The extracted results are shown in Fig.6. It can be seen that composite structure's equivalent permittivity ε_r and equivalent permeability μ_r are negative near 13.89 GHz. According to ε_r , μ_r , the refraction index n is calculated, and it is also negative and near zero, that is n (refraction index of the composite structure) = - 0.12. These results show that the introduction of SRRs and metal straps to the patch antenna may result in negative refractive index with NZI. It indicates that the design of composite structure is feasible.

The property parameters of composite LHM patch antenna are analysed by compared to conventional patch antenna's ones near 13.89 GHz. The corresponding return loss (S_{11}), voltage standing wave ratio (VSWR) and gain are obtained, which are shown in Fig. 7, Fig.8 and Fig. 9.

The return loss (S_{11}) is shown in Fig. 7, the composite patch antenna based on LHM with NZI has a better return loss, that's -26.14 dB at the frequency of 13.89 GHz. Compared to the conventional patch antenna, the loss is 5.47 dB lower than the conventional one which gets -20.67 dB at 13.88 GHz. The results show that the composite LHM with NZI 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 this composite antenna is 1.26 GHz at 13.89 GHz. 2.95 times is added compared to bandwidth of the conventional antenna 0.32 GHz at 13.88 GHz, showing that the bandwidth of composite patch antenna is enlarged obviously.

In the Fig. 8, this composite antenna's VSWR is 1.1038, which is very close to the ideal condition 1.0. But for the conventional patch antenna, the VSWR is 1.2036, which is much larger than that for the LHM.

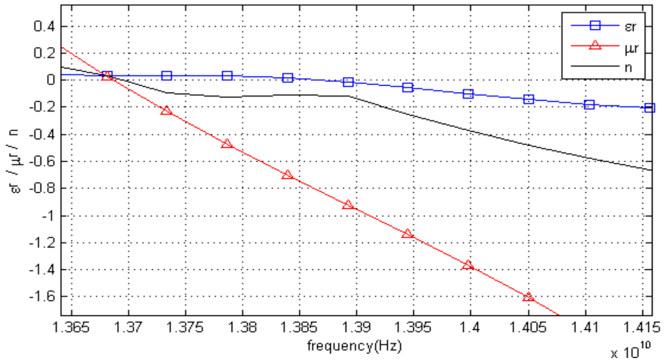


Fig.6. Equivalent permittivity ε_r , permeability μ_r and refraction index n of composite patch antenna based on LHM with NZI.

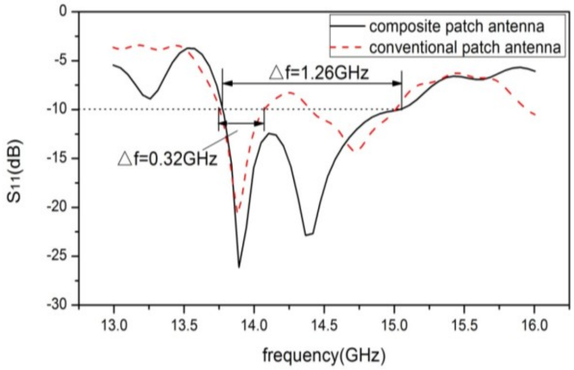


Fig. 7. Return loss (S11) of composite patch antenna based on LHM with NZI and conventional patch antenna.

It can be seen from Fig. 9 that the conventional antenna's maximum gain is 4.301dB at 13.88 GHz, while the composite patch antenna's one is 6.914 dB at 13.89 GHz, which adds 0.61times compared to the conventional antenna's one, and improves 2.613dB. From Fig. 9, it is also found that the directivity of the composite patch antenna based on NZIM is effectively enhanced. The results indicate that the composite LHM with NZI can improve patch antennas' gain obviously. The simulated results are listed in Table 1.

TABLE I
PARAMETERS OF ANTENNAS WITH AND WITHOUT LHM

	Resonant frequency (GHz)	Return loss (dB) [a]	Bandwidth (S_{11}=-10dB)	VSWR (voltage standing wave ratio)	Maximum gain (dB)
composite patch antenna	13.89	-26.14	9.1% (1.26GHz /13.89GHz)	1.1038	6.914
conventional patch antenna	13.88	-20.67	2.3% (0.32GHz / 13.88GHz)	1.2036	4.301

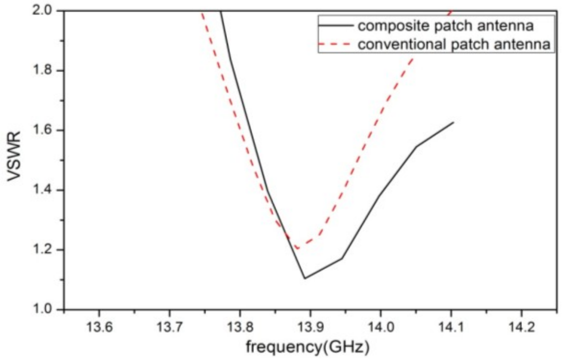
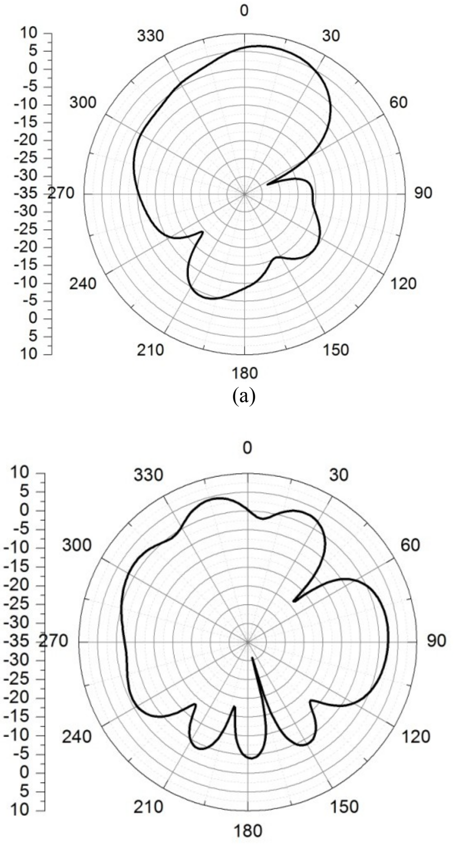


Fig. 8. VSWR of composite patch antenna based on LHM with NZI and conventional patch antenna.



(a)

(b)

Fig. 9. Gain of: (a) composite patch antenna based on LHM with NZI and (b) conventional patch antenna.

It can be easily found that the composite patch antenna based on LHM with NZI has negative equivalent permittivity ε_r and negative equivalent permeability μ_r , and the refraction index n is also negative and near zero in 13.7GHz-14.0GHz, and presents lower return loss and higher gain. This is clear from the following theoretical point of view: the LHM can enhance the EM wave's tunnel effect [14], and the boundary plane between the positive refraction and negative refraction dielectric accord with the surface wave of the EM wave's tunnel traverse model [17]. These surface waves propagate through the boundary plane according to the evanescent waves' coupling effect. The power density near the boundary plane increase rapidly [15], 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. The refraction index n is negative and near zero. According to Snell's law, when the EM wave is incident from inside the NZIM / ZIM into free space, the angle of refraction will be close to zero, the directivity of the antenna based on NZIM is effectively improved [12]. Such effects can enhance the antenna's gain, and improve the system's matching condition.

What's more, periodically tactic SRRs is introduced based on photonic crystal structure, in the frequency range of the band gap, the spread of electromagnetic waves is hindered in some directions. Such photonic band gap effect could inhibit the surface wave spreading along the basement floor media preferably [8-9]. Therefore, the decrease in absorption of electromagnetic waves and increase in reflection of electromagnetic wave energy lead to reduce return loss of the antenna and increase the gain.

IV. CONCLUSION

A composite patch antenna based on LHM with NZI is designed by assembling SRRs and metal 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=13.89GHz, and the equivalent permittivity and permeability of composite material are negative, and its refractive index is also negative and near zero. The electromagnetic wave's tunnel effect and evanescent waves' enhancing effect are formed, which can improve the localization extent of electromagnetic wave's energy and enhance the gain apparently. In addition, the directivity of the composite antenna based on NZIM is effectively improved to enhance the antenna's radiation gain. On the other hand, periodically tactic SRRs is introduced based on photonic crystal structure. Such photonic band gap effect could inhibit the surface wave spreading along the substrate preferably, which will reduce the absorption of electromagnetic wave and increase the reflection of electromagnetic wave energy to the free space. In this case, this composite patch antenna presents lower return loss, higher gain and wider band. 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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