PAPER

Low-Profile Design of Metasurface Considering FSS Filtering Characteristics

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SUMMARY This paper describes a metasurface designed utilizing either a Frequency Selective Surface (FSS) that has band-pass characteristics or one with band-rejection filtering characteristics in order to clarify the relationship between the filtering characteristics of the FSS and the Perfect Magnetic Conductor (PMC) characteristics of the metasurface. The effects of the filtering characteristics of the FSS on the PMC characteristics of the metasurface are described. Calculation results confirm that a low profile metasurface can be achieved using these FSSs. In addition, the effects of the size of the metasurface on the PMC characteristics of the surface are shown.

key words: metasurface, PMC, FSS, low-profile

1. Introduction

A Frequency Selective Surface (FSS) comprises narrow-spaced metal patches, and has frequency-band-rejection or frequency-band-pass characteristics [1], [2]. It is known that a FSS with the ground plane has Perfect Magnetic Conductor (PMC) characteristics in a specific frequency band. This surface is referred to as a metasurface and it can control the phase of a wave that is reflected at the surface [3], [4]. A metasurface is applied to antennas [5]–[9], filters [10], and absorbers [11] to improve the performance of these devices. There are various purposes to apply metasurfaces to antennas, for example, suppressing the mutual coupling between antenna elements [5], [6], improving the gain of antennas [7], [8], and miniaturizing the antennas [9]. When the goal is to achieve a low profile antenna, a low profile metasurface is required.

Several design methods incorporating a metasurface have been proposed. One method is to employ equivalent circuit models [12]. A resonant cavity approach using ray theory was presented in [13] and [14]. In [15] and [16], optimization algorithms such as Genetic algorithms were used to design a metasurface. A number of metasurfaces have already been proposed by using these methods. However, the relationship between the filtering characteristics of the FSS and the PMC characteristics of the metasurface which is designed utilizing the FSS has not yet been clarified. The PMC characteristics of the metasurface change as the filter-

ing characteristics of the FSS change. There are optimum filtering characteristics that are suitable for the design of the required metasurface.

In this paper, a low profile metasurface is designed by utilizing either a FSS that has band-pass characteristics or one that has band-rejection filtering characteristics. The design method uses an approach employing approximate ray theory because its logic is very simple. The theory provides a physical insight of the wave propagation phenomena by describing the total wave fields as a sum of different types of waves. It can directly calculate the characteristics of waves. The design method utilized in [13], [14] is expanded to design the metasurface by using the FSS with various filtering characteristics. The metasurface comprising the FSS which has the total transmission characteristics has already been designed. In this paper, the metasurface utilizing the FSS which has the partial reflection characteristics is designed. The effects of the filtering characteristics of the FSS on the PMC characteristics of the metasurface which is designed utilizing the FSS are described. Furthermore, reflection characteristics of a finite-size low-profile metasurface are clarified.

In Sect. 2, the metasurface configuration is described. A loop-slot or a loop type FSS are utilized to design the metasurface. In Sect. 3, a design method for the metasurface using ray theory is explained. In Sect. 4, the effect of the filtering characteristics of the FSS on the PMC characteristics of the metasurface comprising the FSS is examined. In Sect. 5, reflection characteristics of a finite-size low-profile metasurface are described. In order to verify the obtained calculation results, the designed metasurface is fabricated. In Sect. 6, we present our conclusions.

2. Configuration and Analysis Models of Metasurface

Figure 1 shows the configuration of the metasurface and the analysis models for the FSS elements, FSS, and metasurface. Figure 1(a) indicates the configuration of a loop-slot type metasurface. As shown in Fig. 1(a), the metasurface comprises the FSS and the ground plane. Figure 1(b) indicates the shape of the FSS elements. As shown in Fig. 1(b), we consider two types of FSSs. One is a loop-slot type FSS which has band-pass characteristics, and the other is a loop type FSS which has band-rejection characteristics. In this paper, the loop-slot and loop type FSSs have complementary structures in each other. Here, the frequency f_{BP} is

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Fig. 1 Configuration and analysis models.

defined as the frequency where the loop-slot type FSS has band-pass characteristics. The frequency f_{BR} is defined as the frequency where the loop type FSS has band-rejection characteristics. The reason for choosing these FSSs is described in Sect. 3. The difference in PMC characteristics of the metasurface that is obtained using these FSSs is discussed in Sect. 4. Figures 1(c) and 1(d) show the analysis models for FSS and metasurface structures in the case of the loop-slot type. Each FSS comprises FSS elements shown in Fig. 1(b) arranged on the xy-plane infinitely. The parameter T is the period of arrangement, w is the width of a loop-slot/loop, d is the distance between the FSS and the ground plane, and l is the length of the circumference of a loop-slot/loop. In order to analyze the infinite structures, the periodic boundary condition (PBC) is utilized in the FDTD analysis.

3. Metasurface Design Method

In this section, we discuss the design method for the metasurface comprising FSS at a frequency f by using ray theory. Let S_{11} and S_{21} be the reflection coefficient and the insertion loss of the FSS at frequency f , respectively. When a plane wave propagates from the positive z direction as shown in

Fig. 2 Route of reflected wave at metasurface composed of FSS and ground plane.

Fig. 2 and arrives at the FSS, the amplitudes of the waves reflected by the FSS layer and penetrated through the FSS layer are the $|S_{11}|$ and $|S_{21}|$ times that of the incident wave. The penetrated wave is reflected at the ground plane and going back to the FSS. Then the reflection and penetration are repeated as shown in Fig. 2. Here, n is the number of times that the wave is reflected at the surface of the ground plane. At f_{BP} , all waves pass through the FSS layer, that is, only the reflected wave of $n = 1$ is considered as the reflected wave. Conversely, only the wave of $n = 0$ is considered at f_{BR} because all waves are reflected at the surface of the FSS. Here, E_{in} is the electric field of the incident wave, E_{total} is the electric field of the wave comprising all the reflected waves going back to the positive z direction which are reflect by or penetrate through the FSS, and n is the number of times that the wave is reflected at the surface of the ground plane. In the case of $n = 0, 1$, and 2 , the electric field of the reflected waves going (or propagating) back to the positive z direction is represented as

$$E_0 = E_{in}|S_{11}|e^{j\phi_{11}}, \quad (1)$$

$$E_1 = E_{in}|S_{21}|^2e^{j(2\phi_{21}+2\phi_\varepsilon+\phi_{ref})}, \quad (2)$$

$$E_2 = E_{in}|S_{21}|^2|S_{11}|e^{j(\phi_{11}+2\phi_{21}+4\phi_\varepsilon+2\phi_{ref})}. \quad (3)$$

Here, ϕ_{11} , ϕ_{21} , ϕ_ε , and ϕ_{ref} are the reflection phase of the FSS, the transmission phase of the FSS, the phase rotation between the FSS and the ground plane, and the reflection phase of the ground plane, respectively. The phase rotation ϕ_ε can be expressed as

$$\phi_\varepsilon = \frac{2\pi d}{\lambda}. \quad (4)$$

The equations of the electric field of the reflected waves are a geometrical progression the first term for which is equal to E_1 and common ratio $r = |S_{11}|e^{j(\phi_{11}+2\phi_\varepsilon+\phi_{ref})}$ when n is greater than 1. Therefore, electric field E_{total} of the wave comprising all the reflected waves from $n = 0$ to N can be expressed as

$$E_{total} = E_0 + \sum_{n=1}^N E_n = E_0 + \frac{E_1(1-r^N)}{1-r}. \quad (5)$$

If we rearrange Eq. (5) with $N \rightarrow \infty$, the following equation is obtained

$$E_{total} = E_0 + \frac{E_1}{1-r}. \quad (6)$$

When the amplitude and phase of the reflected wave E_{total}

is equal to that of the incident wave E_{in} at the FSS, this situation corresponds to when the wave is reflected at the surface without phase rotation. Namely the FSS with the ground plane has the PMC characteristics when the electric field E_{total} satisfies Eq. (7).

$$E_{total} = E_{in}. \quad (7)$$

In this paper, we assume that $E_{in} = 1$. Then, the following equation is obtained by substituting Eq. (6) into Eq. (7).

$$E_0 + \frac{E_1}{1-r} = 1. \quad (8)$$

The specific distance d between the FSS and ground plane obtaining PMC characteristics can be derived by substituting Eq. (2), Eq. (4) and common ratio $r = |S_{11}|e^{j(\phi_{11}+2\phi_e+\phi_{ref})}$ into Eq. (8).

$$d = j\frac{\lambda}{4\pi} \log \left[\frac{1-E_0}{e^{j\phi_{ref}} \{ |S_{21}|^2 e^{j2\phi_{21}} + (1-E_0)E_0 \}} \right]. \quad (9)$$

In this paper, we use Eq. (9) to design the metasurface.

As shown in this section, PMC characteristics of the metasurface are obtained by synthesizing the waves that have different routes. The route means that each wave is reflected at the different number of times by the ground plane. We need to utilize the FSS that has both of reflection and penetration characteristics. Hence a loop-slot and loop type FSS are utilized in this paper. These FSSs have the both characteristics at the frequency except f_{BP} and f_{BR} .

4. Design of Metasurface Comprising FSS

4.1 FSS Filtering Characteristics

As described in Sect. 3, the filtering characteristics of the FSS must be determined to design the metasurface by using Eq. (7). To define the filtering characteristics, the transmission and reflection characteristics of the FSS when the plane wave comes from the positive z direction are calculated by using FDTD method. The model presented in Fig. 1(c) is utilized.

Figure 3 shows the filtering characteristics of the loop-slot and loop type FSSs. The parameters $l = 0.01 \lambda_{BP}$, $w = 0.25 \lambda_{BP}$, and $T = 0.26 \lambda_{BP}$. Here, λ_{BP} is defined as the wavelength at the frequency f_{BP} . Figure 3(a) shows the amplitude of the S-parameters, and Fig. 3(b) shows the phase of the S-parameters. The black lines and the gray lines indicate the results of the loop-slot and the loop type FSSs, and the solid line and the dashed line represent the characteristics of S_{11} and S_{21} , respectively. The vertical axis and horizontal axis show the amplitude of S-parameters and the frequency that was normalized by f_{BP} .

As can be seen in Fig. 3(a), the loop-slot type FSS with the structural parameters described in above operates as a band-pass filter. It is also seen that the loop type FSS, which is complementary structure of the loop-slot type FSS, operates as a band-rejection filter around the frequency of 0.9

(a) Amplitude of S-parameter

(b) Phase of S-parameter

Fig. 3 Filtering characteristics of loop-slot/Loop Type FSS.

f_{BP} . Thus we can confirm that both types have almost inverse filtering characteristics. In addition, we can see a discontinuity in the phase characteristics at the frequency f_{BP} and $0.9 f_{BP}$ for loop-slot and loop type FSSs, respectively.

4.2 Transition of Synthesized Electric Field, E_{total}

As explained in previous section, only the reflected wave of $n = 1$ should be considered as the reflected wave at f_{BP} . Similarly, only the reflected wave of $n = 0$ should be considered as the reflected wave at f_{BR} . At other frequencies, there are various reflected waves with different amplitudes, phases, and routes. Thus all these waves should be considered at these frequencies. In this section, we discuss the reflected waves at frequencies other than f_{BP} and f_{BR} .

Figure 4 shows the transition of the synthesized electric field, E_{total} , at $0.5 f_{BP}$. Figures 4(a) and 4(b) show the cases for the loop-slot and loop type FSSs, respectively. This figure 4(a) shows the cases when the distance d between the FSS layer and the ground plane of $0.460 \lambda_{0.5f_{BP}}$, $0.463 \lambda_{0.5f_{BP}}$, $0.465 \lambda_{0.5f_{BP}}$, and $0.468 \lambda_{0.5f_{BP}}$. In Fig. 4(b), the cases for the distance d of $0.051 \lambda_{0.5f_{BP}}$, $0.056 \lambda_{0.5f_{BP}}$, $0.061 \lambda_{0.5f_{BP}}$, and $0.066 \lambda_{0.5f_{BP}}$ is indicated. Here, $\lambda_{0.5f_{BP}}$ is the wavelength at the frequency $0.5 f_{BP}$. Only in the case of specific distance $d = 0.468 \lambda_{0.5f_{BP}}$ or $0.051 \lambda_{0.5f_{BP}}$, the process in which

Fig. 4 Transition of $E_{\text{total}}(f = 0.5 f_{\text{BP}}, N = 50)$.

the reflected waves are synthesized is plotted. We consider reflected waves from $n = 0$ to 50, that is, the transition of E_{total} comprises E_0 to E_{50} and is drawn in Fig. 4. In the case of other distances d , only the results are plotted.

As shown in Fig. 4, it is represented that the electric field E_{total} converges at a certain value as the number n of reflected waves is increased in both cases. It is also shown that the converged electric field changes as distance d changes. The absolute value of the converged electric field E_{total} is nearly equal to 1 regardless of distance d . For the loop-slot type FSS, when distance $d = 0.463 \lambda_{0.5 f_{\text{BP}}}$, the imaginary part of the electric field E_{total} equals 0 and the real part of E_{total} is greater than 0. Accordingly, the metasurface, which operates at the frequency $0.5 f_{\text{BP}}$ can be designed by setting distance $d = 0.463 \lambda_{0.5 f_{\text{BP}}}$. Similarly, for the loop type FSS, the metasurface that operates at the frequency $0.5 f_{\text{BP}}$ can be designed by setting distance $d = 0.056 \lambda$. Consequently, it is clear that a thinner metasurface can be designed by using a

(a) Thickness

(b) PMC bandwidth

Fig. 5 Thickness and PMC bandwidth of designed metasurface.

loop type FSS at the frequency $0.5 f_{\text{BP}}$.

4.3 Thickness and PMC Bandwidth of Metasurface

Figure 5 indicates the thickness and the PMC bandwidth of the designed metasurface. Here, the thickness means the distance between the FSS layer and the ground plane when PMC characteristics can be realized at each normalized frequency. Figure 5(a) shows the thickness, and Fig. 5(b) shows the PMC bandwidth. Here, the PMC bandwidth is defined as the frequency band within the reflection phase of ± 90 degrees. In both figures, the solid line and dashed line represent the cases for the loop-slot and loop type FSSs, respectively.

For the loop-slot type FSS, the thickness of the metasurface becomes thinner as the design frequency for metasurface becomes higher. On the other hand, for the loop type FSS, the thickness of the metasurface at the frequency less than $0.9 f_{\text{BP}}$ tends to be thinner than that obtained at the frequency more than $0.9 f_{\text{BP}}$. Consequently, the thickness of the metasurface for the loop type FSS is thinner (thicker) than that for the loop-slot type at a low (high) frequency. In the case of the loop-slot type FSS, we can achieve a metasurface with the thickness of 0.05λ at the frequency $1.5 f_{\text{BP}}$. On the other hand, for the loop type FSS, a metasurface with the thickness of 0.05λ can be obtained at the frequency $0.5 f_{\text{BP}}$.

It is shown in Fig. 5(b) that the PMC bandwidth of the metasurface changes as the frequency changes. In addition, we find that there is a peak in the PMC bandwidth in the case of the loop-slot type FSS. The peak is obtained at the frequency $1.0 f_{BP}$. The frequency corresponds to the frequency where the amplitude of S_{21} of the FSS nearly equals 0 dB. For the loop-slot type FSS, the maximum PMC bandwidth of the metasurface is 26.5%. On the other hand, we can achieve a thinner metasurface using the loop type FSS. The metasurface with a 100% PMC bandwidth is obtained at the frequency $0.1 f_{BP}$.

To obtain a thin metasurface, we have to design it at lower (higher) frequency by using loop (loop-slot) type FSS. To achieve a wideband metasurface, we need to design it at the frequency $1.0 f_{BP}$ for the loop-slot type FSS. In the case of the loop type FSS, we need the frequency to be $0.1 f_{BP}$.

5. PMC Characteristics of Finite Size Low-Profile Metasurface

5.1 Effects of Number of Elements on PMC Characteristics

In the previous section, we assume that the metasurface has infinite size. However, an actual low-profile metasurface would have a finite structure. Therefore, the metasurface must be re-designed taking account of a finite size.

Figure 6 shows the reflection phase at the surface of the metasurface (phase of E_{total}). Figures 6(a) and 6(b) show the cases for the loop type and loop-slot type FSSs, respectively. Here, we consider the low-profile metasurface with the thickness d of 0.05λ . From Fig. 5(a), the design frequency f_1 with PMC characteristics is $0.50 f_{BP}$ for a loop type, and the frequency f_2 is $1.46 f_{BP}$ for a loop-slot type. In Fig. 6, the solid line, dashed line, and dotted line indicate an infinite structure, 7 by 7 element structure, and 5 by 5 element structure, respectively.

As shown in Fig. 6, the frequency f_{PMC} where the metasurface has PMC characteristics becomes lower as the number of element is increased. When the number of elements is 7 by 7, the frequencies with PMC characteristics are $0.57 f_{BP}$ for the loop type FSS and $1.46 f_{BP}$ for the loop-slot type FSS. The error Δf_{PMC} of the design frequency is 10% in the case of loop type FSS. That for loop-slot type FSS is 0.3%. Here, the error Δf_{PMC} is defined as the relative error between the frequency f_{PMC} for infinite size metasurface and that for finite size. As compare the cases for the loop type and the loop-slot type FSSs, it is found that the error Δf_{PMC} of them is different although the number of their elements is same.

The period T of arrangement for the loop type FSS and that for the loop-slot type FSS is same in this paper. However, the design frequency where the metasurface is designed by using these FSSs is different. Thus the normalized size, which is normalized by the wavelength at the designed frequency, of these metasurfaces with 7 by 7 elements is different. Accordingly, the effects of the normalized size of metasurfaces on the error Δf_{PMC} of them should be consid-

(a) Loop type

(b) Loop-slot type

Fig. 6 Reflection phase at the surface of low-profile metasurface.

Fig. 7 Relative error of the designed frequency of finite metasurface.

ered. Figure 7 shows the relationship between the normalized size of metasurfaces and the error Δf_{PMC} of them. The vertical axis and horizontal axis show the error Δf_{PMC} of the finite size metasurface and the normalized length L/λ of the circumference of the metasurface. In Fig. 7, the solid line and dashed line indicate the case of loop type and loop-slot type FSSs, respectively. As shown in Fig. 7, the error Δf_{PMC} becomes smaller as the normalized size of the metasurface is increased in both cases. It is also found that the error Δf_{PMC} can be suppressed to 2% or less by setting the size of the metasurface $L \geq 1.5\lambda$. Consequently, the number of the elements should be decided so that the length L of the finite size metasurface becomes 1.5λ or more.

(a) Fabricated metasurface

(b) Experimental setup

Fig. 8 Reflection phase at the surface of low-profile metasurface.

5.2 Verification Through Experiment

In order to verify the above-mentioned calculated results, the loop type metasurface with 7 by 7 element was fabricated.

Figure 8 shows a photograph of the experimental configuration. Figures 8(a) and 8(b) show a photograph of the fabricated metasurface and experimental environment. The FSS elements are constructed of copper. The size of elements is shown in Fig. 8(b) and that of the ground plane is $7T \times 7T$. The thickness of the metasurface is set to 0.1λ . As shown in Fig. 8(b), a horn antenna is utilized to generate an incident plane wave in the experiment. When the reflection phase of the metasurface is measured, a flat metal plane of the same size with the metasurface is utilized as a reference.

Figure 9 indicates the calculated and experimental reflection phase of the finite metasurface. The solid line represents the experimental results and the dashed line represents the calculated results. As shown in Fig. 9, the calculated results almost agree with the experimental results. That is why we conclude that the calculate results are appropriate. In the case of the calculation, the frequency where the metasurface has PMC characteristics, f_{PMC} , is $0.46 f_{BP}$. On the other hand, in the experiment, the frequency f_{PMC} equals $0.48 f_{BP}$.

Fig. 9 Reflection phase at the surface of low-profile metasurface.

6. Conclusion

A novel design method based on the ray theory was proposed to design the metasurface by using the FSS which has partial reflection characteristics. The metasurface was designed using a loop-slot or loop type FSS. Based on the simulation results, it was clarified that a low-profile metasurface could be achieved by using these FSSs. It had a low profile structure with the thickness of $1/10$ wavelength. Furthermore, the effects of the size of the metasurface on the frequency where the surface has PMC characteristics were shown. It was clarified that the number of the elements should be decided so that the length of the circumference of the metasurface becomes 1.5λ or more. Finally, the validity of the design method was presented by the experimental results.

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