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零に近い屈折率を有するメタマテリアル素子の設計と数値シミュレーション

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Design and Numerical Simulation of a Near-zero Refractive-index Metamaterial Unit

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Abstract A new near-zero refractive-index metamaterial unit is proposed in this paper. The basic structure of the proposed unit consists of two face-to-face E-type microstrip lines, which connect to the background microstrip line by two vias through the crossbar of the E sharped microstrip line. The retrieved refractive-index, equivalent permittivity and permeability from scattering parameters are calculated. The results show that the real part of the refractive-index as well as the equivalent permittivity is near zero at the bandwidth from 10.5 GHz to 14.5 GHz. A Shelby lens based on the proposed metamaterial unit can perform negative refraction at the near-zero refractive-index bandwidth. Furthermore, a rectangular electromagnetic invisible cloak is designed and simulated based on the proposed metamaterial unit. The simulated results show that the rectangular cloak can make the cylinder with pure copper electromagnetic invisible, which validates the correctness of the proposed near-zero refractive-index metamaterial unit.

Key words Electromagnetic invisibility cloak, near-zero refractive index

1. Introduction

Metamaterials have attracted more and more attention since they have been reported with the potential ability to realize negative refraction for the first time as their fantastic phenomenons which cannot be shown by the nature materials [1]～[3]. These unique phenomenons include negative equivalent permittivity, negative equivalent permeability and abnormal Veselago [4]. Nowadays metamaterials based structures are widely used in acoustic [5], microwave [4], terahertz [6] and optical [7] engineering to shape the required electromagnetic waves. During all these kinds of various metamaterials, the near-zero refractive-index metamaterial has became a new hot point as its ability to manipulate the shape and direction of the output electromagnetic waves [8]～[10].

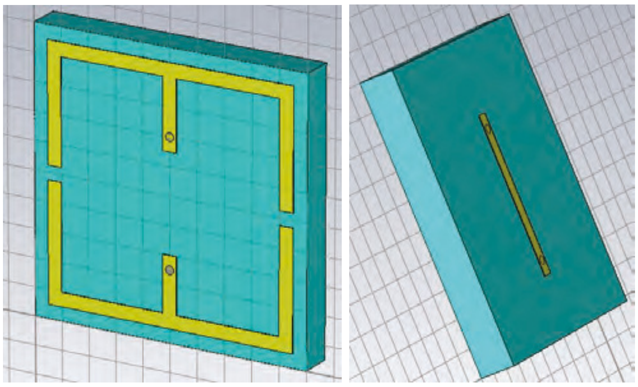
According to the predominant electromagnetic response, the near-zero refractive-index metamaterial can be classified as epsilon-near-zero (ENZ), $\epsilon \approx 0$, mu-near-zero(MNZ), $\mu \approx 0$ and epsilon-and-mu-near-zero (EMNZ) $\epsilon \approx 0$ and $\mu \approx 0$. As the refractive index $n = \sqrt{\epsilon\mu}$, all the aforementioned three classes can make the equivalent refractive index near zero at the designed frequency bandwidth [10]. According to the Snell law, the emitted electromagnetic wave from the near-zero refractive-index material to the air is perpendicular to the exit surface, which can be employed to change the propagation properties of different electromagnetic waves, such as the high-gain Vivaldi antenna [11], optical circuitry [12], cloaking [13], Shelby lens [14] and so on.

As the fundamental of various near-zero refractive-index metamaterials, it is important to design a practical near-zero refractive-index periodic element unit. However, there is no universal equations or methods to guide this design nowadays. The most common used method is to etch different pattern microstrip lines on substrate, such as the split-ring resonators (SRR), electric inductance-capacitance (ELC) resonator, I-shaped nonresonant cell and meander microstrip line [11]. Different kinds of near-zero refractive-index element units have their specific working frequency and applications because it is always required to design various near-zero refractive-index element unit on different working frequency bandwidths. Recently Guo had etched two stubs on the top and bottle sides of the substrate and made the two stubs coupling by a via, which can realize near-zero refractive index over a wide bandwidth. However, the real part of the refractive index varies in a large interval and be zero only at one frequency [14].

In this paper, a novel near-zero refractive-index metamaterial unit which shows refractive index over 10.5-14.5 GHz is proposed. The basic design idea is to produce the electric resonator and magnetic resonator on the same element unit substrate. When the external electric field is smaller than the mixed electric and magnetic resonating frequency of the substrate, the equivalent refractive index becomes zero or near-zero. Since the broadband electric resonator and broadband magnetic resonator are simultaneously realized, the equivalent refractive index could be near-zero over a broad bandwidth.

2. Metamaterial Unit Design

The proposed metamaterial unit is shown in Fig. 1, which consists of two face-to-face E-type microstrip lines on the top side of the substrate and one stub on the back side of the substrate. Each E-type microstrip line has two arms and one crossbar. A via is applied to make the E-type microstrip line be connected to the stub of the backside of the substrate. All the copper lines have the same width and the two E-type microstrip lines are symmetrical for simplification. However, the stepped-impedance microstrip lines can be used to optimize the required refractive index over different bandwidths.



(a) (b)

図 1 Structure of the proposed near-zero refractive-index metamaterial unit. (a) top view; (b)back view.

The two arms of each E-type microstrip line can be treated as two capacitors and the crossbar with the via can be treated as an inductor. The two capacitors and the inductor will resonate at certain frequency. There are two main coupling methods for the two E-type microstrip lines: the first coupling is realized by the via and the back side microstrip line and the second coupling is realized by the electric coupling of the corresponding arm of the each E-type microstrip line. These two kinds of coupling can be treated as mixed electric and magnetic coupling and the coupling coefficient can be set as M, which is shown in the equivalent circuit of the whole near-zero refractive-index metamaterial unit in Fig. 2. In this equivalent circuit, $C_1 = C_2 = C_3 = C_4$ and $L_1 = L_2$ due to the symmetrical structure of the unit.

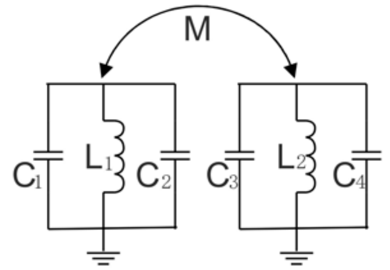


図 2 Equivalent circuit of the proposed metamaterial unit.

The substrate Risho CS3376C with relative permittivity 3.3 is used to design the metamaterial unit. The length and width of the substrate are both 10 mm and the hight is 0.8 mm. The width of the microstrip line and the gap of two E-type microstrip lines are both 0.5 mm. The crossbar is at the middle of the two arms with length 2.5 mm. The diameter of the via is 0.3 mm and the background microstrip line is 6 mm.

The full wave simulation software CST studio Suit ([17]) was used to investigate the performance of the proposed metamaterial unit. The Floquet method was used to get

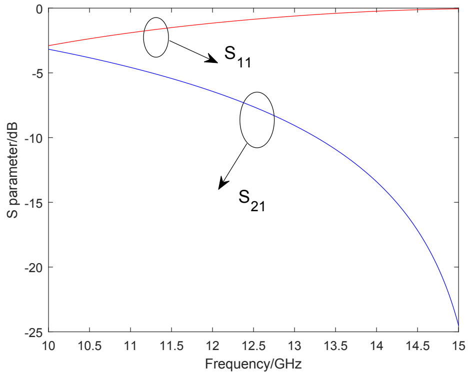


図 3　Simulated S parameters of the proposed metamaterial unit.

its S parameter by setting the x-axis unit cell boundary condition, y-axis unit cell boundary condition and z-axis open boundary condition, respectively. The simulated S parameter results are shown in Fig. 3.

The retrieve method was used to explore the equivalent refractive index of the proposed metamaterial unit ([15]). This method was given by Smith, which can be rewritten as follows.

$$n = \frac{1}{k \cdot d} \cos^{-1}\left[\frac{1 - S_{11}^2 + S_{21}^2}{2S_{21}}\right] \tag{1}$$

$$Z = \pm\sqrt{\frac{(1 + S_{11})^2 - S_{21}^2}{(1 - S_{11})^2 - S_{21}^2}} \tag{2}$$

$$\epsilon = \frac{n}{Z} \tag{3}$$

$$\mu = n \cdot Z \tag{4}$$

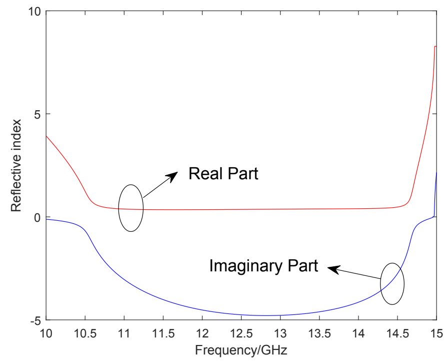
where n is refractive index, k is the wave number, d is the thickness of the substrate, Z is the wave impedance, ϵ is the equivalent permittivity and μ is the equivalent permeability.

It is worthy to note that the final results of equation (1)-(4) should satisfy the following equations in order to keep the proposed metamaterial unit performance as negative or near-zero refractive index.

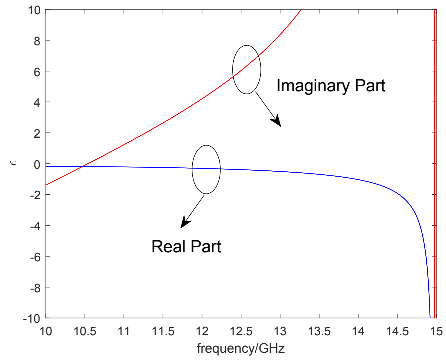
$$\begin{cases} \mathrm{Re}(Z) > 0 \\ \mathrm{Im}(n) \geqq 0 \\ \mathrm{Im}(\epsilon) \geqq 0 \\ \mathrm{Im}(\mu) \geqq 0 \end{cases} \tag{5}$$

The retrieve results from S parameters of the proposed near-zero refractive-index metamaterial unit are illustrated in Fig. 4. It is transparent that the real part of the refractive index is near zero at the bandwidth from 10.5 GHz and 14.5 GHz while the imaginary part varies from -4.8 to -0.5. The equivalent permittivity ϵ is also near zero at the bandwidth from 10.5 GHz and 14.5 GHz.

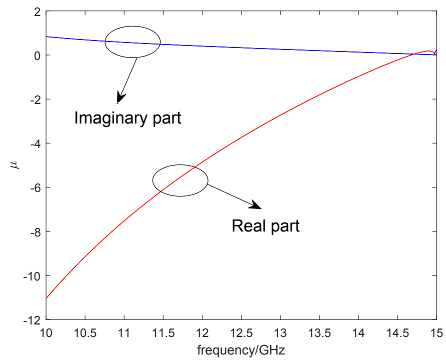
The simulated current density distribution of the proposed metamaterial unit is shown in Fig. 5, where the direction of



(a)



(b)



(c)

図 4　Retrieve results from S parameters of the proposed near-zero refractive-index metamaterial unit. (a) refractive index; (b) equivalent permittivity; (c) equivalent permeability.

the arrows represent the direction of the current and the size of arrows represent the current density, respectively. The left side has anticlockwise current while the right side has clockwise current. Both current would produce the magnetic resonance. On the other hand, the adjunct metamaterial unit would produce electric resonance. When the outside electronic field is less than the resonance frequency, the equivalent refractive index will be less than zero or near to zero.

3. Simulation Verification

In order to further verify the performance of the proposed

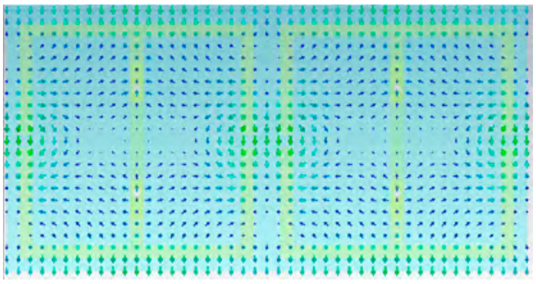


図 5 Simulated current density distribution of the proposed metamaterial unit.

metamaterial unit, two simulation experiments are designed.

A device made by the proposed metamaterial unit is the Shelby lens ([16]), which is constituted with trapezoidal metamaterial units array. The whole simulation platform in CST studio suit is shown in Fig. 6. There are eight layers of the whole lens and the distance between the adjunct layers is 0.6 mm. There are seven metamaterial units for the first and second layers and each layer reduces one metamaterial unit from the third layer to eighth layer. The input plane is designed on the top of the first layer while the output plane is composed by these trapezoidal metamaterial unit, which has a 172° angle for the x-axis. Other space is filled with air. The boundaries of the X-axis, Y-axis and Z-axis are set as “open space with added space”.

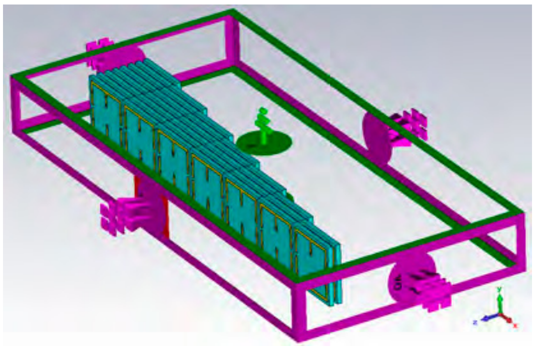
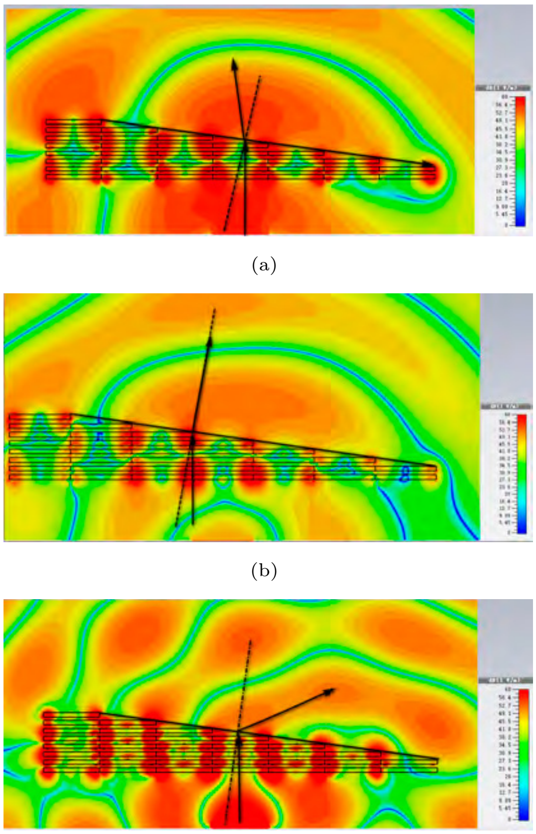


図 6 Simulation platform of the Shelby lens with several proposed metamaterial units.

The simulated electric distribution results are illustrated in Fig. 7. First the normal refraction is given in Fig. 7 (a), where the incident wave and the refracted wave are separated to two different directions of the normal. The negative refraction is also shown in Fig. 7 (c), where the incident wave and the refracted wave are at the same direction of the normals. Fig. 7 (b) shows the exactly near-zero refraction, where the refracted wave is perpendicular to the output plane. This phenomenon is often used to change the shape of the wave by designing different output plane.

Another application of the proposed metamaterial unit is the cloaking phenomenon. For simplified, the rectangular



(a)

(b)

(c)

図 7 Simulated results of the Shelby lens constituted with the proposed near-zero refractive-index metamaterial unit. (a) normal refraction; (b) near-zero refraction; (c) negative refraction.

cloak with scattering cancellation technique is designed in this paper. The scattering cancellation technique requires the metamaterial unit surround the target object, which is a cylinder with pure copper in this paper, to cancel scatting wave at the cloaked frequency. For this purpose, a rectangular cloak, which is shown in Fig. 8 is designed. This rectangular cloak consists of four orthogonal planes. Each plane is made up of six proposed metamaterial units. A cylinder with outer radius 4 mm and inner radius 3.5 mm is located at the center of the rectangular cloak. A plane wave is incident for the -Z-axis.

The simulated S parameter of the rectangular cloak is shown in Fig. 9 and is observed. When the operational frequency is less than 12 GHz, S_{11} decreases when the frequency increases. S_{11} reaches its minimum at the frequency 12.3 GHz, where the scattering cancellation technique reaches its best performance. It is worthy to note that the bandwidth of the good scattering cancellation technique is still narrow, which is mainly disadvantage of the metamaterial unit nowadays.

The simulated electric field distribution results of the rectangular cloak constituted with the proposed near-zero

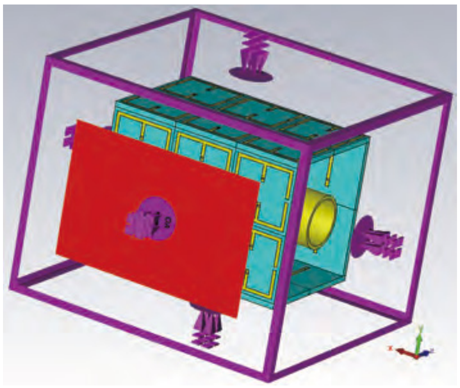


図 8　Simulation platform of the rectangular cloak with several proposed metamaterial units.

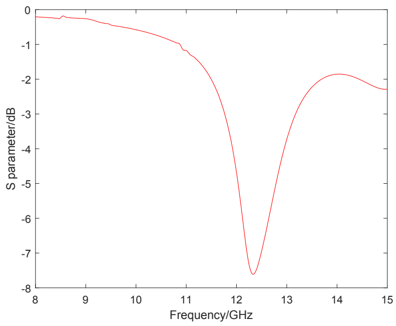
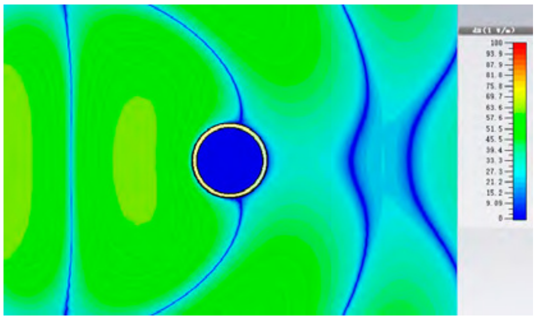


図 9　Simulated S parameter of the rectangular cloak with several proposed metamaterial units.

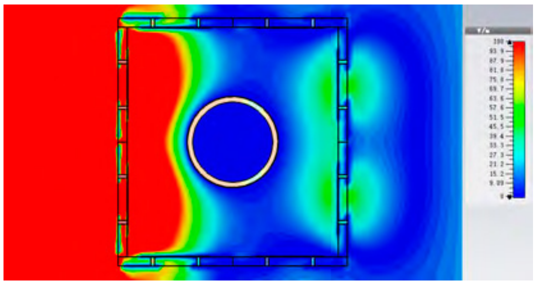
refractive-index metamaterial unit are illustrated in Fig. 10. The cylinder without rectangular cloak is also in Fig. 10 (a) for comparison. It is clear that little power can pass through the cylinder when the cylinder is at uncloaked frequency because the power is diffused and blocked by the cylinder. However, when the rectangular cloak is at the cloaked frequency, the electric distribution has changed but has almost the same electromagnetic energy as the left side of the rectangular cloak, where the electromagnetic energy is like the free space. It is clear that the rectangular cloak can realize the electromagnetic invisible cloak.

4. Conclusion

A novel metamaterial unit is designed and verified by electromagnetic simulation in this paper. The proposed metamaterial unit consists of two E-type microstrip line which are linked to a background microstrip line by two vias. The retrieved refractive-index, the equivalent permittivity and equivalent permeability are calculated by Smith method. The refractive-index is near zero at the bandwidth from 11 GHz to 14 GHz. Two experiments are designed to verify the performance of proposed metamaterial unit. The first experiment is about the Shelby lens, which performs the negative refraction at the near-zero refractive-index frequency, while the second experiment is about the rectangular cloak, which performs the electromagnetic invisible cloak at the cloaked frequency.



(a)



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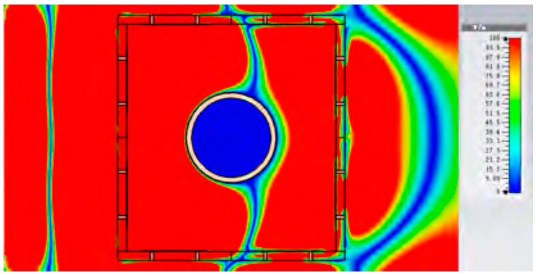

(c)

図 10　Simulated electric distribution results of the rectangular cloak constituted with the proposed near-zero refractive-index metamaterial unit. (a) the cylinder without rectangular cloak; (b) the cylinder without rectangular cloak at uncloaked frequency; (c) the cylinder without rectangular cloak at cloaked frequency.

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