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Metamaterial 기판에 의한 평행평판 공진 및 임피던스 특성

(Characteristics of the Resonance and Impedance of Parallel Plates due to the Embedded Metamaterial Substrate)

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요 약

본 논문에서는 금속 평행평판에 일반 유전체 기판인 FR4 대신 Metamaterial을 삽입할 경우에 발생할 수 있는 전자기 공진 특성과 임피던스 변화에 대하여 연구하였다. 기판을 DPS는 물론 Metamaterial인 ENG, MNG, DNG 형으로 나눠, 투자율 함수를 위해 SRR 형식의 Lorentz 모델과, 유전율 함수를 위해 금속선 주기 배열 형식의 Drude 모델을 정확한 계산이 가능한 Full-wave 모드해석기법에 반영하여 평행평판이 가지는 공진모드들과 임피던스의 변화양상을 관측하였다. 관측을 통해 전자장비의 품질을 저하시키는 평행평판의 불요공진모드 억제를 위한 기판설계 가이드라인을 수립할 수 있었다.

Abstract

This paper conducts the research on the variation in the characteristics of the resonance and impedance of the metallic parallel plates due to the replacement of the normal dielectric substrate by the metamaterial. The ENG($\epsilon < 0$), MNG ($\mu < 0$) and DNG($\epsilon, \mu < 0$) types of metamaterial as well as the DPS(Double Positive) material are taken into consideration a full-wave modal analysis method known for accurate computation, as the SRR-kind of Lorentz model for permittivity and metal wire-periodic array-kind of Drude model for permeability, and the behaviors of parallel plates' resonance mode and impedance are observed. Based upon the observation, the design guidelines for the substrate can be addressed regrading how to suppress the parallel plates' spurious resonance modes that degrade the quality of the electronic equipment.

Keywords : Parallel Plates, Resonance, Metamaterial, DNG, ENG, MNG, Lorentz Model, Drude Model

I. Introduction

Wireless communication is made to happen with the development of state-of-the-art RF components embedded in the electronic equipment and telecommunication devices. The RF components will be antennas and microwave passives, etc. There are a number of typical and popular categories of physical structures for the antennas as the radiator and the guiding geometry as the transmission line, and the parallel plates are very common. In particular, where there is a PCB of multiple layers, there appear pairs of metal plates.

In view of electromagnetics, the metallic parallel plates can be treated as transversely infinite metal planes or a cavity. The cavity seems more realistic and sound in examining the electric behaviors. It is obvious that the cavity results in the standing wave trapped inside the geometry when it is excited by the RF signal and the concentration and run-away of the energy as the constructive interference. This phenomenon is called 'resonance'.

The resonance for a structure is observed in the form of electromagnetic fields and impedance. It is noticeable that the impedance of the feeding probe in

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the parallel plates increases sharply along with the resonance and this has driven PCB designers and antenna engineers to tackle the resonance-oriented problems in mismatch and deteriorated digital outputs.

Many approaches have been taken to suppress the resonance by using lumped elements and geometrical perturbation in the parallel plates[1~2]. Also, the brand new feeding scheme has been suggested[3]. Definitely, all these methods bring the change in the electromagnetic environment and the change of the material comes into our mind as an alternative method. Especially, what if the filling material as the substrate for the parallel plates is replaced by the metamaterial.

Since the concept of the metamaterial was introduced, attention has been paid to implementation and theoretical foundation for applications[4]. The DNG(Double Negative) as negative permittivity ϵ and negative permeability μ has seen its realized version in passive components as RF engineering[5~6]. As one of the theoretical activities for this field, the modeling for ϵ and μ plays an important role as a basis for accurate computer simulations like the FDTD[7]. However, it has not worked with the modal analysis method.

In this paper, the computational experiments are carried out to investigate accurately the resonance and impedance of the PEC parallel plates with the conventional substrate of FR4 changed to the metamaterial. The Lorentz and Drude models are employed to express the SRR-type MNG, the metal wire array-type ENG, the DNG and the DPS for the metamaterial substrate. After checking out the accuracy of the present numerical method through the comparison with the measurement, the metamaterials' case is dealt with, by applying the frequency-dependent Lorentz and Drude models to ϵ and μ and their related elements in the modal representation. Ultimately, seeing the resonance behaviors of the parallel plates for different cases, the guidelines on the way to mitigate spurious resonance for the PCB design will be proposed.

Ⅱ. Electromagnetics on the Parallel Plates

One of the commonly used structures for RF components' realization takes the form of parallel plates. It is pictured as the following simple geometry that generates resonance phenomena

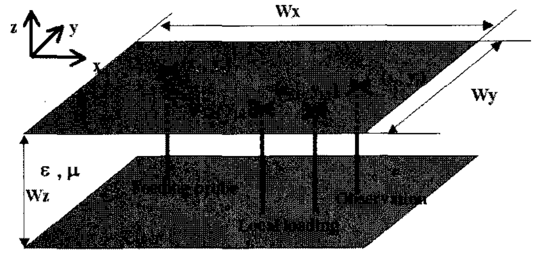


그림 1. 평행평판 형상
Fig. 1. Illustration of the parallel plates.

The top and the bottom are metal planes identical in size as $W_x \times W_y$. The electric current is carried along the feeding probe situated at (X_s, Y_s). And it is used as port 1. Port 2 is any arbitrary observation point at (X_f, Y_f) where induced voltage is observed. Loads are placed at (X_L, Y_L). The intermediate region between the two planes is the W_z thick substrate, and 4.2 and 0.02 are given as its relative dielectric constant ϵ_r and loss tangent, respectively for FR4. If this substance is replaced by the metamaterial, right steps must be taken to change ϵ_r and relative permeability μ_r and their models will be discussed later in this paper. Referring to the structure's boundary conditions, the two planes are the PEC and the walls are the PMC. Then, impedance due to the vertical component of electric field E_z is expressed as the following equation whose computation is as accurate as other reliable methods.

$$Z_{Ld} = \sum_{m=0}^{\infty}\sum_{n=0}^{\infty} \frac{\gamma_{mn} \cdot c_{mn}(X_s, Y_s) \cdot c_{mn}(X_f, Y_f) \cdot W_z/(W_x W_y)}{\varepsilon\omega/Q + j\left(\varepsilon\omega - \frac{k_{xm}^2 + k_{yn}^2}{\omega\mu}\right)} \tag{1}$$

where

$$c_{mn}(X_i, Y_i) = \cos(k_{xm} X_i) \cdot \cos(k_{yn} Y_i) \cdot \mathrm{sinc}(k_{xm} P_{\xi}/2) \cdot \mathrm{sinc}(k_{yn} P_{yi}/2)$$

$$k_{xm} = m\pi/W_x \qquad k_{yn} = n\pi/W_y \qquad w = 2\pi f$$

$$Q = \left[\tan\delta + \sqrt{2/\omega\mu_0 k W_z^2}\,\right]^{-1}$$

γ_{mn} is 1 and 4 for (m =0, n =0) and (m$\neq$0, n$\neq$0) each. When (m$\neq$0, n=0) or (m=0,n$\neq$0), γ_{mn} takes 2. tanδ, f, (Pxi, Pyi) and j denote loss-tangent, frequency, port i's width in x and y axes and $\sqrt{-1}$, respectively.

Ⅲ. Metamaterial Modelling

Metamaterial does not exist in the nature which abides by the RH(Right-hand) law of wave propagation. But the LH(Left-handedness) is artificially made by imposing the condition that the refraction index is minus, or both effective ϵ_r and effective μ_r are less than 0. The following figure presents the four different pairs of ϵ_r and μ_r.

From the first quadrant to the fourth in counter-clockwise, they are DPS(ϵ_r, μ_r>0), ENG(ϵ_r<0, μ_r>0), DNG(ϵ_r<0, μ_r<0), and MNG(ϵ_r>0, μ_r<0). The DPS is the RH region as in the normal case, and the DNG as the LH property is where the propagation constant vector is anti-parallel to the Poyintng vector. The second quadrant as the ENG is understood with plasma that causes attenuation. The ferrimagnetic material exemplifies the MNG. From the standpoint of realizing the MNG and the ENG, the SRR(Split Ring Resonator) and the periodic array of metal wires are brought up quite often times[4]. By adjusting the physical dimensions, say, the period and the gap between the inner and outer rings, one of the four combinations of ϵ_r and μ_r will appear. For the fixed geometry, the frequency-dependant behaviors of constitutive parameters(ϵ_r, μ_r) follow the Lorentz model or Drude model without loss of generality. Firstly, in order to implement the MNG, the SRR is employed which captures the penetrating magnetic field and turns it into the current that goes through capacitive gaps. Its frequency response can be expressed by the Lorentz formula.

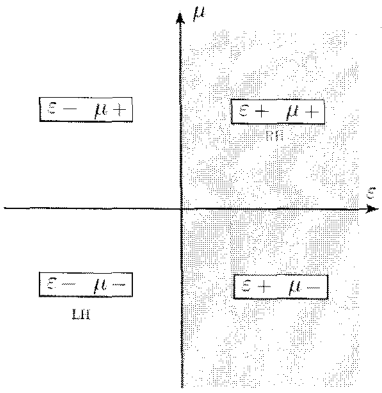


그림 2. 구성매질 퍼래미터
Fig. 2. Constitutive parameters.

$$\mu_r = 1 - F_\mu\omega^2/(\omega^2 - \omega_{0m}^2 + j\omega\zeta_m) \quad (2)$$

where ω_{0m} is the magnetic plasma frequency.

It is noteworthy that the Lorentz model has a singular point which flips the sign from plus to minus very sharply. On the other hand, the metal wire array catches the parallel polarized electric field and makes the inductive effect which corresponds to the minus permittivity. This ENG property takes the Drude expression.

$$\epsilon_r = 1 - \omega_{pe}^2/(\omega^2 + j\omega\zeta_{pe}) \quad (3)$$

where ω_{pe} means the electric plasma frequency.

Unlike the Lorentz model, there is no singular point in the curve of eqn (3).

Ⅳ. Validation

Firstly, the accuracy of the present modal analysis method is verified in comparison to the measurement of the impedance.

To guarantee the accurate computation using eqn (1), for convergence in the double summation, 400 is taken as the truncation number for indices m and n. The top or bottom of the parallel plates has the size of W_x =200mm and W_y =150mm. The FR4 substrate is 1.5mm thick. Ports are assigned to (X_0=0, Y_0= W_y/2) and (X_f=0, Y_f= W_y/2). The measurement has been performed up to just 1 GHz and shows excellent agreement with the computational prediction and

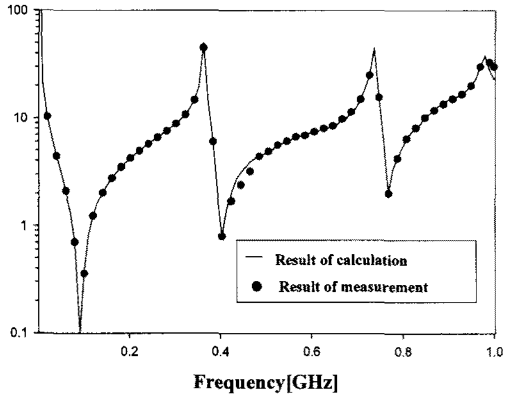


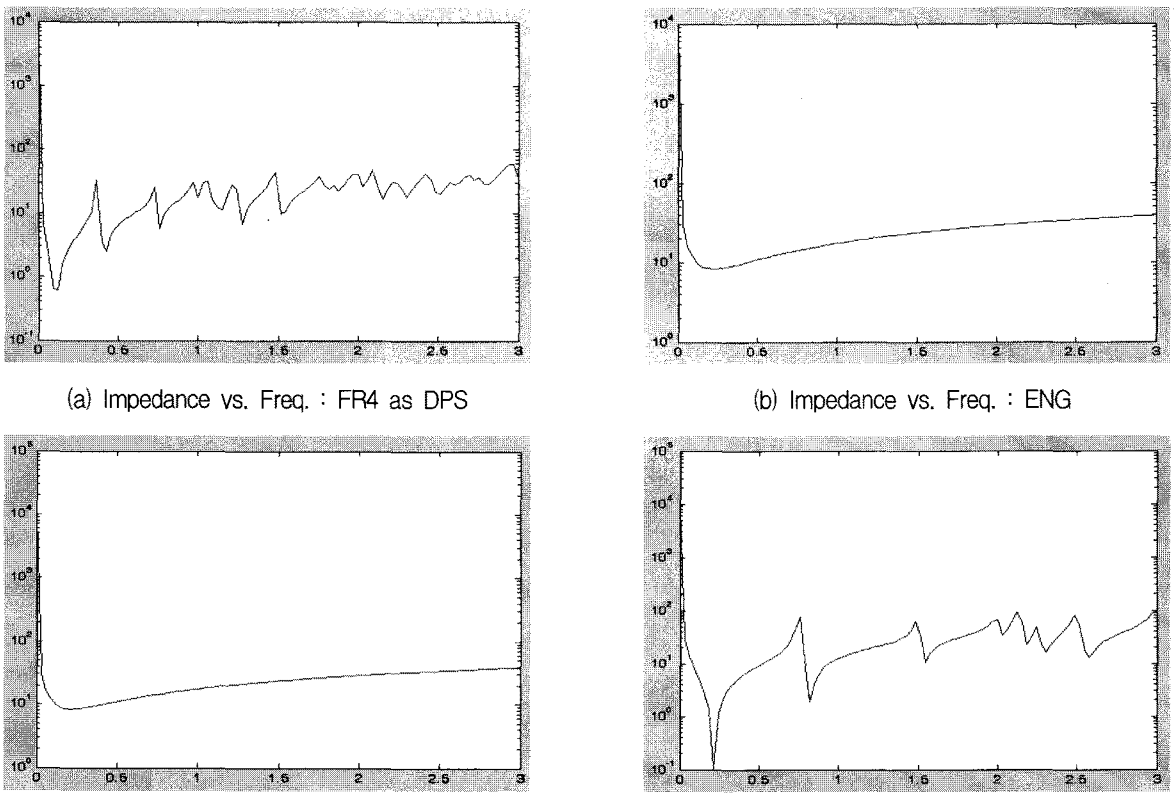
그림 3. 계산과 측정치 비교
Fig. 3. Computation VS. measurement.

proves the validity of the method. Definitely, there appear resonance modes as the peaks in the impedance profile. They are of concern in being sure of the good quality in an electronic system.

In the second place, the experiment is tried to see how the impedance of the parallel plates changes with the homogeneous metamaterial substrate. It should be noted that constant ϵ_r and μ_r, which are independent of frequency, are used for ENG, MNG and DNG.

Fig. 4(a) is the extended version of Fig. 3 up to 3GHz to make it easy to watch what happen to many more resonance modes. Using the ENG(ϵ_r=-1, μ_r=+1) or MNG(ϵ_r=+1, μ_r=-1) for the substrate, very effective suppression of the resonance is obtained over the entire frequency band, since the ENG and DNG's purely imaginary refractive indices account for the attenuation. The DNG(ϵ_r, μ_r=-1) removes some resonance modes, but it has standing waves creating the resonance. From now, ϵ_r and μ_r are assumed to vary with *f*.

The Lorentz model is employed to represent the magnetic property and the Drude model is for the electric characteristics, about the substrate in the parallel plates. For the sake of convenience, one type of electric plasma frequency $f_{pe}(=\omega_{pe}/2\pi)$ is set as



(a) Impedance vs. Freq. : FR4 as DPS

(b) Impedance vs. Freq. : ENG

(c) Impedance vs. Freq. : MNG

(d) Impedance vs. Freq. : DNG

그림 4. 평행평판 기판용 FR4, ENG, MNG와 DNG에 따른 임피던스 결과
Fig. 4. Impedance profiles of FR4, ENG, MNG and DNG for the parallel plates.

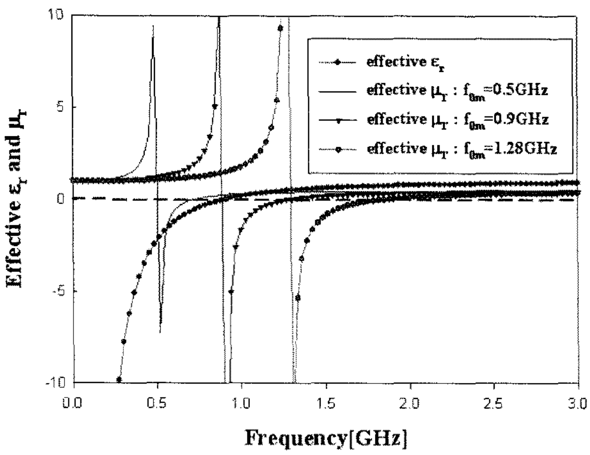


그림 5. 주파수 함수인 상대 유전율과 상대 투자율
Fig. 5. Frequency-varying ϵ_r and μ_r.

표 1. 메타재질의 가능한 종류
Table 1. Possible kinds of metamaterials.

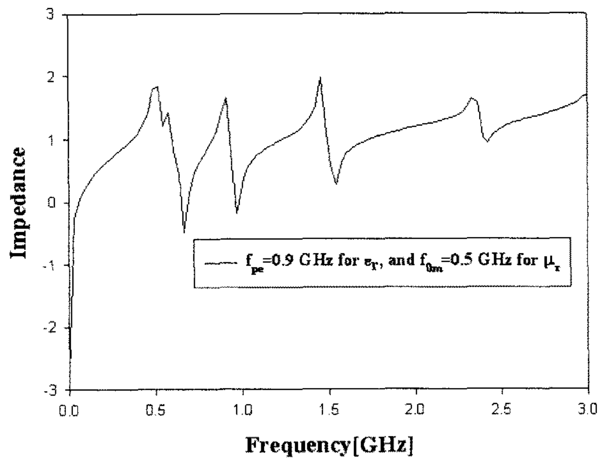
f_{0m} vs status	ENG	MNG	DNG	DPS	ENZ	MNZ
500MHz	O	X	O	O	O	O
900MHz ≡ f_{pe}	O	O	X	O	O	O
1280MHz	O	O	X	O	O	O

900MHz for the Drude model. Instead, three different cases of magnetic plasma frequency $f_{0m}(=\omega_{0m}/2\pi)$ are taken into account as a variety of combinations of constitutive parameters.

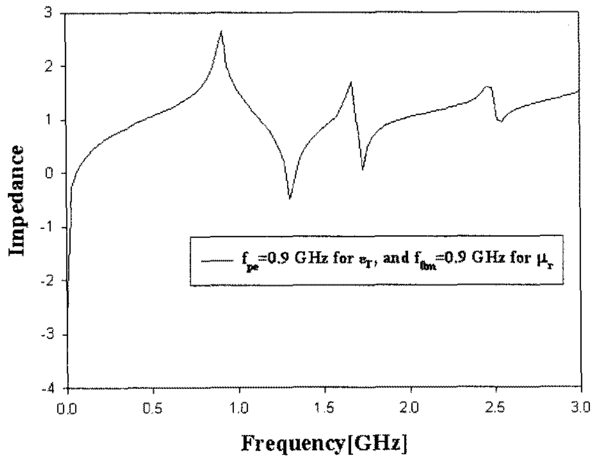
In other words, depending on the choice from three f_{0m}'s, possibilities are ENG, MNG, and DNG, and even zero-refraction-index, ENZ($(0<|\epsilon_r|<1)$ and MNZ$(0<|\mu_r|<1)$ as well. The following table summarizes the possible line-ups of metamaterials.

If only the cases with f_{0m}=900MHz and 1280MHz are considered for the substrate, there will be no DNG effect. If it is critically necessary to investigate how the DNG influences the parallel plates' resonance and impedance, f_{0m} should be lower than f_{pe}. Therefore, 500MHz is set for f_{0m} as case 1 where double negative constitutive parameters. Using the frequency-varying ϵ_r and μ_r shown in Fig. 5, into eqn.(1), the impedance profiles of the parallel plates are plotted as follows.

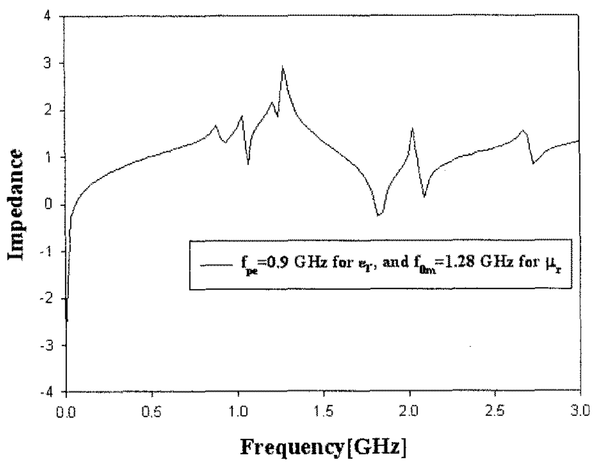
Overall, case 1 can get rid of many resonance modes compared to Fig. 4(a), but the DNG region(roughly from 500MHz to 1GHz) still has



(a) Impedance vs. Freq. :f_{0m}=500MHz



(b) Impedance vs. Freq. :f_{0m}=900MHz



(c) Impedance vs. Freq. :f_{0m}=1280MHz

그림 6. 자기 플라즈마 주파수가 500MHz, 900MHz와 1280MHz인 경우의 임피던스 결과
Fig. 6. Impedance profiles of the cases with f_{0m} =500MHz, 900MHz and 1280MHz

resonance. This follows the interpretation of the DNG-type standing wave's influence on the parallel plates' impedance as is associated with Fig. 4(d). On the contrary to the case 1, case 2 with Fig. 6(b) and case 3 with Fig. 6(c) are more effective in reducing the number and level of the impedance peaks than case 1. Among other things, the frequency ranges corresponding to the ENG and MNG regions are shown to have weakened resonance mode. It is the same as what is found and learnt from Fig. 4. These findings can give directions to the PCB designers and RF engineers who deal with the parallel plates.

V. Conclusion

This paper sheds a light on what the change from the FR4 substrate to the metamaterial will cause toward the impedance and resonance properties of the parallel plates as a commonly used means for the guided or radiated waves. A rigorous full-wave simulation technique the modal analysis method is used to accurately predict the electromagnetic characteristics of the parallel plates. It is found out that the use of the metamaterial for the substrate can remove many resonance modes and lower the impedance levels. This will be helpful to the quality PCB design in the electronic device..

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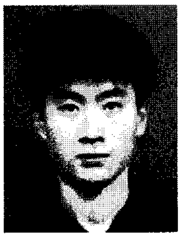

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