



Technique for Reducing Surface Wave at an Air/Left-Handed Medium (LHM) Interface or Excitation of the Forward Wave in an LHM

Halim Boutayeb¹, Ke Wu¹, and Kouroch Mahdjoubi²

¹ Poly-GRAMES Research Center, Ecole Polytechnique de Montreal, Montreal, QC,
h.boutayeb@polymtl.ca

² IETR (Institut d'Électronique et de Télécommunications de Rennes), UMR CNRS 6164,
Avenue du Général Leclerc, 35042 Rennes, France.

Abstract – In this paper, we analyze the illumination by an electromagnetic wave of an air/left-handed medium (LHM) interface. It is shown that by placing a periodic structure of resistors near the LHM it is possible to suppress or to reduce the surface wave that is present at the interface. For our demonstration, we consider a semi-infinite lossless left-handed medium having the same constitutive parameters as those of air but with opposite signs. Numerical results, obtained by using a full-wave time domain technique, are presented to validate our approach and the proposed scheme. This work can extend the potential applications of left-handed materials, because it shows that it is possible to use LHM slabs having large width. In addition, this work shows that it is possible to excite the forward wave of an LHM instead of the backward wave.

Key words: *Left-handed materials, surface mode, periodic structures, impedance matching*

1. Introduction

Forty years ago, Veselago explored the properties of media where both the permittivity and the permeability are negative [1]. He observed that in such media, the wave vector \mathbf{k} , the electric field vector \mathbf{E} , and the magnetic field vector \mathbf{H} form a left-handed system. For this reason, these media are called left-handed media or left-handed materials (LHMs). He also deduced that these media possess negative refractive indexes, and proposed to use them for designing flat lenses, by using this property. The term Negative Refractive Index (NRI) material is often used to call a material with negative permittivity and permeability. In 2000, the idea of the flat lens has been reintroduced and further analyzed by Pendry, who has also proposed the concept of the "Perfect Lens" [2]. Since then, much attention has been attracted to this research area both theoretically and experimentally.

To demonstrate the negative index of refraction, different methods have been proposed for designing LHMs, by using artificial periodic structures, and experimental prototypes have been fabricated [3-6]. These artificial materials are also called metamaterials, because they have characteristics that can not be found in materials of the nature. It has been shown that for a metamaterial made from a periodic structure consisting of split-ring resonators and metallic wires, originally proposed by Pendry *et al.* [7, 8] and Smith *et al.* [9], the effective parameters can be extracted from the reflection and transmission coefficients of a metamaterial sample within a certain frequency region and the metamaterial exhibits a negative index of refraction in this region [10].

In the past few years, Surface waves or Surface Plasmons (SPs) at the interface of left handed and right handed materials have attracted some interest [11-13]. The flat lens is based on the use of an LHM slab [1, 2]. Surface waves or surface plasmons take an important role in the characteristics of an LHM slab, as long as the slab width is small as compared to the wavelength [14-17]. On the other hand, if the slab width is very large, the LHM slab can not be used anymore for designing a flat lens and surface wave can represent a problem for this case, because the energy is confined at the interface. The applications of LHMs are thus limited to thin slabs. The aim of our paper is to present a method for reducing or suppressing surface wave that is present at an air/left-handed medium interface. Our method is equivalent to excite the forward wave of the LHM instead of the backward wave. This can extend the potential applications of left-handed materials. To

facilitate the analysis, we consider the LHM as a semi-infinite homogeneous non-dispersive medium without loss. Taking into account the effects of loss and dispersion does not change the principal conclusions of our paper.

The remainder of the paper is organized as follows. In the next section, we describe the phenomenon of surface mode due to the illumination by an electromagnetic wave at an air/left-handed medium interface and we present an original method for reducing the effect of this surface mode. Then, Section 3 presents numerical results, obtained by using a full-wave time domain technique. These results validate our approach and proposed scheme. Finally, concluding remarks are given in Section 4.

2. Analysis and Design

2.1. Presence of a surface mode at an air/LHM interface

Let us consider the illumination by a monochromatic TMz polarized (also called P- polarized) plane wave of an interface between air and a left-handed medium, as illustrated in Fig. 1. The left-handed medium is considered homogeneous, non-dispersive, semi-infinite and lossless. We call r the reflection coefficient at the interface ($x = 0$), which is the ratio of the amplitude of the reflected field over the amplitude of the incident field. As shown by Pendry [2] and several other authors [16, 18, 19], the reflection coefficient r can tend to infinity if the characteristics of the LHM tend to $\epsilon = -\epsilon_0$ and $\mu = -\mu_0$

$$\lim_{(\epsilon, \mu) \rightarrow (-\epsilon_0, -\mu_0)} r = \infty \quad (1)$$

This resonance equation reveals the presence of a surface mode at the interface [14]. This mode can exist even if the incident field does not contain evanescent waves [14]. This surface mode is also called surface plasmon, or surface plasmon polariton, because it is due to the negative signs of the permittivity and the permeability, by analogy with the phenomenon observed with metals.

In an LHM slab, surface plasmons at the interfaces can be coupled and this coupling takes an important role in the characteristics of a flat lens, if the slab is sufficiently thin [14-17]. According to Pendry, the ‘‘Perfect Lens’’ works by the excitation of surface plasmons [17]. If the LHM slab is thick, surface plasmons become not coupled and thus the LHM slab can not be used as a flat lens. For these cases, most of the energy is confined at the interface, which can represent a limitation in the utilization of left-handed materials.

Although surface wave plays a key role in the physics of the sub-wavelength imaging, it can be of a lot of interest to reduce or to suppress it for thick LHM slabs.

An interpretation of the surface mode suppression is presented in the next subsection.

2.2. Impedance matching for forward and backward waves in air and LHM

Recently [20], we have presented an original analysis of LHMs, which has been validated with a classical numerical method and with commercial software (Ansoft HFSS). According to our analysis [20] and by taking the convention for current flow to be from generator end to load, we have obtained the following results:

- In air, the forward wave has positive intrinsic impedance η_0 ($=120\pi\Omega$), and the backward wave has mathematically negative intrinsic impedance $-\eta_0$.
- In LHM, if $\epsilon=-\epsilon_0$ and $\mu=-\mu_0$, the backward wave has positive intrinsic impedance η_0 and the forward wave has negative intrinsic impedance $-\eta_0$.

The surface mode excitation can be seen as a mismatch between forward-waves' impedances in air and LHM. Thanks to the multiple wave-reflections between the two interfaces of an LHM slab, the forward waves inside the LHM can be negligible as compared to the backward waves inside the LHM. From this, the LHM slab, as it is usually used, can be seen as matched to free space.

However, if the LHM slab width is large, it is of a lot of interest to match forward-waves' impedances of air and LHM. This procedure is equivalent to suppressing the surface mode. For this purpose, a method is proposed in the next subsection.

2.3. Periodic structure of resistors

We consider that a 2-D periodic structure composed of resistors having resistance R and with a period P very small compared the wavelength is placed very close to the air/left-handed medium interface as illustrated in Fig. 2(a). The circuit model is shown in Fig. 2(b) and the cross-section view of the periodic sheet is shown in Fig. 3. According to Fig. 2(b), a resistance R is now connected in parallel with $-\eta_0$. The impedance matching condition for forward waves in air and LHM can be written

$$\frac{-\eta_0 R}{-\eta_0 + R} = \eta_0 \quad (2)$$

which results in

$$R = \frac{\eta_0}{2} = 60\pi\Omega \quad (3)$$

By using a periodic sheet of resistors having this resistance value R , we can ensure that the reflection coefficient at the air/LHM interface is null or near zero, and thus we can suppress or reduce the surface wave.

In the next section, numerical results are presented to validate our proposed scheme.

3. Numerical results

In this section, we present full-wave simulation results for the excitation by a plane wave of an air/left-handed medium interface with a sheet of resistors placed near the interface, as described in the previous section.

We use a Finite Difference Time Domain (FDTD) code, which has been well validated for modeling and simulating a wide range of electromagnetic problems. This method is based on a direct discretization in space and time domains of Maxwell's equations.

In the FDTD method, we use a TMz polarized (P-polarized) plane wave and a Gaussian pulse in the frequency band 0-5 GHz. Figure 4 shows the computational domain. Perfect Electric Conductors, Perfect Magnetic Conductors, and Perfect Matched Layers [21] are used at the boundaries to limit the computational domain. Near the interface, resistors with resistance value of $R=60\pi\Omega$ are located in each cells in y - z plane, as illustrated in Fig. 5. The space mesh in all the directions is $\Delta_x=\Delta_y=\Delta_z=\Delta=5\text{mm}$, which is also the period of the surface of resistors ($P=\Delta$). The LHM is modeled by using a medium with the following parameters: $\epsilon=-\epsilon_0$ and $\mu=-\mu_0$. The space between the periodic surface of resistors and the interface is equal to a half space mesh $d=\Delta/2=2.5\text{mm}$.

When the periodic structure is not added, the surface mode leads to a divergent result, and thus it is not possible to present the results for this case. This divergence can be explained by equation (1). From this, only results obtained by placing the sheet of resistors near the interface are presented. The fact that the solution diverges if we do not add the sheet of resistors and converges if we add it is by itself an interesting point. This shows clearly that the divergence is not due to the numerical method but it is due to the excitation of a surface plasmon.

Figure 6 shows the field component E_z versus x -direction at different time instants. From these curves, several remarks can be made. First, the figure demonstrates that the results converge with a wide frequency band excitation. Second, these curves show that the plane wave passes through the interface nearly without being affected. Only a very small part of the energy is reflected, and the Gaussian pulse is quasi-totally found in the left-handed medium (see at time $t=0.8$ ns). No important amount of energy is confined at the interface. Thus, the surface wave is strongly reduced. Also, it can be noted that the energy is not absorbed by the sheet of resistors, but the resistors allow the matching of forward-waves' impedances in air and LHM. Finally, it can be noted that, inside the LHM, the wave propagates in the same direction and speed as those in air.

Figure 7 shows the field component H_y versus x -direction at different time instants. From this figure, one can note that the sign of H_y changes in the right side of the interface, whereas the sign of E_z (Fig. 6) and the direction of the wave propagation do not change. It is important to note that, although we have excited the forward wave of the LHM instead of the backward wave, these results confirm the prediction of Veselago that a *left-hand rule* has to be used to get the direction of the wave propagation inside a medium with negative permittivity and permeability. Also, it should be noted that, in the usual utilization of an LHM (without the sheet of resistors R), this is the \mathbf{k} vector that switches direction from air to LHM.

4. Conclusion

In this paper, we have shown that by using a periodic structure of resistors it is possible to suppress or to reduce the surface wave that is present at an air/left-handed medium interface. This surface mode suppression can also be seen as an impedance matching between forward-waves of air and LHM. For our demonstration, we have considered a lossless semi-infinite homogeneous non-dispersive left-handed medium having the same constitutive parameters as those of air but with opposite signs. Numerical results, obtained by using a Finite Difference Time Domain technique, have been presented to validate our approach and the proposed scheme. Although we have presented a new scheme for exciting an LHM, we have confirmed some properties of media with negative permittivity and permeability. This work has potential applications in the analysis and design of thick LHM slabs or for designing reconfigurable LHMs, by controlling the direction of the \mathbf{k} vector inside an LHM.

Acknowledgement

The authors gratefully acknowledge the support of this research from Centre de Recherche en Electronique Radiofréquence (CREER) and Fonds Québécois de la Recherche sur la Nature et les Technologies (FQRNT). The authors wish also to thank Dr. Claude Kondo Assi for helpful discussions.

REFERENCES

1. V. G. Veselago, The electrodynamics of substance with simultaneous negative values of ϵ and μ , Soc Phys Usp 10 (1968), 509-514.
2. J.B. Pendry, Negative refraction makes a perfect lens, Phys Rev Lett 85 (2000), 3966-3969.
3. R.A. Shelby, D.R. Smith, and S. Schultz, Experimental verification of a negative index of refraction, Science 292 (2001), 77-79.
4. H. Chen, L. Ran, J. Huangfu, X. Zhang, K. Chen, Left-handed materials composed of S-shaped resonators, Phys Rev E 70 (2004), 057605-1-057605-4.
5. C. G. Parazzoli, R. B. Gregor, L. Li, and M. H. Tanielian, Experimental verification and simulation of negative index of refraction using Snell's law, Phys Rev E 90 (2003), 107401.
6. A. A. Houck, J. B. Brock, and I. L. Chuang, Experimental observations of left-handed material that obeys Snell's law, Phys Rev E 90 (2003), 137401.
7. J. B. Pendry, A. J. Holden, W. J. Stewart, and I. Youngs, Extremely Low Frequency Plasmons in Metallic Mesostructures, Phys Rev Lett 76 (1996), 4773-4776.
8. J. B. Pendry, A. J. Holden, D. J. Robbins, and W. J. Stewart, Magnetism from conductors and enhanced nonlinear phenomena, IEEE Trans Microwave Theory Tech 47 (1999), 2075-2084.
9. D. R. Smith, W. J. Padilla, D. C. Vier, S. C. Nemat-Nasser, and S. Schultz, Composite Medium with Simultaneously Negative Permeability and Permittivity, Phys Rev Lett 84 (2000), 4184-4187.
10. D. Seetharamdoo, R. Sauleau, K. Mahdjoubi, and A. C. Tarot, Effective parameters of resonant negative refractive index metamaterials: Interpretation and validity, J Applied Phys 98 (2005), 063505.

11. R. Ruppin, Surface polaritons of a left-handed medium, *Phys Lett A* 277 (2000), 61-64.
12. R. Ruppin, Surface polaritons of a left-handed material slab, *J. Phys : Condens Matter* 13 (2001), 1811-1819.
13. K. Park, B. J. Lee, C. Fu, Z. M. Zhang, Study of the surface and bulk polaritons with a negative index metamaterials, *J. Opt Soc Am B* 22 (2005), 1016-1023.
14. M. W. Feise, P. J. Bevelacqua, and J. B. Schneider, Effects of surface waves on the behavior of perfect lenses, *Phys Rev B* 66 (2002), 035113.
15. D. R. Smith, D. Schurig, M. Rosenbluth, S. Schultz, S. A. Ramakrishna, and J. B. Pendry, Limitations on subdiffraction imaging with a negative refractive index slab, *App Phys Lett* 82 (2003), 1506-1508.
16. C. Luo, S. G. Johnson, J. D. Joannopoulos, and J. B. Pendry, Subwavelength imaging in photonic crystals, *Phys Rev B* 68 (2003), 045115.
17. J. B. Pendry, Negative refraction, *Cont Phy* 45 (2004), 191-202.
18. T. Andrade, A. Grbic, G. V. Eleftheriades, Growing evanescent waves in continuous transmission-line grid media, *IEEE Micro Comp Lett* 15 (2005), 131-133.
19. W.C. Chew, Some reflections on double negative materials, *Progress in Electromagnetic Research* 51 (2005), 1-26.
20. H. Boutayeb, K. Wu, and K. Mahdjoubi, On the impedance matching of left-handed materials to free space, in *NATO Advanced Research Workshop - Metamaterials for Secure Information and Communication Technologies*, Marrakesh, Morocco (2008).
21. J.P. Berenger, Three-dimensional perfectly matched layer for the absorption of electromagnetic waves, *J. Comput Phys* 127 (1996), 363-379.

Figure Captions:

FIG. 1: An incident plane wave illuminates an air/left-handed medium interface. The left-handed medium is considered semi-infinite and lossless.

FIG. 2: (a) A periodic surface of resistors is placed near the air/LHM interface. (b) Circuit model. The objective is to determine R in order to obtain zero reflection

FIG. 3: Cross-section view of the periodic surface made of resistors. The period P is considered small compared to the wavelength.

FIG. 4: Schematic for the simulation in the FDTD method. The PEC boundaries in the xy planes are not shown in the figure.

FIG. 5: Model of the sheet of resistors in the FDTD method. Note that for a TM_z (P-polarized) wave excitation only the resistors in z -direction are required.

FIG. 6: Distribution of the field component E_z versus x -direction at different time instants.

FIG. 7: Distribution of the field component H_y versus x -direction at different time instants.

FIG. 1

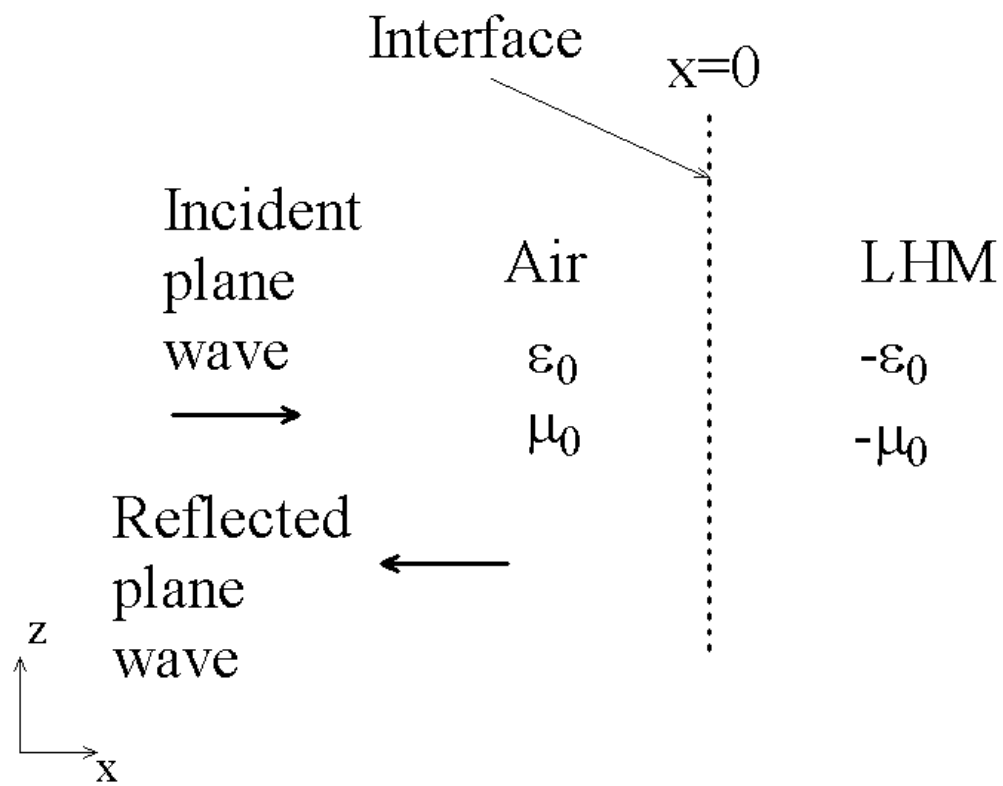


FIG.2

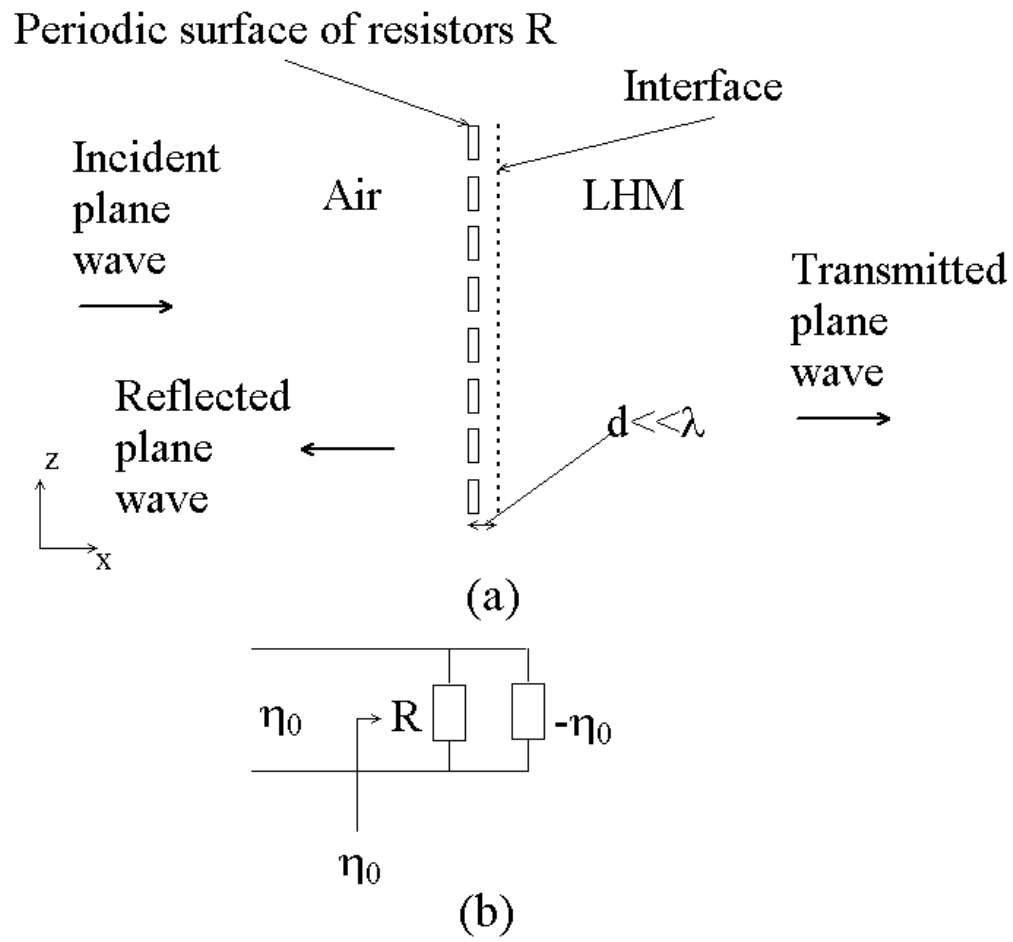


FIG.3

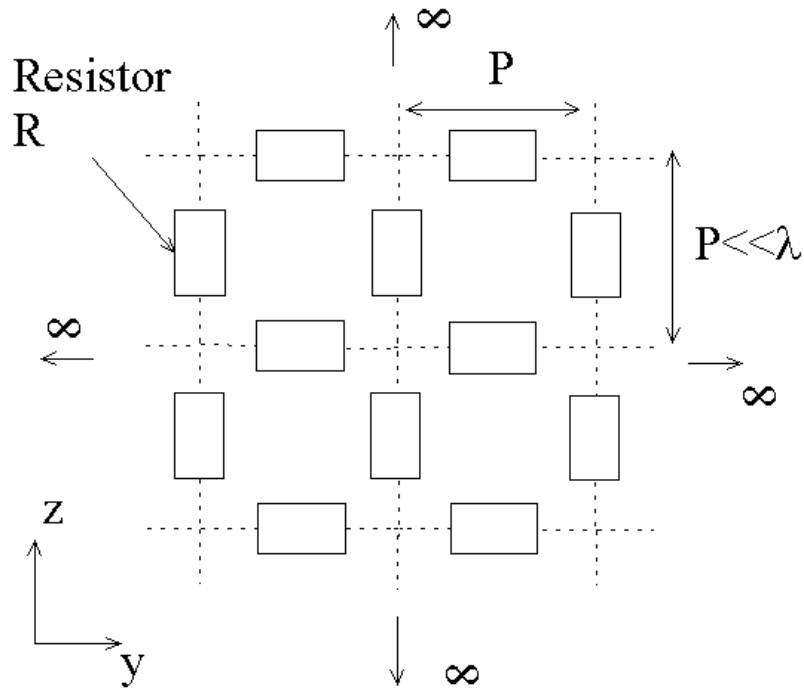


FIG. 4

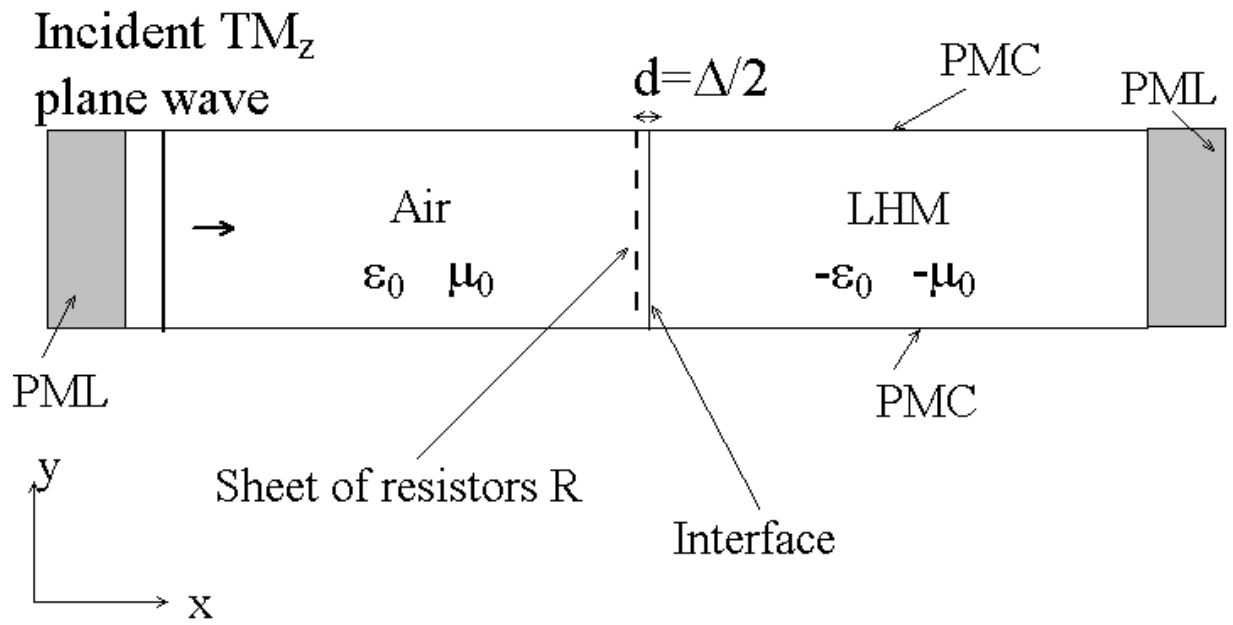


FIG.5

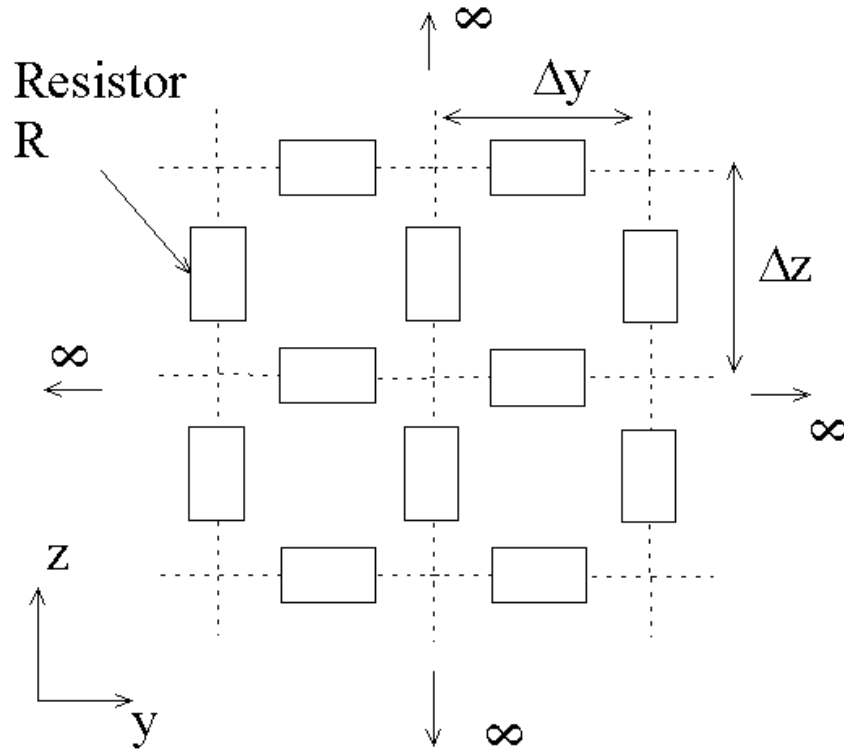


FIG.6

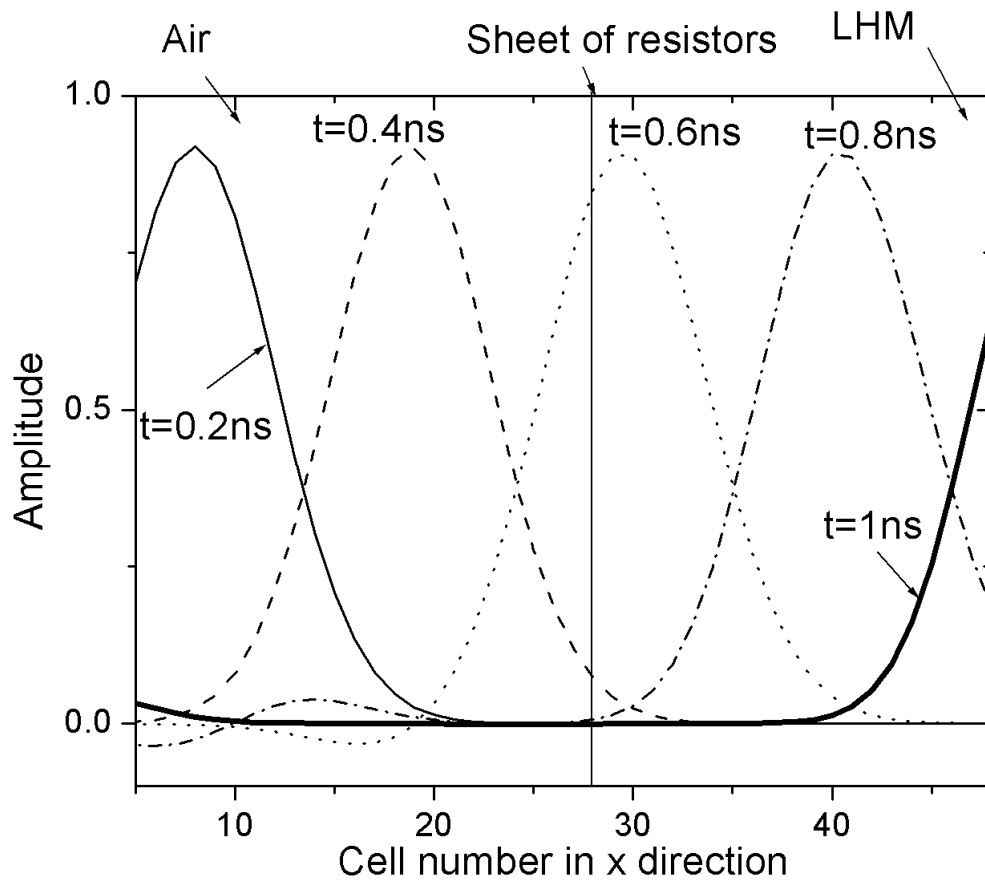


FIG. 7

