Study on Wave Absorption of 1D-/2D-Periodic EBG Structures and/or Metamaterial Layered Media as Frequency Selective Surfaces

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Abstract

This paper conducts a study on the frequency-dependent filtering and blocking effects of a variety of periodic structures, dubbed frequency selective surface(FSS). The periodic structures of interest are 1D and 2D repeated patterns of metal patches or slots sitting on the interface between the two different regions in the layered media which will show the capacitive or inductive behaviors and incorporated with the electromagnetic bandgap(EBG) geometry as another stratified media. Besides the normal substances so called double positive(DPS)-type in the layered media, metamaterials of double negative(DNG) are considered as layering components on the purpose of investigating the unusual electromagnetic phenomena. Frequency responses of transmission(absorption in terms of scattering) and reflection will be calculated by a numerical analysis which can be validated by the comparison with the open literature and demonstrated for the periodic structures embedding metamaterials or not. Most importantly, numerous examples of FSS will present the useful guidelines to have absorption or reflection properties in the frequency domain.

Key words : 1D Periodic Structures, 2D Periodic Structures, Frequency Selective Surface, EBG, Wave Absorprion, Metamaterials

Ⅰ. Introduction

In an attempt to provide the electromagnetic scattering phenomena with frequency dependency or frequency selectivity such as filtering and blocking, the physical appearance of the scattering object will take the form of finitely or infinitely periodic arrangement. Of course, aperiodic geometries can answer the wanted question on the frequency selectivity, though. It is easier to find the solution from the periodic structure as we can see the electric filter built up as the infinitely periodic placement of the circuit elements. In this regard, the Image Parameter method is referred to as a good example[1].

What is more meaningful to the frequency selectivity in the electromagnetic radiation and scattering is the design of frequency selective surface[2]. The shape, the periodicity, the spacing between the adjacent elements, the material, the thickness of each layer, etc determine the absorption and reflection coefficients of a incident wave. In a great number of examples for the FSS, though the pertinent combinations of the transverse physical parameters(spacing, periodicity and shapes) and the longitudinal parameters(thickness, material arrangement and so on and so forth, etc the direction of layering) make the wanted absorption or reflection happen, most of them are assumed infinitely periodic. It is no wonder that they adopt the finite number of material layers for practicality, but they are not going further to other possible solutions.

Therefore, we incorporate today's buzzword 'metamaterials' or 'MTM' introduced in [4] with the 1D- and 2D periodic geometries with or without capacitive and inductive screening surfaces and try to find the unexploited ways to have right frequency selective filtering and blocking. Particularly, one interesting feature of metamaterials, wave matching condition from the right paring of the DNG and DPS[5]~[12], is toyed with, and analyzed with the related cases.

In this paper, 1D(longitudinally) periodic EBG geometries are investigated in the first place. And then periodic metallic patches or slots are placed in the transverse planes in 1D layered media, which is the 2D periodic structure. Next, we will see what happens to the 1D and 2D-FSS, when they host the metamaterials. Finally, designs are made to change the EBG property to the transmission over widened frequency bands for desirable absorption performances.

Ⅱ. 1D Periodic EBG Structures as FSS

First of all, the characteristics of 1D layered media with or without infinite periodicity are addressed. Fig. 1 is the stacked geometry of dielectric layers.

There is a plane wave impinging on the interface be-

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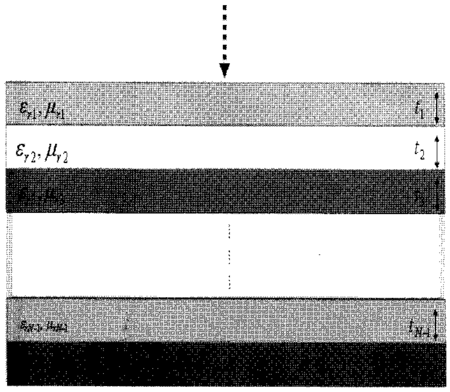


Fig. 1. Geometrical illustration of 1D FSS.

tween the top layer and the air, which is the normal incidence and is assumed throughout this paper. The analysis technique for evaluating 1D layered and 2D periodic geometries' properties is shown in [3], the transfer-matrix method and the mode-based inductive- and capacitive screen formulae.

Given ε_r=13 and t=2 cm for the odd numbered layer and ε_r=1 and t=8 cm for the even numbered layer in a total of 8 dielectric layers, the clear bandgaap(solid-line) is formed from 600 MHz through 1.4 GHz. Checking the accuracy of the calculation technique, this EBG characteristic overlaps the result of the work reported in [13]. This technique is proven accurate again, applied to another 1D-EBG shown in [14] where the higher and lower refractive index materials of 2.25 and 1.45 respectively alternate, and the last layer has the higher refractive index again, and each of the 21 layers is the quarterwave thick regarding the center frequency of 200 GHz.

Apparently, this example has the stopband(solid line) centered in the calculated frequency range. In line with this, we need to have a look at the retrieved effective permittivity and permeability as well as impedance to know the physics hidden in the transmission and reflection coefficients.

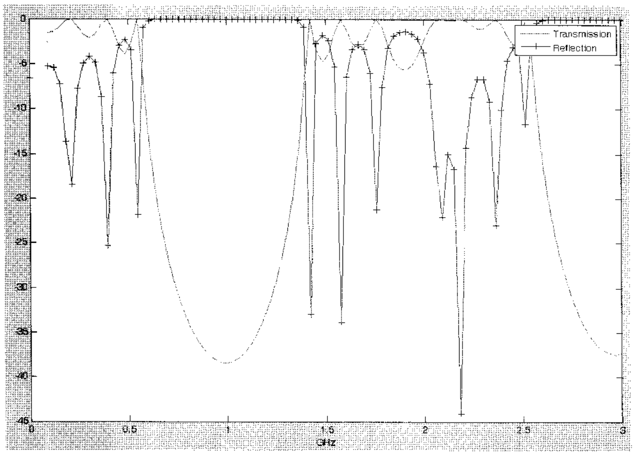


Fig. 2. Frequency selectivity of a 1D EBG.

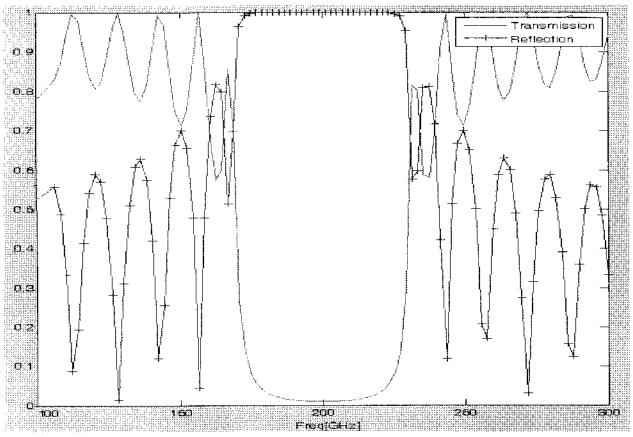


Fig. 3. Frequency selectivity of another 1D EBG.

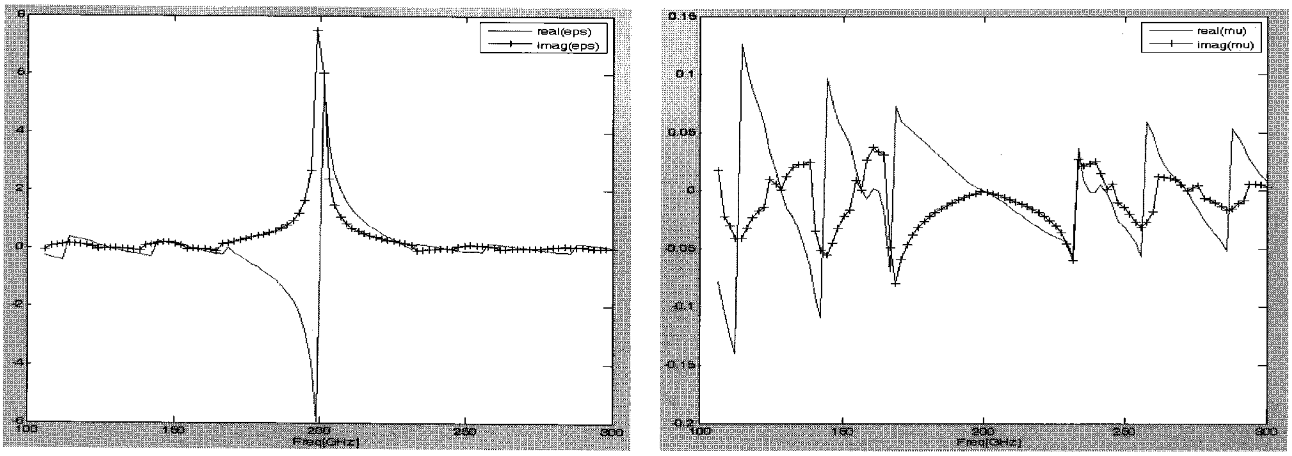
III. Retrieved Impedance and Permittivity and Permeability of the 1D EBG Structure

Transmission and reflection coefficients with respect to a composite material like the inclusions in a host geometry can be converted to the effective ε and μ, refractive index(n) and impedance that account for the reasons of the go-and-stopband characteristics. The followings are the retrieved permittivity and permeability, refractive index and impedance of the Fig. 3's EBG.

Observed at the distance where the microscopic scattering and diffraction effects from the top and bottom planes are ignored, the averaged values of ε, μ, n and Z are retrieved and plotted as in Fig. 4. Seeing Fig. 4(a), where the imaginary term of the effective epsilon becomes big, despite its real term being positive or negative, this results in the increased attenuation and this region coincides with the stopband in Fig. 3. Likewise, in Fig. 4(b), Mu has the imaginary term way below 0 and regardless of the variation of its real term, the wave stops propagating. The stopband is also found in Fig. 4(c) that has a larger imaginary part of n. Fig. 4(d) obviously shows the stopband corresponds to '0 real part' and 'purely imaginary part' of the impedance. So this sort of approach(watching the retrieved constitutive parameters and impedance) brings us the excellent physical interpretation of thee FSS and it can apply to the following cases with no sweat.

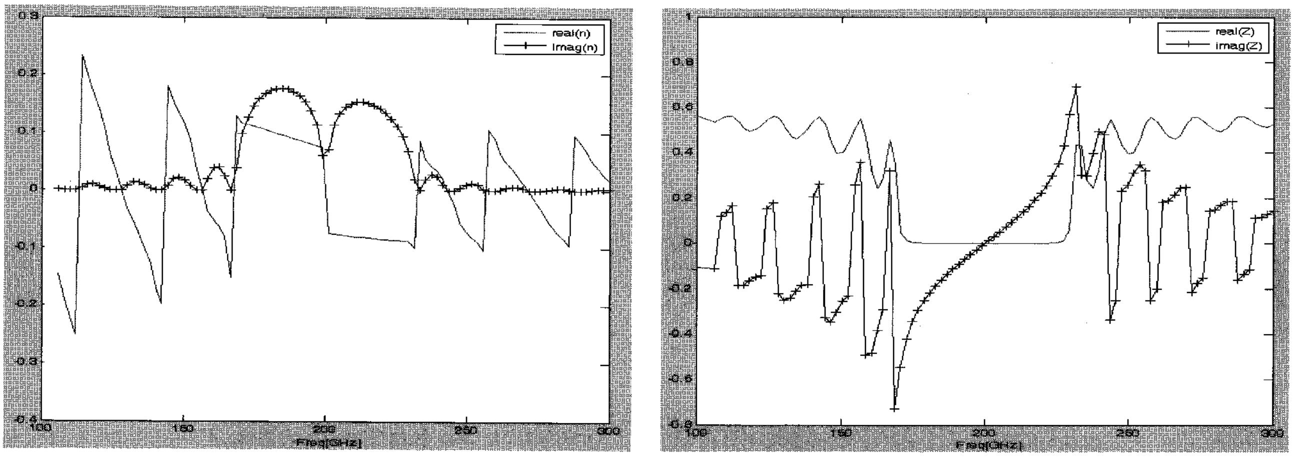
IV. 2D Periodic Metal Patches and Slots

When 1D periodic structures can't push the envelope of size constraints(particularly in the longitudinal direc-



(a) Effective complex permittivity of the Fig. 3 EBG(real part: sold line, imaginary part: -+-)

(b) Effective complex permeability of the Fig. 3 EBG(real part: sold line, imaginary part: -+-)



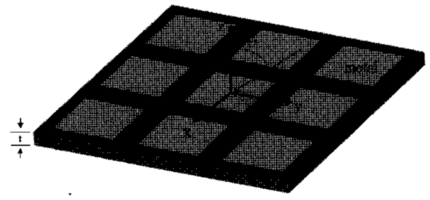
(c) Refractive index of the Fig. 3 EBG(real part: sold line, imaginary part: -+-)

(d) Impedance of the Fig. 3 EBG(real part: sold line, imaginary part: -+-)

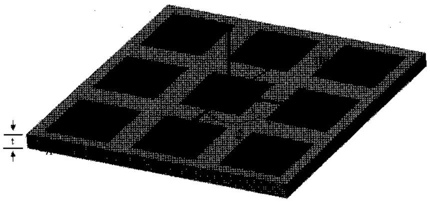
Fig. 4. The retrieved permittivity and permeability, refractive index and impedance of the Fig. 3's EBG.

tion) and performance requirements, we have no alternative but go to 2D approaches. Typically, periodic metal patches or slots are formed on the transverse plane part of the 1D layered media.

Fig. 5 presents the 3D view of the metallic patch-type and slot-type FSS of 2D transverse periodicity. As for the metal-patch-type periodic FSS, it is called the capacitive FSS or lowpass filtering screen. On the contrary, Fig. 5(b) is called the inductive screen where the metal and aperture parts of the capacitive screen have been replaced by the slots and metalization. The double modal summation as Floquet harmonics expresses the scattered electric field from each of the screens and its electromagnetic properties on the transmission and reflection are converted to the electric counterpart admittance or susceptance[3]. Before doing experiments on capacitive and inductive screening, we test whether the present analysis method is valid as follows. The example to be tested has the square slot(7*7 mm^2) elements with periodicity of 1 cm(=*Pre*) on the 0 thick metaliza-



(a) Wave hitting periodic metal patches on the top dielectric of the layered media



(b) Wave hitting periodic slots on the PEC with layered media backed

Fig. 5. Sketch of two 2D periodic layered structures with metal patches and slots.

tion. Its transmitted power is calculated with varying the ratio of *Pre* to wavelength(=*Pre*/ λ) and compared with the reference.

The results agree and show the highpass filtering effect of the inductive screen. Using this validated calculation technique, we will investigate the electromagnetic change of the 1D EBG of Fig.'s 1 and 2, if 2D periodic inductive and capacitive screens are taken into account in the three positions(top layer(first layer), middle layer and bottom layer(*N*th layer)) in order.

Now we obtain the transmission and reflection coefficients of Fig. 7 as follows.

With *Pre*=1 cm, the patch of 2*2 mm^2 and the slot of 2*2 mm^2, the capacitive screen plays kind of lowpass filtering over 1.25∼2.5 GHz, but the inductive with very small apertures blocks most of the incoming energy.

Presently, we move the capacitive and inductive screens from the top layer to the middle layer of the EBG geometry of Fig. 2. There's no change in the size of the screens.

Overall, we have similar results to the top layer screening, except the shift and slight increase of passband to 1.75∼1.9 GHz the center of 1.25∼2.5 GHz.

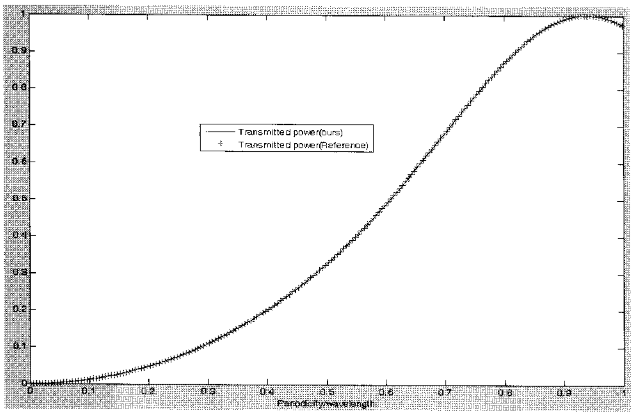


Fig. 6. Calculated transmitted power for the reference inductive screen with square apertures.

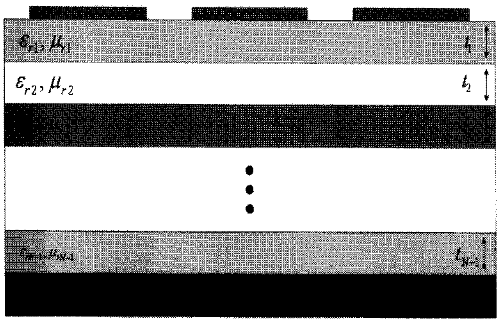
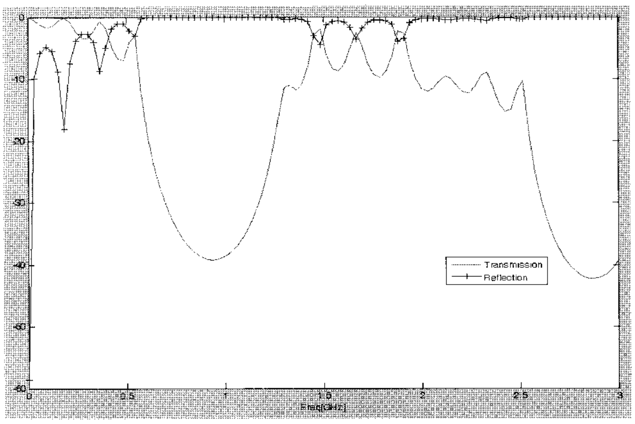
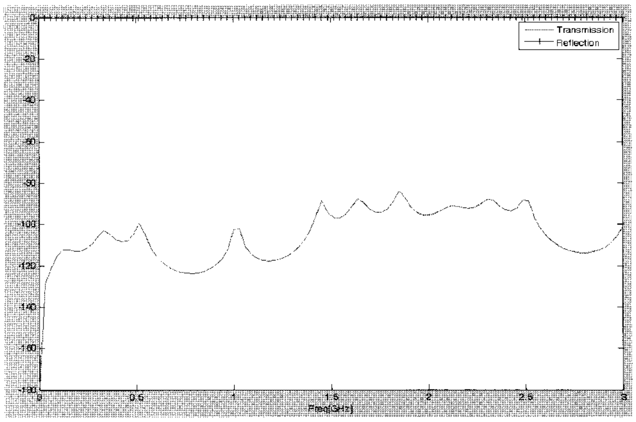


Fig. 7. 2D transversely periodic patches or slots on the top layer of 1D EBG(Fig. 2).



(a) Capacitive screen as the top layer of the EBG(transmittance: solid line, reflectance: -+-)



(b) Inductive screen as the top layer of the EBG transmittance: solid line, reflectance: -+-)

Fig. 8. Transmittance and reflectance of the capacitive and inductive top-layer attached 1D-EBG.

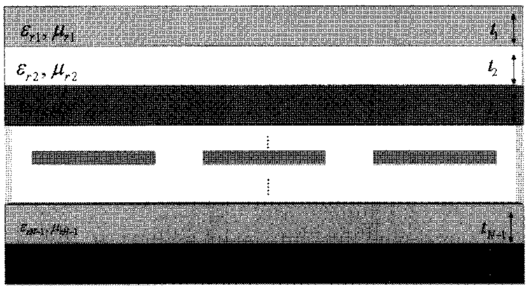
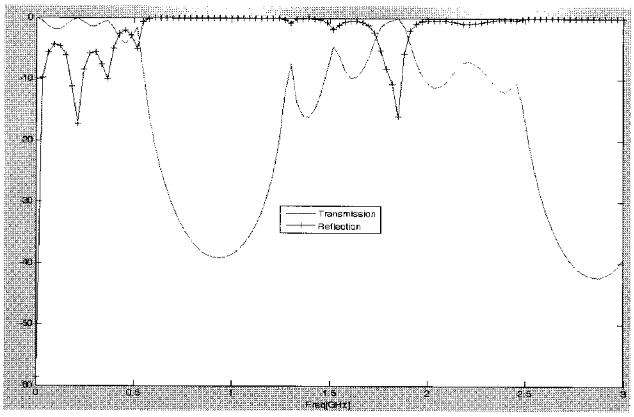


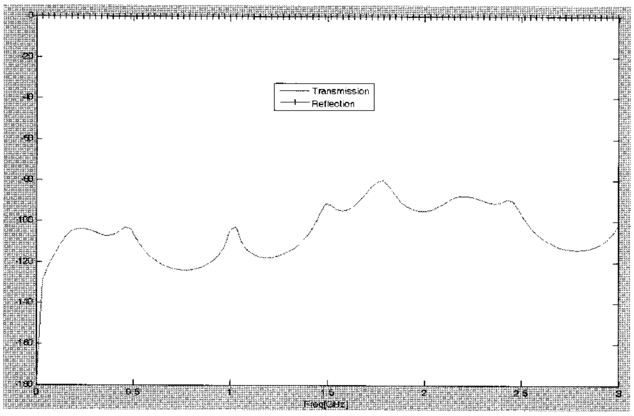
Fig. 9. Patches or slots on the middle layer.

Next, we will check the way the transmittance and reflectance of Fig. 1 and the immediate past two cases change, when the same sizes of screens are placed at the bottom layer.

Similar to the previous cases, the EBG is formed and the higher reflectance is dominant. Though the screens have not been optimized, other ways should be tried to improve the transmittance. Therefore, from the next section on, we suggest a number of schemes to have a

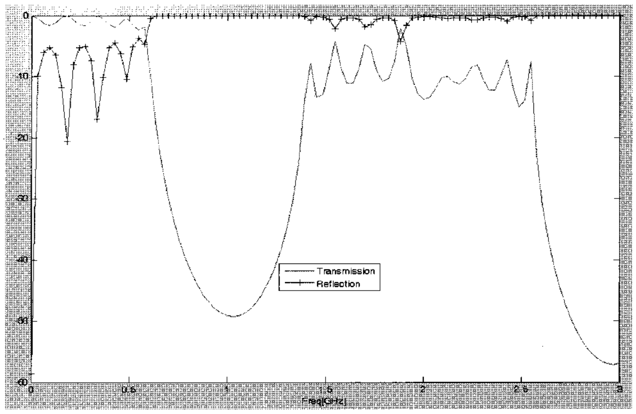


(a) Capacitive screen as the middle layer of the EBG(transmittance: solid line, reflectance: -+-)

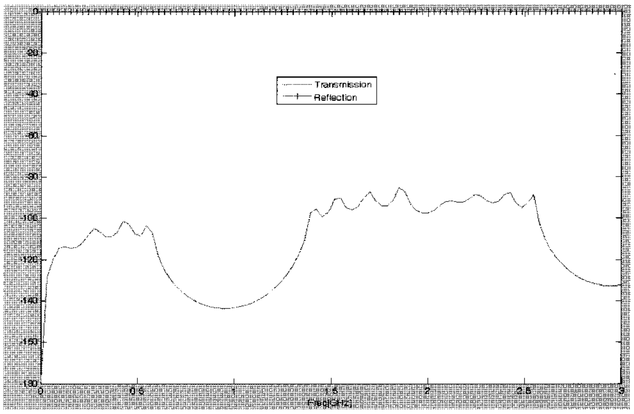


(b) Inductive screen as the middle layer of the EBG(transmittance: solid line, reflectance: -+-)

Fig. 10. Transmittance and reflectance of the capacitive and inductive mid-layer attached 1D-EBG.



(a) Capacitive screen as the bottom layer of the EBG(transmittance: solid line, reflectance: -+-)



(b) Inductive screen as the bottom layer of the EBG(transmittance: solid line, reflectance: -+-)

Fig. 12. Transmittance and reflectance of the capacitive and inductive bottom-layer attached 1D-EBG.

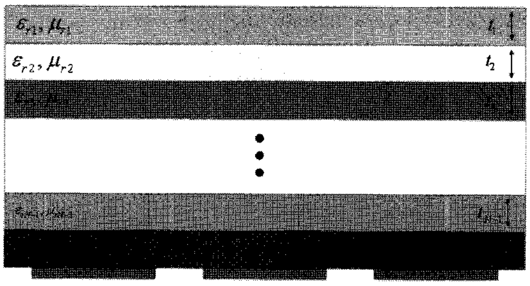


Fig. 11. Patches or slots on the bottom layer.

wider passband and test the metamaterial layers as elements for the 1D periodic structure with or without the screens mentioned until now.

V. Passband(Absorption) Improvement Techniques including the Use of Metamaterial Layers with or without the Periodic Metal Patches and Slots

In the first place, a design is carried out to have a clear and wider passband. To have a passband in the practical frequency band, say, 2∼4 GHz, and feasibility, the structure has the formation of CPs_1-De_1-CPs_2-De_2-CPs_3-De_3-CPs_4 where CPs_n and De_{n+1} mean the nth capacitive screen and the n+1th Dielectric layer.

The electrical length and characteristic impedance of De_1, De_2, and De_3 are 2.72 rad, 291 rad, 2.72 rad, respectively and 50 Ω. The susceptance values of the capacitive screens CPs_1, CPs_2, CPs_3, and CPs_4 are $6.96*10^{-3}$, $2.41*10^{-3}$, $2.41*10^{-3}$, and $6.96*10^{-3}$. In Fig. 13, the passband occurs from 2 GHz to 4 GHz and is much wider than before and found really useful for filtering the impinging wave. And we believe it is easy to realize. Secondly, we employ the metamaterial layers, which don't have either capacitive or inductive screen.

For evaluating the transmittance and reflectance of Fig. 14, the even-numbered layers of the Fig. 2 is replaced by the DNG material $n=-1(\varepsilon_r=\mu_r=-1)$. Obviously, compared to Fig. 2 of the normal dielectric EBG case, Fig. 14 has no ripples in both stopband and

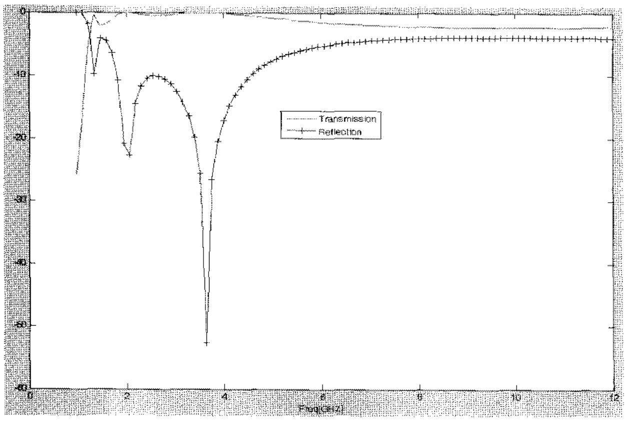


Fig. 13. Transmittance and reflectance of a 7-layer FSS designed for a wider passband(transmittance: solid line, reflectance: -+-).

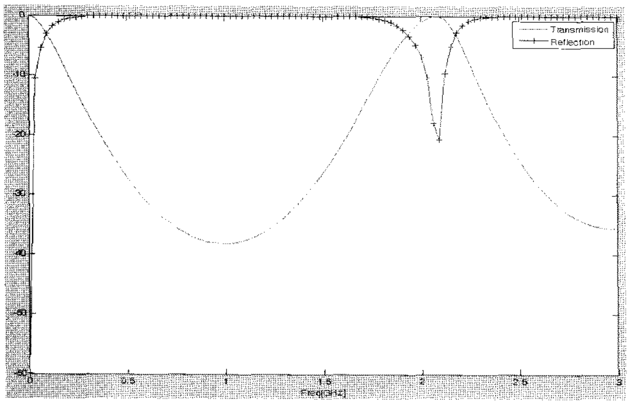


Fig. 14. Fig. 2 EBG with even numbered layers of $n=-1$ (transmittance: solid line, reflectance: -+-).

passband. Especially, this is perfect for a wide band-stop filter against the incident field. Thirdly, we will have a time to consider the influence of the pair of DPS and DNG layers with perfect matching condition $n_{DPS}=-n_{DNG}$ and the same path length of wave propagation. Through this investigation, we will secure the passband to the fullest.

Perfect transmission with n of DPS and DNG the same in magnitude and opposite in sign, and the same in the length, confirms the matching condition in [4]~[11]. Fourthly, the metal patches are added to Fig. 15.

When the capacitive screen is sitting on the top layer of the Fig. 15 of MTM, the full-band pass characteristic is lost and periodic ripples occur in Fig. 16, since the perfect matching condition is globally violated. Also the average of the transmittance curve shows pseudo-low-pass filtering according to the main feature of the capacitive screen. Presuming the last result and the result of Fig. 15, the use of metamterials requires special care to have a desired transmission or reflection performance.

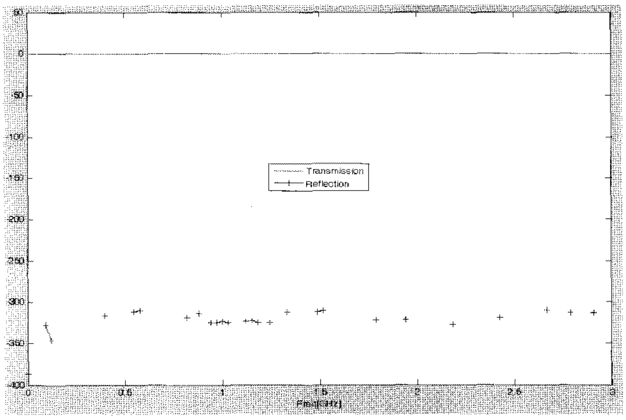


Fig. 15. Modified Fig. 2 with repeated pairs of DPS($\varepsilon_r=13$, $\mu_r=1$) and DNG($\varepsilon_r=-13$, $\mu_r=-1$) for all transmission(transmittance: solid line, reflectance : -+-): No more EBG geometry.

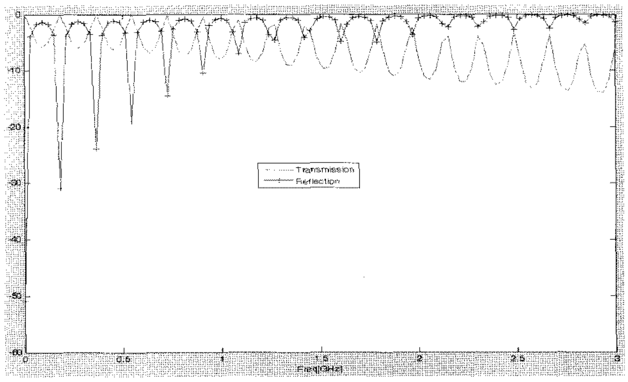


Fig. 16. Fig. 5 with MTM(TX: solid line, RX :-+-).

Ⅵ. Conclusion

In this paper, to investigate and seek the conditions for required FSS properties, a variety of combinations stacking of layers and materials and design practices have been carried out. It is found out the simple periodic dielectric layered structure can make an EBG, but it can be changed by the placement of the 2D periodic metal patches and slots which have been thought of as the means to filtering and blocking. However, the clear absorption over the desired band can be achieved by the design of the normal materials with practical sizes. This absorption can be further improved by meeting the matching condition on the DPS-DNG paired metamaterials with a full-band transmission phenomenon. Plus, care should be taken of in order not to deteriorate the transmission characteristics of well- engineered MTM formation by just adding 2D capacitive screens. Ultimately, the optimal choice of the physical formation and constitutive parameters makes FSS designs work properly.

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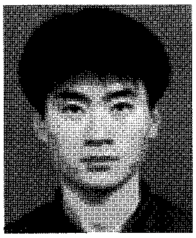

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