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Study on the Electromagnetic Wave Propagation in the Parallel-Plate Waveguide with the Metamaterial ENZ Tunnel Embedded

Metamaterial ENZ 터널이 포함된 평행 평판 도파관 내 전자기파의 전파 특성에 관한 연구

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Abstract

This paper discusses how to change the electromagnetic waves' property in the cut-off causing discontinuity existing in the guiding structure of the RF passive component by using the metamaterial and elaborates on its principle. Particularly, we find and explain, from the viewpoint of electromagnetics and circuit theories, the so-called tunneling condition that when the segment with an extremely narrow cross-section leading to blockage in the parallel-plate waveguide is given the ENZ(Epsilon Near Zero) for its filling material, the wave starts to propagate through the segment. The analysis method as a transmission-line theory taking the discontinuity and material change into consideration is shown valid through the comparison with other methods for analyzing parallel-plate waveguides, and provides the illustration of the *S*-parameters and impedance describing the characteristics of the tunneling.

요 약

본 논문에서는 초고주파 수동 부품의 전송 구조 내부에 전자기파의 차단 현상을 유발하는 불연속이 존재할 때 metamaterial을 이용하여 전파 특성에 변화를 유도할 수 있는 방법을 논의하고 원리를 규명한다. 특히 평행 평판 도파관 내부에 전파가 되지 않을 정도로 협소한 단면을 가진 영역의 매질이 ENZ(Epsilon Near Zero)의 metamaterial로 바뀔 때 전자기파가 진행되는, 이른바 터널링(tunneling) 조건(혹은 관통 효과)을 찾고 전자기학적 관점과 회로 관점으로 설명할 것이다. 전송선 이론에 불연속 구조는 물론 매질 변화를 고려한 평행 평판 도파관의 해석 결과를 다른 기법의 결과와 비교하여 타당성을 보이고, 이에 바탕을 두어 관통 효과 특성을 산란계수와 임피던스로 도시한다.

Key words : Parallel-Plate Waveguide, ENZ, Tunneling

Ⅰ. Intoduction

As the demands on wireless communication services have been getting more complicating and tougher than ever before, new areas of RF technologies have been sought for overcoming the shortcomings identified from the already-existing classical ones. Since the last decade of the 20th century, metamaterials have been recognized as one of the fascinating research topics and have got the RF community's attention to meet and beat the challenging issues in components' design and implementation[1]~[3].

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Popular along with ENG(Epsilon Negative) and MNG (Mu Negative) throughout the metamaterial research topics, the DNG(Double Negative) material has motivated the theoreticians and practical designers for RF passive device development[4] to familiarize themselves with unusual properties due to the left-handed wave propagation, where permittivity and permeability are below zero. When the DNG and DPS(Double Positive) are combined and engineered to have the phase compensation between the DNG's phase lead and DPS' phase lag for the effective size reduction of a component[5]~[10]. While people were working on the above constitutive parameters, the ENZ(Epsilon Near Zero) has been tapped as a relatively new field[11],[12].

Of late, A. Alu et al have demonstrated an unprecedented phenomenon that the complete attenuation of the wave in a normal dielectric-filled segment with a very small cross-section(called a narrow channel) will turn into the state of propagation(tunneling), when the segment's dielectric is replaced by a specific value of ENZ[12]. Though they illustrate numerous cases of tunneling through the ENZ channel, all the plots are concerned with only the transmission coefficient from left to right with reference to the channel.

In this paper, the tunneling by the right choice of ENZ value for the narrow channel is figured out by the electromagnetic and circuit approaches which will endow the RF component designers insight on the way the cut-off state of the electromagnetic wave can be converted to the transmission state. In order to do this, the parallel-plate waveguide as a typical passive component is chosen and is toyed with for various experiments. At the beginning of the experiment, the transmission-line theory is devised to analyse a filter and a planar parallel-plate EBG taking into account the discontinuities and the predicted results are compared with other techniques to prove the validity of the analysis method. And the geometry is tested with the narrow channel having DPS or DNG or ENG or ENZ on the basis of the method. In particular, the tunneling is addressed to happen with the S-parameters and impedance that include the matched impedance throughout the overall parallel-plate waveguide.

Ⅱ. Analysis Method for Parallel-Plate Waveguides

Before dealing with the dielectric- or metamaterial-filled narrow channel in the parallel-plate waveguide, we need to check whether the present analysis method is trustworthy and acceptable to use. Regarding the method, assuming the parallel-plate waveguide supports the dominant TEM-mode, the transmission-line modeling is adopted. When you picture parallel plates having spacing d and width w and their intermediate lossless substrate of ε and μ, the characteristic impedance Z_c and propagation constant β are expressed as follows.

$$L=\frac{\mu d}{w},\quad C=\frac{\varepsilon w}{d} \tag{1}$$

$$Z_c=\sqrt{\frac{L}{C}},\quad \beta=\omega\sqrt{LC} \tag{2}$$

Since the above equations are with a uniform transmission-line, when the multiple lines are connected through the discontinuities, their transfer matrices are cascaded and result in the S-parameters or impedance matrix through the conversion formulae[13].

Firstly, a filter is designed to have a stopband from 6 GH through 10 GHz and its sizes are obtained. The physical dimensions of Fig. 1 along with ε_r=4.2 and μ_r=1, port width 5.6 mm, and port height 1.5 mm are put in the analysis method and the result is compared to that of the circuit theory[13]. Fig. 2 shows the S-parameters 'S_{21}' and 'S_{11}' of the filter obtained by the present analysis method and good agreement with the other approach.

Secondly, another filter is designed to have a wider stopband than the previous one. Taking the form of the

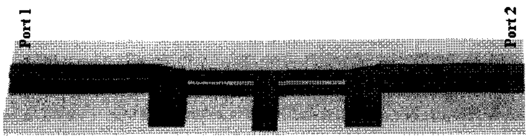


Fig. 1. Geometrical illustration of a designed filter.

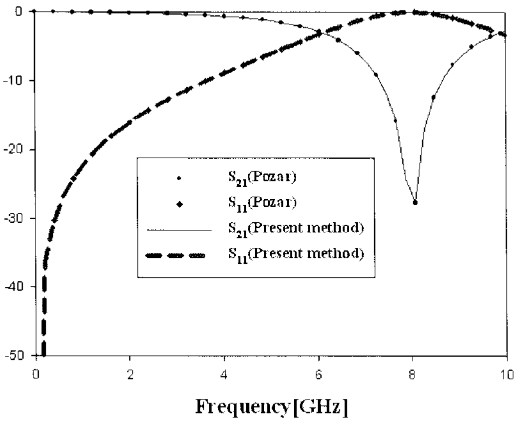


Fig. 2. S_{21} and S_{11} of a designed filter.

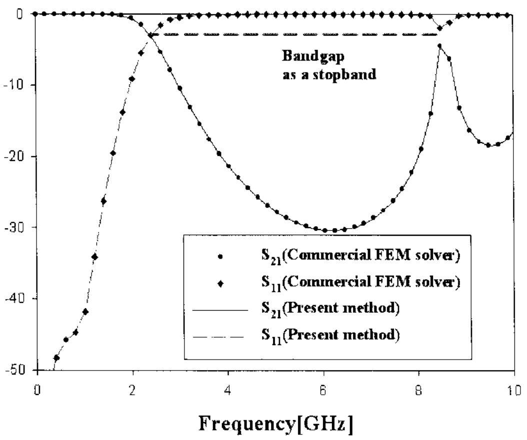


Fig. 3. S_{21} and S_{11} of a bandgap filter.

periodicity in neighboring dielectric segments having a high contrast, we can easily enlarge the stopband which is wanted to be 2 GHz through 8 GHz. Through iterations, the physical dimensions and the unit pair of the dielectric segments are found.

From the computation, we have got 20 Ω and 120 Ω for the composition of the unit dielectric pair. Fig. 3 shows the present method is acceptable agreeing well with a much acclaimed FEM solver. Plus, note there occurs a wider bandgap like that of an EBG geometry.

Ⅲ. Narrow Channel Tunneling in the Parallel-Plate Waveguide

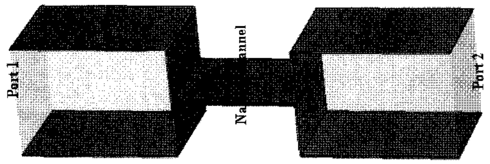


Fig. 4. Larger waveguide sections connected by the narrow channel.

From now, we will see what will happen to the wave through the narrow channel according to the change in the channel's material from a normal dielectric. For this, the geometry of our concern should be addressed.

The narrow channel with an extremely small aperture is in the middle of the parallel-plate waveguide whose ends are larger sections as shown above. The three segments have the same width set as 5.6 mm and the same material 'FR4'(DPS) in the beginning. However, the height of the ending segments is 1.5 mm for 50 Ω, and the narrow channel has the height of 3 μm. The abrupt change in the cross-section ends up with the cut-off of the wave transfer('attenuation').

In Fig. 5, over almost the entire frequency band(from 0.1 ~ 10 GHz) for simulation, the electromagnetic wave is blocked with S_{21} less than −20 dB except for the highest frequency where the cut-off condition is no more imposed. Thus, we probably have a question what kind of material enables the wave to flow through the narrow channel.

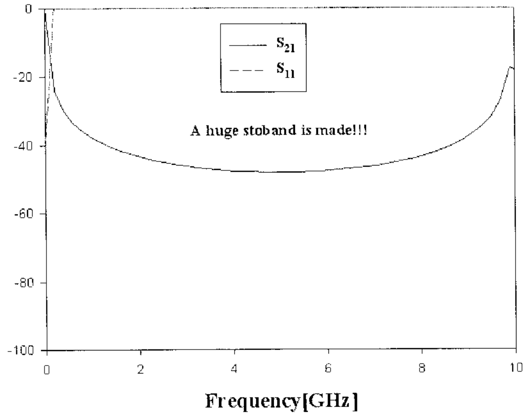


Fig. 5. S_{21} and S_{11} through the narrow channel with FR4 in the waveguide.

First, the ENG is considered filling the narrow channel. Simply, $\varepsilon_r=-4.2$ is assumed.

In Fig. 6, it is noted that the ENG for the narrow channel goes against the way to improve the field transfer(going way down from −40 dB in S_{21} after 0.5 GHz). The reason S_{21} with the ENG goes worse than the normal FR4 is inferred as the ENG will make the wavenumber purely negative real in a lossless medium.

Second, instead of the ENG, we think of the DNG as the filling material for the narrow channel, where $\varepsilon_r=-4.2$ and $\mu_r=-1.0$. Fig. 7 presents the same result as the FR4 case(the DNG returns its impedance to that of Fig. 5(S_{21} less than −20 dB from 0.1~10 GHz).

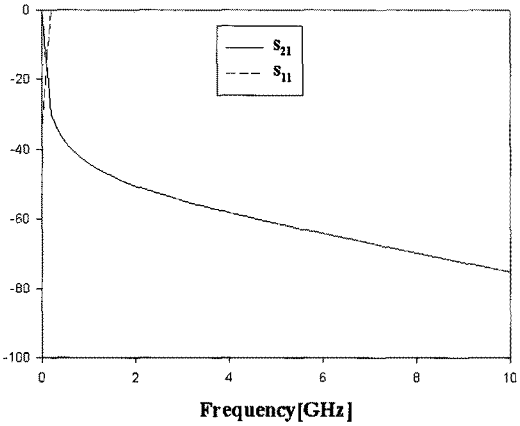


Fig. 6. S_{21} and S_{11} through the narrow channel with ENG($\varepsilon_r=-4.2$) in the waveguide.

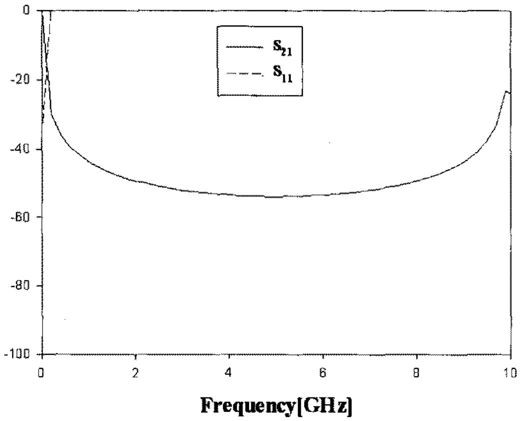


Fig. 7. S_{21} and S_{11} through the narrow channel with DNG($\varepsilon_r=-4.2$, $\mu_r=-1.0$) in the waveguide.

Third, we choose the ENZ and its value($\varepsilon_r=4*10^{-6}$, $\mu_r=1.0$).

In Fig. 8, it is found out that the current value of the ENZ for the narrow channel finally lets the field completely transfer. This is the tunneling, which brings us the matched impedance in the waveguide.

To understand better the tunneling from the standpoint of circuit theory, we investigate the impedance as well as the transmission and reflection coefficients of the narrow channel in the waveguide at a fixed frequency 2.4 GHz, varying ε_r.

And the observation is made with two different cases of the narrow channel, say, thinner($d_{channel}$=3 μm) and relatively thicker($d_{channel}$=0.3 mm).

We can try more cases of the height of the narrow channel, but these two cases will help us draw the generalized idea to determine the ENZ value for the tunneling condition. For Fig. 9, ε_r varies from $-5*10^{-4}$ to $+5*10^{-4}$. On the other hand, the simulation is conducted with ε_r ranging from −1 through +1. Seeing Fig. 9 and Fig. 10 together, we can realize the thinner channel requires the smaller ENZ to have the highest transmission. The other way around for the thicker channel. The lowest reflection(S_{11}) and maximum transmission can be interpreted as the tunneling for the

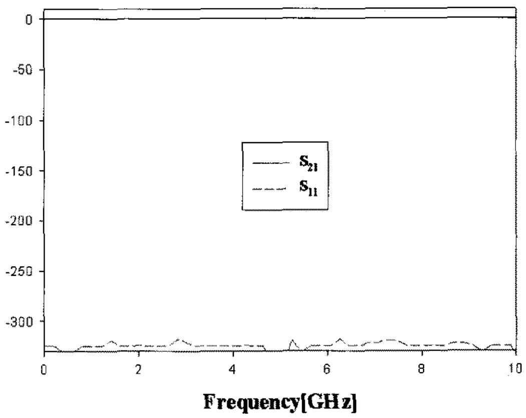
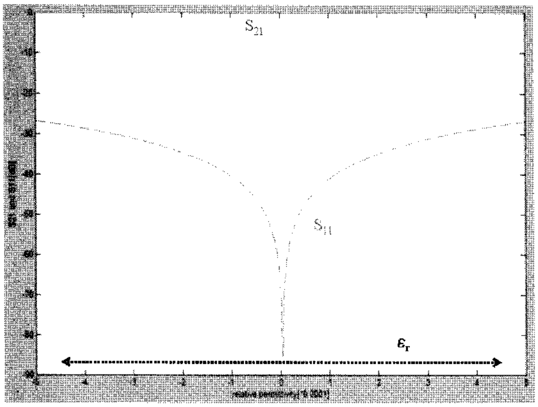
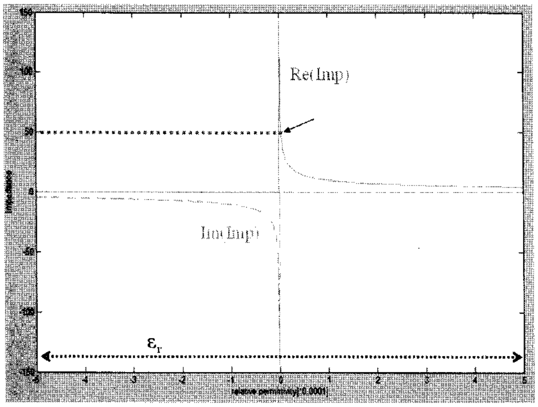


Fig. 8. S_{21} and S_{11} through the narrow channel with ENZ($\varepsilon_r=4*10^{-6}$) in the waveguide.

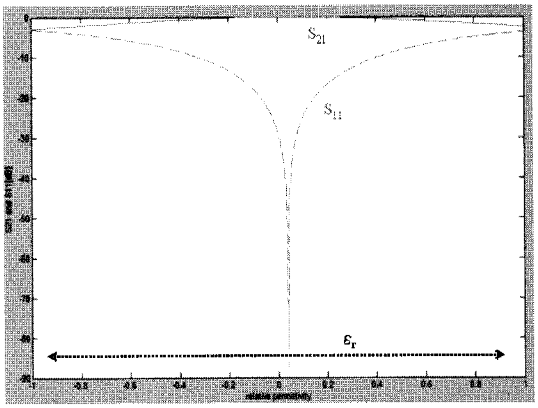


(a) S_{21} and S_{11} at frequency 2.4 GHz to find the most suitable ENZ value for the tunneling through the narrow channel with varying ε_r: $d_{channel}$=3 μm(x-axis: ε_r in 0.0001, S_{21}: solid, S_{11}: dotted)

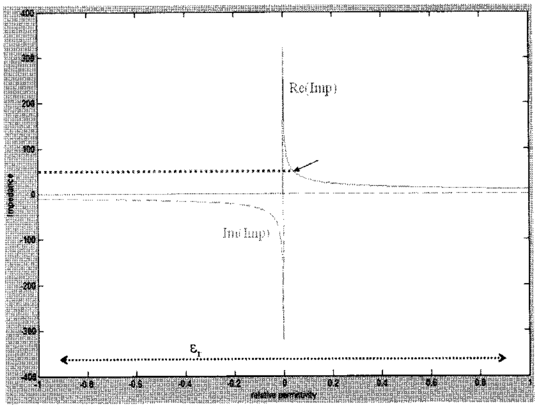


(b) Impedance at frequency 2.4 GHz to find the most suitable ENZ value for the tunneling through the narrow channel with varying ε_r: $d_{channel}$=3 μm(x-axis: ε_r in 0.0001, Re(Imp): solid, Im(Imp): dotted)

Fig. 9. S_{21}, S_{11}, and impedance at frequency 2.4 GHz to find the right ENZ value for the tunneling through the narrow channel with varying ε_r: $d_{channel}$=3 μm.



(a) S_{21} and S_{11} at frequency 2.4 GHz to find the most suitable ENZ value for the tunneling through the narrow channel with varying ε_r: $d_{channel}$=0.3 mm(x-axis: ε_r, S_{21}: solid, S_{11}: dotted)



(b) Impedance at frequency 2.4 GHz to find the most suitable ENZ value for the tunneling through the narrow channel with varying ε_r: $d_{channel}$=0.3 mm (x-axis: ε_r, Re(Imp): solid, Im(Imp): dotted)

Fig. 10. S_{21}, S_{11}, and impedance at frequency 2.4 GHz to find the right ENZ value for the tunneling through the narrow channel with varying ε_r: $d_{channel}$=0.3 mm.

narrow channel. What is found is that the tunneling happens at the ENZ region, where ε_r is between 0 and 1. Also what is noteworthy tells us that the tunneling coincides with the ε_r point that its impedance becomes 50 Ω and equals that of the larger waveguide segments, in other words, matching condition.

Ⅳ. Conclusion

This paper conducted the observation and study on the unusual phenomenon that the wave can transmit through the narrow channel which blocks the field with the normal dielectric but plays the role of tunneling with the correctly decided ENZ value for the relative permittivity as the filling material. The tunneling was rigorously proved and interpreted as the matched impedance and maximum transmission by the transmission-line that can handle the discontinuities and material change in the parallel-plate waveguide.

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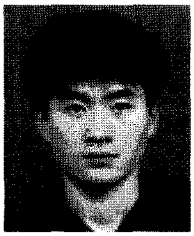

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