Design of a New Broadband Left-handed Material

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Abstract. The left-handed materials(LHM) are widely used in antenna, filter and other microwave devices due to its negative permittivity and negative permeability. This paper proposed a new kind of left-hand materials, by means of equivalent circuit analysis, electromagnetic simulation, and extract the equivalent electrical parameters, the results show that the structure realized double negative features in the 9.3 GHz to 14.2 GHz. At the same time, the real part of the equivalent negative refractive index is negative and the imaginary part is approximately to zero. The structure has the characteristics of low loss, wide frequency band and the technology is simple. It provides reference for the design of LHMs in microwave filed.

1. Introduction
The left-handed material(LHM) refers to the electromagnetic metamaterial with negative permittivity and permeability. It has super-physical optical properties such as the opposite of phase velocity and group velocity, negative refractive index, etc, which does not exist in nature. In 1968, Veselago¹ formally proposed the concept of LHMs. Then Pendry² realized left-handed coal by using fine metal rods and metal resonant rings of periodic array. In the early 21st century, Smith³, Ò made the composite structure LHM of Split Ring Resonator (SRR) and metal wire in the microwave band, thus turning the hypothesis into reality.

Due to the extraordinary characteristics, the LHMs has a wide application space. In recent years, research on LHMs are divided into two aspects: part of the focus on left-hand material structure innovation and performance optimization, such as multi-open field shape⁵, Ò Type⁶, Jerusalem structure⁷, etc; another part focuses on the application of LHMs in antennas⁸, microwaves⁹, etc.

The goal of this paper focus on the increase of bandwidth of the LHM and reduce the cell loss. A novel LHM structure is designed by using an SRR loaded with metal wires. In this paper, the equivalent circuit analysis of the model is carried out to clarify the mechanism of the left-handed structure of the structure. The simulation results of Ansoft HFSS software show that the LHM has double negative characteristics in the 9.3GHz-14.2GHz frequency band, and the real part of the equivalent negative refractive index is negative, and the imaginary part is approximately to zero, which realizes the left-hand characteristic. Compared to other traditional LHMs, the structure of LHMs designed in this paper is smaller, wider band and lower loss.

2. Structure of LHM and analysis

2.1 Design of units
At a certain frequency, when the electromagnetic wave incident into the unit structure, an electric plasma will be excited and generate electric and magnetic resonance. And the left-handed
characteristic exhibited when the frequency band of magnetic resonance coincides with the frequency band of electric resonance, that is, the equivalent permittivity and permeability of the material are both negative. The left hand material unit proposed in this paper is shown in Fig 1. The unit is symmetric about the Z-axis and consists of four symmetrical SRR structures and metal wires. The dielectric substrate is Rogers RO4350 ($\varepsilon=3.48$), structure size is $l_x=l_y=2.9$mm and thickness $h=0.508$mm. The width of the left material element is $d=0.2$mm, the length of the central cross-shaped strip are $1.7$mm and $1.3$mm, and the width is $g=0.1$mm, which is the same as the gap width between the surrounding patches.

![Fig 1 Structure of LHM](image)

2.2 Analysis of equivalent negative permittivity and negative permeability

The structure of this paper could generate negative permeability by four centrally symmetric SRRs under the action of a magnetic field. When the magnetic flux passing through the peripheral resonant ring changes, an induced current is generated on the SRR, and the induced current is generated under the action of the electric field.

![Fig 2 Equivalent circuit model of LHM](image)

When a Z-direction polarized wave is incident, the equivalent circuit model is shown in Fig 2. $C_i$ is the capacitance generated by the adjacent SRR, and $L_i$ is the inductance determined by the length and width of the SRR. We can be obtained from the magnetic resonance equivalent circuit that the total inductance of the loop $L_m=4L_0$ and the total capacitance $C_m=C_0/4$. In the electrical resonance equivalent circuit, the total inductance of the loop $L_e=L_0$, the total capacitance $C_e=C_0$, so the magnetic and electrical resonant frequency of the loop can be obtained:

$$f_m = \frac{1}{2\pi}\sqrt{\frac{L_m}{C_m}} = \frac{1}{2\pi}\sqrt{\frac{L_0}{C_0}}$$  \hspace{1cm} (1)

$$f_e = \frac{1}{2\pi}\sqrt{\frac{L_e}{C_e}} = \frac{1}{2\pi}\sqrt{\frac{L_0}{C_0}}$$  \hspace{1cm} (2)

According to Pendry’s theoretical analysis[12], the introduction of metal wires into the center of the structure can enhance its electrical resonance. In this paper, a cross-shaped metal wire is introduced at the center of the unit. When the electromagnetic wave is incident in parallel, the effect of the magnetic field on the metal wire can be negligible, and the electric field acts on the metal wire to realize the
negative permittivity. Since the introduction of the metal wire does not form a current loop, the original magnetic response is little affected, and the symmetry of the original structure is not destroyed.

3. Structure of LHM and analysis

The model established by HFSS is shown in the Fig 3. The overall size is 5.9mm*5.9mm*0.508mm, and the spacing between each unit is 0.1mm. The HFSS simulation results are shown in Fig 4(b), (d).

Fig 4 (a) Simulation results of S-parameters of unit structure /dB, (b) simulation results of S-parameters of periodic structure /dB, (c) results of S-parameters of unit structure /rad, and (d) results of S-parameters of periodic structure /rad

It can be seen Fig 4(a) and Fig 4(c) that the LHM resonates at 14.6 GHz, and Fig 4(b) and Fig 4(d) are the results of the S-parameter simulation of the LHM of the periodic arrangement. It can be seen that the amplitude and phase of the S-parameter are abrupt at 11 GHz and 15.6 GHz, which means a left-hand characteristic in the frequency band. In order to visualize the left hand features directly,
utilize the NRW inversion algorithm, programming with mat lab, and obtain the equivalent permittivity
and equivalent permeability through the parameter extraction method in this frequency band[10][11], as
shown in Fig 5 (a), (b).

\[
Z = \sqrt{\frac{(1 + S_{11})^2 - S_{21}^2}{(1 - S_{11})^2 - S_{21}^2}}
\]

(3)

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

(4)

\[
\varepsilon_{\text{eff}} = \frac{n}{Z}
\]

(5)

\[
\mu_{\text{eff}} = n \times Z
\]

(6)

As can be seen from the Fig 5, the equivalent permittivity is less than zero in the frequency range
of 6.8-15.15 GHz, the equivalent permeability is less than zero in the range of 9.35-14.35 GHz, and
the equivalent refractive index is less than zero in 8.35-14.85 GHz. Therefore, the left-hand band of the
structure is obtained in the range of 9.35-14.35 GHz and the bandwidth is 5 GHz.

The loss of the structure is measured by the quality factor FOM, and the expression is

\[
FOM = \left| \frac{\text{Re}(n)}{\text{Im}(n)} \right|
\]

(7)

The higher the value of FOM is, the smaller the structure loss is. As can be seen from Fig 6, the
value of FOM reaches 250 within the left-handed band 9.35-14.35 GHz, indicating that the structure
has low loss characteristics.
Fig 6 Loss curve in left-hand frequency domain

4. Conclusion
The characteristics of the proposed left-hand material are briefly analyzed and verified by HFSS simulation and NRW algorithm. The results show that in the range of 9.35 - 14.35 GHz, the structure has negative permeability, negative permittivity etc, and the left-hand frequency band reaches 5 GHz, which has great reference value for the application of LHMs in devices such as filters and antennas.

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