*American Journal of Materials Engineering and Technology, 2013, Vol. 1, No. 1, 1-7*
Available online at http://pubs.sciepub.com/materials/1/1/1

DOI:10.12691/materials-1-1-1

# Metamaterial Cloaks for EM Wireless Multi-Channel Telecommunications

**José Fabricio Zelada Rivas***

Facultad de Ciencias e Ingeniería – Especialidad de Ing. De las Telecomunicaciones, Pontificia Universidad Católica del Perú, Lima, Perú
*Corresponding author: a20032259@pucp.edu.pe

*Received December 28, 2012; Revised January 31, 2013; Accepted February 28, 2013*

**Abstract** In this paper, a spatial and frequency selective electromagnetic shield, employing an anisotropic metamaterial device, is analyzed and developed. The results are based on a numerical analysis using the Finite Element Method (FEM). The device is based on the cloaking concept. This is constructed employing a coordinate transformation considering Maxwell's Equations independence from coordinate system. The frequency selection is obtained due to the frequency dispersion characteristic of metamaterials, and varies over time by tuning its resonance frequency which is a consequence of entropy condition on resonant media. A full device system is simulated in order to analyze the advantage of using such systems in EM wireless communications.

***Keywords:*** *cloaking, metamaterial, electromagnetic field manipulation, electromagnetic shield*

## 1. Introduction

### 1.1. Historical Background

In 1967 Victor Veselago proposed the theoretical possibility of material with exotic characteristics [1]: Materials with negative constitutive parameters (electric permittivity ε and magnetic permeability μ) which lead to Negative Refraction Index (NRI) materials with uncommon properties. Following this trend, in 2000, D. R. Smith, Willie J. Padilla, D. C. Vier, S. C. Nemat-Nasser, and S. Schultz [2] were able to synthesize a real NRI material using Complementary Split Ring Resonator (CSRR) based on 1996's SRR model of J.B. Pendry, A. J. Holden, W.J. Stewart and I. Youngs [3]. These periodic structures behave as metamaterials depending on their resonance characteristic. Further investigations developed materials with different parameters from the constitutive ones. This new materials are now known as Metamaterial in the same way as defined by Walser, Weiglhofer & Lakhtakia [4] in 1999.

In 2006, J. B. Pendry, D. Schurig and D. R. Smith [5] established that surrounding a volume of space with a shell that have certain values of its electric parameters, will conceal the volume. The material parameters are determined by tensors $\overline{\overline{\varepsilon}}$ and $\overline{\overline{\mu}}$. i.e. must be anisotropic. This approach has been applied on this research.

## 2. Theoretical Analysis

### 2.1. Metamaterials

Metamaterials have brought about a new perspective to the field of electromagnetism. Underlying the metamaterials concept is the idea that a periodic arrangement of scattering elements can be treated as a good approximation to homogeneous material. The latter is characterized by bulk parameters such as the electric permittivity, ε, and the magnetic permeability, μ. A periodic array of conducting elements can behave as an effective medium for electromagnetic scattering waves when the wavelength (λ) is much longer than the element dimension and lattice spacing. As general rule the wavelength should be at least four times the element dimension.

ε and μ are "macroscopic" parameters, in the sense that they represent an average over the "microscopic" or sub-wavelength structure of the inhomogeneous composite. Consequently, the behavior of metamaterial structures could be predicted only by substituting the expected or retrieved macroscopic values of ε and μ in place of the microscopic metamaterial structure [4].

Several methods has been developed to model the resonance behavior of metamaterials [6-8], nevertheless the Transmission Line (TL) method proposed by Caloz & Itoh [9] has become a really powerful tool for the calculation of the metamaterial properties. This method starts with a LC resonant circuit, then generates a 1-dimensional metamaterial and extend this concept to 2D and 3D metamaterial using periodic element arrange model.

#### 2.1.1Cloaking

The idea of conformal mapping was introduced by Ulf Leonhardt in 2006 [11]. He employed the Fermat Principle [12] to describe light path in dielectric media using a variable refraction index (η) and proposed the use of this type of media to construct invisibility devices.

By the same time, J. B. Pendry, D. Schurig and D. R. Smith[5,13] introduced the idea of using metamaterial as exotic lens, where the conserved quantities of electromagnetism: electric displacement field D, magnetic induction field B and Poynting vector S are all displaced in a consistent way.

The main goal of these approaches is to cancel all scattered fields outside a clocking shell. This is obtained by bending the fields around the hidden object. In order to demonstrate this approach a model is constructed with an arbitrary arrangement of sources embedded in a dielectric and magnetic medium. This primary structure has the same topology as the final one.

The topology is initially described by a Cartesian mesh. This will be pulled and stretched to accomplish the field distortion. If (x, y, z) are the original coordinates of our Cartesian mesh, the deformed one will have (u(x, y, z), v(x, y, z), w(x, y, z)) as new coordinates [5].

Maxwell's equations remain the same disregard the coordinate system. When they are replaced in the deformed mesh the values of the electric permittivity, ε and the magnetic permeability, μ are re-scaled by a common factor. Then, using Maxwell ́s equations for constitutive relation:

$$B' = \mu_0 \mu' H'$$

$$D' = \varepsilon_0 \varepsilon' E'$$

Considering an orthogonal system, the normalized values are:

$$\varepsilon'_u = \varepsilon_u \frac{Q_u Q_v Q_w}{Q_u^2}$$

$$\mu'_u = \mu_u \frac{Q_u Q_v Q_w}{Q_u^2}, etc$$

$$E'_u = Q_u E_u,$$

$$H'_u = Q_u H_u, etc.$$

where,

$$Q_u^2 = \left(\frac{\partial x}{\partial u}\right)^2 + \left(\frac{\partial y}{\partial u}\right)^2 + \left(\frac{\partial z}{\partial u}\right)^2$$

$$Q_v^2 = \left(\frac{\partial x}{\partial v}\right)^2 + \left(\frac{\partial y}{\partial v}\right)^2 + \left(\frac{\partial z}{\partial v}\right)^2$$

$$Q_w^2 = \left(\frac{\partial x}{\partial w}\right)^2 + \left(\frac{\partial y}{\partial w}\right)^2 + \left(\frac{\partial z}{\partial w}\right)^2$$

Let's consider a cylinder of radius R1 (see Figure 1) as volume of space intended to be concealed from external electromagnetic fields. The cloaking region is a concentric cylinder of external radius R2. The electric and magnetic fields are polarized parallel to the cylinder axis, which is placed in the z axis, and 'r' is the radial polar variable. The main idea is to deform the propagation area into the cloak, such that the incident fields will circumscribe this space. In order to accomplish the concealed area is "squeezed" into the cloaking region.

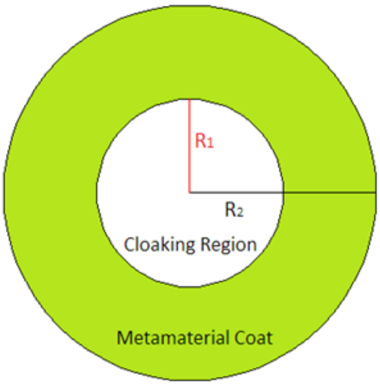



**Figure 1.** 2D cloak model variables

The transformation functions to translate the original coordinate system into the deformed one are:

$$r' = R_1 + \frac{r(R_2 - R_1)}{R_2},$$

$$\theta' = \theta,$$

$$z' = z$$

For $R_1 > r > R_2$:

$$\varepsilon_r = \mu_r = \frac{r - R_1}{r},$$

$$\varepsilon_\theta = \mu_\theta = \frac{r}{r - R_1},$$

$$\varepsilon_z = \mu_z = \left(\frac{R_2}{R_2 - R_1}\right)\frac{r - R_1}{r}$$

For r<R1 any value could be taken, without restriction, considering that no field will cross this section.

Subsequently, a radius-dependent [13] anisotropic relative permittivity $\left(\overline{\overline{\varepsilon_r}}\right)$ and permeability $\left(\overline{\overline{\mu_r}}\right)$ specified in cylindrical coordinates are obtained.

## 3. Analysis of Cloak Performance

In order to demonstrate the feasibility of the proposed device, a simulation was performed using Finite Element-based software. This will show how incident waves behave within the cloaking coat. FEM is a numerical technique for finding approximate solutions to partial differential equations (PDE) and their systems by dividing up a very complicated problem into small elements that can be solved in relation to each other. FEM is a special case of the more general Galerkin method with polynomial approximation functions. The solution approach is based on eliminating the spatial derivatives from the PDE. This approach is useful and practical for this analysis because it will allow us to set boundary conditions in order to depict a system.

### 3.1. Simulation Model

The model comprises a cylindrical coat which contains the cloaking region and the shielded area. A TEM electromagnetic wave will be applied along the x axis. The simulation chamber has PML (Perfect Matching Layers) boundaries to avoid EM reflections and PMC (Perfect Magnetic Conductor) to absorb the magnetic field in those regions. All these can be observed in Figure 2. The metamaterials parameters are distributed according to the expressions described in section II-B. The frequency of the wave is fixed to 2 GHz (This considering that frequency belongs to the IEEE band L; where most of the mobile data transmissions occur).

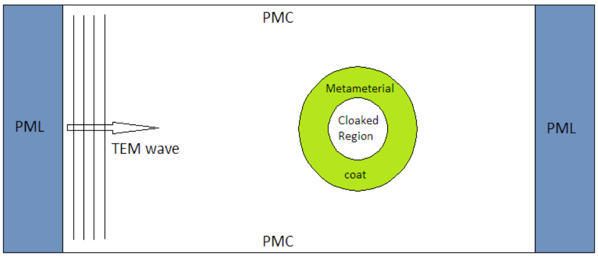



**Figure 2.** Computational domain and details for the full-wave cloaking simulation

## 3.2. Simulation Output

In Figure 3, a TEM plane wave propagation, in empty chamber, is shown, as a comparison basis. Then, the cloak is placed in the chamber, resulting in the EM wave propagation shown in Figure 4, which demonstrates the shielding effect of the cloak metamaterial, i.e. no electric field is detected inside the coat. The amount of scattered field is displayed in Figure. 5, as it can be observed, any field inside the cloak will present a very low value of electric field.

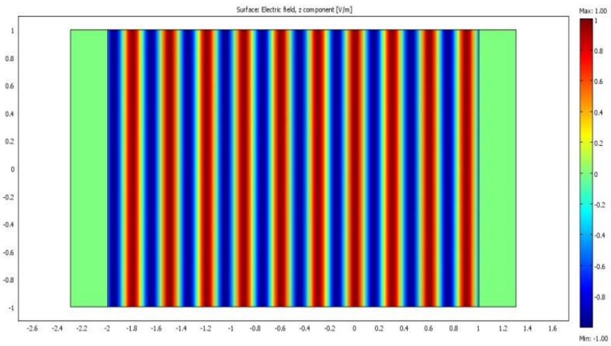


**Figure 3.** Full complex electric field in empty chamber

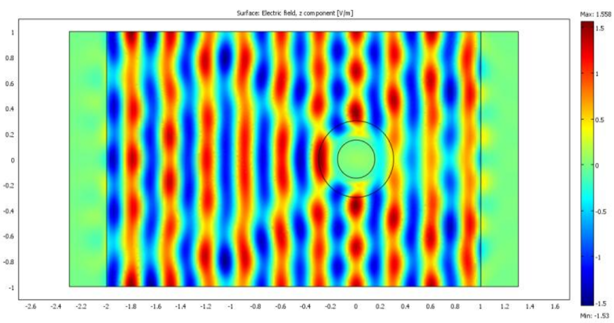


**Figure 4.** Electric field behavior with metamaterial cloak

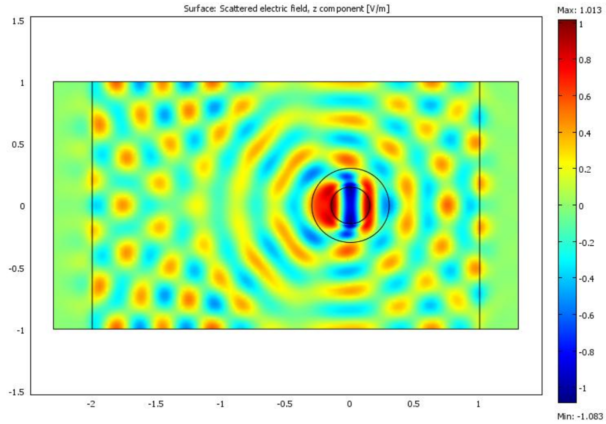



**Figure 5.** Scattering electric field inside metamaterial

In Figure 6, the electric field values versus the position along the chamber can be observed, the y coordinate is set to zero. As expected, the electric field exhibits low values in the cloaking area, indicating that this has been displaced.

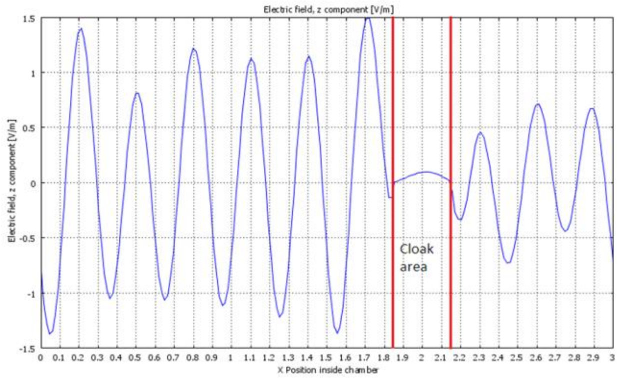



**Figure 6.** Electric field along the chamber, y=0

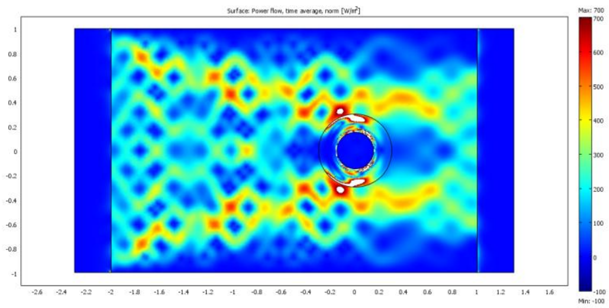


**Figure 7.** Time average power flow

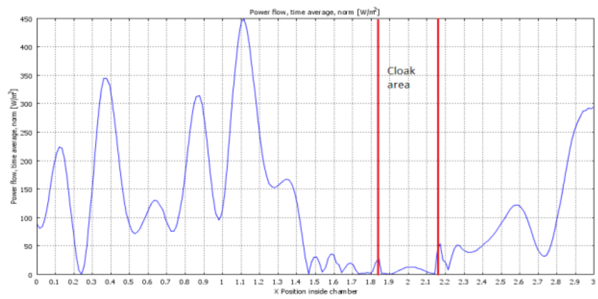



**Figure 8.** Time average power for y=0

Based on the simulation output shown in Figure 4, a time-averaged of these values is taken in order to calculate the power figure which is observed in Figure 7. Similarly, a graph showing the average power versus the position along the chamber is displayed in Figure 8. The average of the total transmitted power is virtually zero inside the cloak area.

### 3.3. Geometry of the Coat

The material described above constitutes an approximation to the ideal surrounding metamaterial, aiming to obtain invisibility coat. In this case, the purpose is to eliminate any sort of scattering outside the cloak, however the goal of a shield material is different, it is only to bend the fields away from the shielded object. Therefore, the coat shape is less restricted that in the case of invisibility coat, and it could take different forms as far as it bends away the EM field.

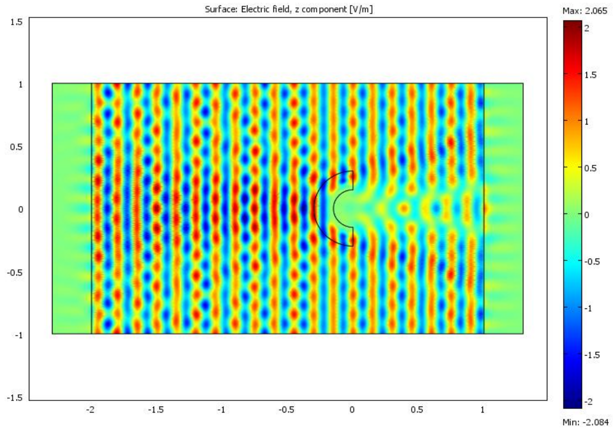



**Figure 9.** Half cylinder cloak

As an example, a semi-circle shaped material is employed instead of the full-circle one, on the simulation shown in Figure 9. This kind of shape can be positioned for barring a particular field coming from a specific direction. For more general coat shapes refer to [14,15,16,17].

#### 3.3.1 Full System Implementation

In this section, all the concepts described above will be applied in a more practical scenario. It is well known that EMI is a critical factor on current telecom applications. For instance, in the 802.11a wireless system, a material that isolates RF channels in a spatial way and with different frequencies could be necessary to improve the performance of the system, optimizing the spectra use. Therefore, a system that could shield EM waves coming from different places and exhibiting different frequencies is presented next.

To this purpose, an arrangement based on the semicircular metamaterials is proposed, as indicated in Fig. 10. Three metamaterial coats are placed such that they provide an isolation of 360°. Each coat is separated approximately 120° from the other ones, and designed to work at specific frequencies. A circular shielded area is defined inside the cloaking materials (area number 4). Then, three incoming waves with different frequency and directions (with a spatial separation of 120°) are applied to the arrangement. The tensor parameters, advised by Ma Hua, Qu Shao-Bo, XuZhuo, Zhang Jie-Qiu and Wang Jia-Fu [18] are employed. They proposed a more general approach to determine metamaterials electrical parameters disregards the wave polarization.

The cloaking coat 1 is tuned at 2GHz, coat 2 at 3GHz, coat 3 at 1GHz (IEEE band L and band S), and zone 4 is the reception area

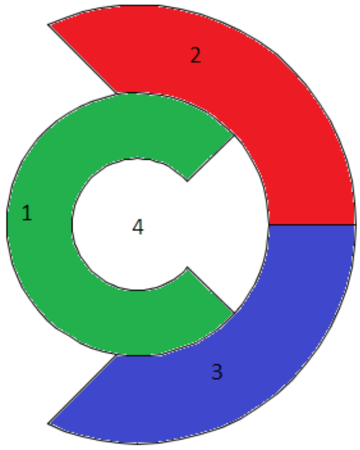



**Figure 10.** Schematic of coat distribution

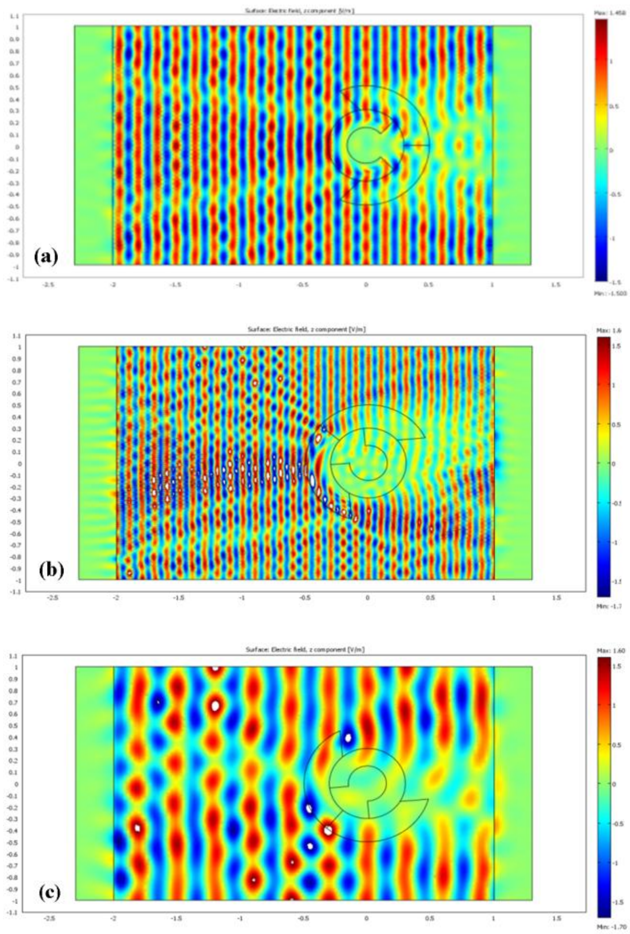



**Figure 11.** Electric field. Up-Down: 2GHz, 3Ghz, 1GHz

As shown in Figure 11, each coat is designed to work in certain frequencies letting other frequency waves to propagate freely. The simulation run at 2 GHz is displayed on Figure 11 a, it can be observed that coat 1 shields the space behind it meanwhile the others coats has no shielding effect. Likewise, the shield protection of the coat 2 at 3 GHz is observed at Figure 11 b, and the response of the coat 3 at 1GHz is presented in Figure 11 c. It is important to establish that coat, out of their resonance frequency, behave as dielectric medium with a very low loss-tangent [19].

### 3.4 Amplificatory Configuration

The shields used in the examples above will have a really low refraction index in the interior face this provides the capacity to act as reflector and given its geometry they will perform as parabolic amplificators. We can determine the value of the refraction index by:

$$\varepsilon_r = \mu_r = \frac{r - R_1}{r}\Big|_{r=R_1} = 0$$

Ergo, we can calculate the amplification factors. Figure 12 is an example how this phenomenon works. This condition can be used to provide on-site wave amplification with frequency selection.

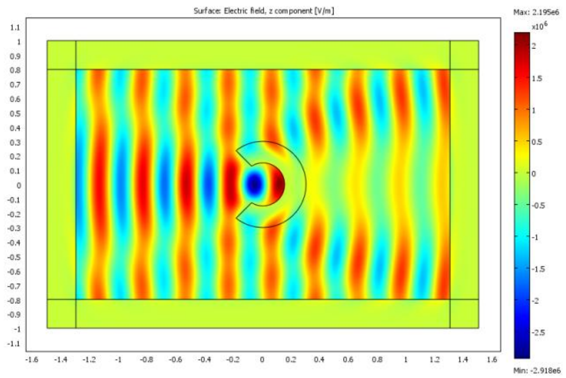


**Figure 12.** Amplification effect and scattering

## 4. Metamaterial Implementation

### 4.1. Resonant Media

In the last decade, many models where design in order to create media that could have tailored electromagnetic parameters (Metamaterials). First, they determine which parameters and configurations the modeled material should have; like the ones proposed on [6,7,8], as well as the one proposed by Caloz and Itoh [9] that provides one of the most practical and good described approximation, this by using Transmission Lines in order to model the media as a dielectric transited by a wave.

Describing the methods and techniques used to determine the relation between the models and the design parameters goes beyond the scope of this paper; nevertheless, there are many documents that cover this matter in a wide way [9,14,15,16,17].

After selecting a model that will set the required parameters to be improved in our cloaks; the next step is to focus in the constitutive unit of the device. As referred in the introduction, the first models of Metamaterial made use of cell containing SRR. Nowadays, the use of resonator rings has evolved into more modern shapes and adaptations [14]; though, the basic principle is still the same. In the transmission media model used in [9], there are units that compose the full implementation of a TL network; each of these units is a resonant circuit, as show in Figure 13.

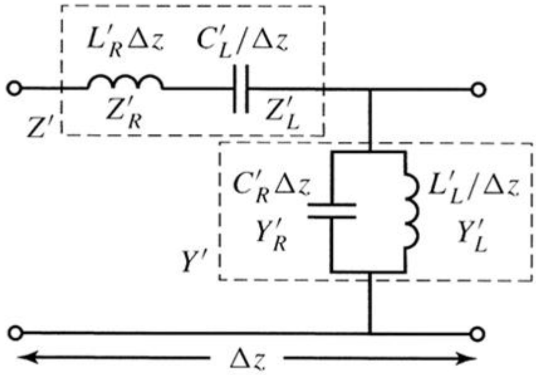



**Figure 13.** Resonant Circuit for CRLH material

Which, is equivalent to Figure 14, if Δz < λ/4. This is known as the thumb rule. As is condition to obtain behavior of homogenous material as described by Brillouin in [21], but also the size of equivalent circuit must be ≈λ/10; this condition is explained in [20].

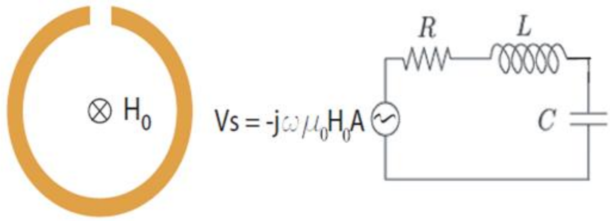



**Figure 14.** Split Ring Resonator and its equivalent circuit

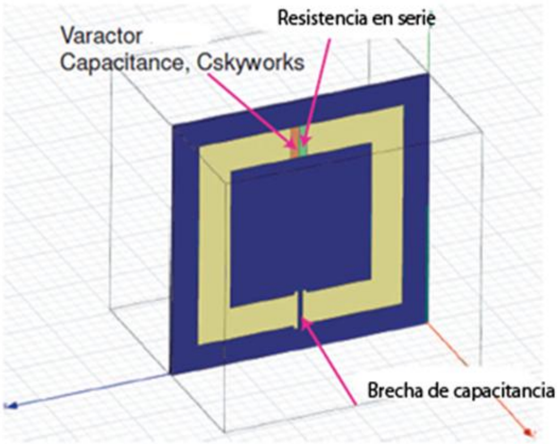
This new unit provides the tailored values by creating an enormous magnetic dipole by unit of volume as depicted in [22].

### 4.2. Tunable Media

This means that the media, in this case, the cloak have the ability to change its electromagnetic constitutive parameters. This will allow the cloaking device to have different response according our requirements; hence it will have time selective characteristics.

Many studies that try to achieve this focus on the change of the physical attributes of the dielectric media [23], or varying the resonant elements [24,25]. Nevertheless it seems that the more optimal result are obtained by using active elements like pin diodes, varactors, RF MEM switches or thin film capacitors [20,26,27,28] that allow to modify the behavior of the resonant circuit. All of this is a natural and simple step into reach the concept of tunable addressed cell; where each cell has an address or coordinate in order to select an adequate applied voltage to change its parameters [29,30].

From all the previous studies and conclusions it is easy to realize that the use of varicaps provide a wide frequency range variation with more stability on the shifted value. Varicaps make use of a PN join in order to reduce the capacitation in an inverse proportion to the applied voltage. The varicap is added in parallel to the capacitance of the arranged cell, so this can change the value of the total capacitance of the resonant circuit.




In Figure 15, a full implemented cell is shown, and in Figure 16 the characteristic response when different voltages are applied [29]

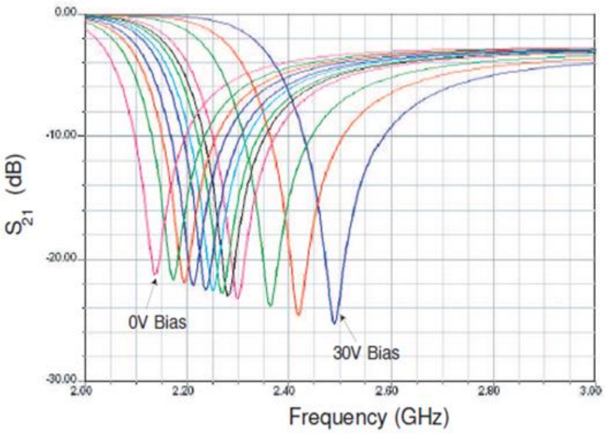



**Figure 16.** Characteristic response with different applied voltages

## 4.3. Practical Implementation

Practical implementations of the kind of devices have lot of factors that need to be analyzed in to order to obtain the desired performance. The following lines present a simulation of a practical model for which a TE wave is used as incident wave. This fact allow so simply the transformation equations, hence the constitutive parameters relation can be simplified and described by:

$$\varepsilon_z = \left(\frac{R_2}{R_2 - R_1}\right)^2$$

$$\mu_r = \left(\frac{r - R_1}{r}\right)^2$$

$$\mu_\theta = 1$$

Now, the values are radius dependent, then if set a discrete values for “r” are selected; and considering a 2GHz (λ=0.15m) incident wave. A cell of size 0.003m (≈50λ) will accomplish the design requirements [YO].

As shown in Figure 18, the multilayer system provides a similar response than an ideal model.

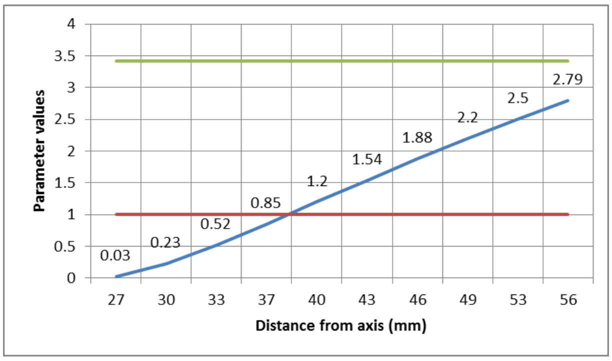



**Figure 17.** Green Line $\varepsilon_z$=3.423, red line $\mu_\theta$=1 blue line 10 µ

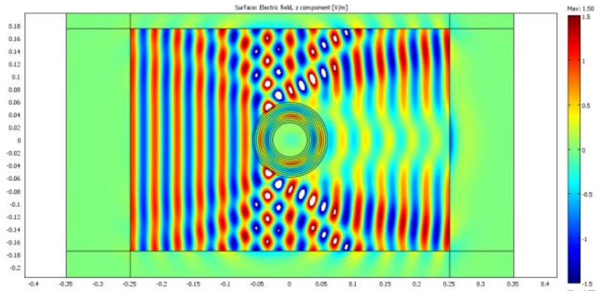


**Figure 18.** Multilayer practical implementation

A full wave analysis to demonstrate the ability to create electromagnetic shields using metamaterials has been presented. The frequency characteristic of the metamaterials has been applied in this work to obtain selectivity at three different frequencies, avoiding the coupling among them. It is important to mention that an appropriate shape and distribution of the coat should be tailored to the construction of practical systems. Also , the addition of the concept of tunable material allow to create more flexible and dynamic devices Finally, the presented results give shades on the possibility to applying this type of technology to optimize EM spectrum use, which ultimately could lead to a potential reduction of the EM pollution.

# References


[1] V. Veselago, “The electrodynamics of substances with simultaneously negative values of ε and µ”. *Sov. Phys. Usp.* 10(4): 509-14, 1968.

[2] D. R. Smith, Willie J. Padilla, D. C. Vier, S. C. Nemat-Nasser, and S. Schultz, “Composite medium with simultaneously negative permeability and permittivity”, *Phys. Rev. Lett.* 84(18): 4184-4187, 2000.

[3] J. B. Pendry, A. J. Holden, W. J. Stewart, and I. Youngs, “Extremely low frequency plasmons in metallic mesostructures”, *Phys. Rev. Lett.* 76(25): 4773-4776, 1996.

[4] R. M. Walser, W. S. Weiglhofer, and A. Lakhtakia, “Introduction to Complex Mediums for Electromagnetics and Optics”. Bellingham, WA, USA. SPIE Press. 2003.

[5] J. B. Pendry, D. Schurig, and D. R. Smith, “Controlling Electromagnetic Fields”, *Science* 312(5781): 1780, 2006.

[6] I.V. Lindel, S. A. Tretyakov, K.I. Nokoskinen, and S. Ilvonen, “BW media – media with negative parameters, capable of supporting backward waves”, *Micr. Opt. Technol. Lett.* 31(2): 129-133, 2001.

[7] M. W. McCall, A. Lakhtakia, and W. S. Weiglhofer, “The negative index meta-materials supporting 2-D waves”. IEEE-MTT Int. Symp. 2002.

[8] J. Pacheco, T. M. grzegorzcyk, B. I. Wu, Y. Zhang, and J. A. Kong. “Wave propagation in homogeneus isotripic frecuency-

dispesive left-handed media". *Phys. Rev. Lett.*, Vol. 89(25): 257401-257404, 2002.

[9] C. Caloz, and T. Itoh, "Electromagnetic Metamaterials: Transmission Line Theory and Microwave Applications", Hoboken, New Jersey: John Wiley & Sons Inc. 2006.

[10] R. Yang, Y. J. Xie, X. F. Li, Y. Y. Wang, R. Wang, and J. Jiang. "Causality in the resonance behavior of metamaterials". *EPL Journal,* 84(34001). 2008.

[11] U. Leonhardt, "Optical Conformal Mapping", *Science*, 23(5781): 1777-1780, 2006.

[12] M. Born, and E. Wolf, "Principles of Optics", Cambridge Univ. Press, Cambridge. 1999.

[13] D. Schurig, J. J. Mock, B. J. Justice, S. A. Cummer, J. B. Pendry, A. F. Starr, and D. R. Smith, "Metamaterial Electromagnetic Cloak at Microwave Frequencies", *Science*, 314(5801): 977-980, 2006.

[14] Wei Xiang Jiang, Tie Jun Cui, Guan Xia Yu, Xian Qi Lin, Qiang Cheng, and Jessie Yao Chin. "Arbitrarily elliptical–cylindrical invisible cloaking" *J. Phys. D: Appl. Phys.* 41(8), 085504. 2008.

[15] Chao Li, and Fang Li. "Two-dimensional electromagnetic cloaks with arbitrary geometries". *Opt. Express.* 16(17), 13414-13420, 2008

[16] Yu Luo, Jingjing Zhang, Hongsheng Chen, and Bae-Ian Wu. "Full-wave analysis of prolate spheroidal and hyperboloidal cloaks". *J. Phys. D: Appl. Phys.* 41(235101). 2008.

[17] Li Chao, Yao Kan, and Li Fang. "Two-Dimensional (2D) Polygonal Electromagnetic Cloaks". *Chin. Phys. Lett.* 26(6), 064206. 2009.

[18] Ma Hua, Qu Shao-Bo, Xu Zhuo, Zhang Jie-Qiu, and Wang Jia-Fu. "The design of metamaterial cloaks embedded in anisotropic medium". *Chinese Physics B* 18(3): 1025-1028. 2009.

[19] G. Sisó,M. Gil, J. Bonache, and F. Martín. "On the dispersion characteristics of metamaterial transmission lines". *Journal of Applied Physics* 102(7), 074911. 2007.

[20] Thomas H. Hand y Steven A. Cummer. "Controllable magnetic metamaterial using digitally addressable split-ring resonators". IEEE Antennas and Wireless Propagation Letters

[21] L. Brillouin. "Wave propagation in Periodic Structures". McGraw-Hill, 1946.

[22] Y. Yuan, S. Palit, C. Bingham, T.H. Hand, W.J. Padilla, D.R. Smith, N. Jokerst y S.A. Cummer. "Dual-Band Planar Electric Metamaterial in the Terahertz Regime" *Optics Express* 16(13): 9746-9752, 2008.

[23] Zhongyan Sheng & Vasundara V. Varadan. "Tuning the effective properties of metamaterials by changing the substrate properties". *Journal of Appl. Phys.* 101(1), 014909, 2007.

[24] Hongsheng Chen, Lixin Ran, Jiangtao Huangfu, Xianmin Zhang y Kangsheng Chen. "Left-handed materials composed of only S-shaped resonators". *Physical Review E,* 70(5), 2004.

[25] Yi-Jang Hsu, Yen-Chun Huang, Jiann-Shing Lih y Jyh-Long Chern. "Electromagnetic resonance in deformed split ring resonators of left-handed meta-materials". *Journal of App. Physics.* 96(4), 2004.

[26] Z. X. Xu & W. G. Lin. "Controllable Absorbing Structure of Metamaterial at Microwave". *Progress In Electromagnetics Research,* 69: 117-125, 2007.

[27] A. Ourir, S.N. Burokur & A. de Lustrac. "Electronically reconfigurable metamaterialfor compact directive cavity antennas" *Elect. Lett.* 43(13):698-700, 2007.

[28] Thomas H. Hand y Steven A. Cummer. "Characterization of Tunable Metamaterial Elements Using MEMS Switches". *IEEE Antennas and Wireless Propagation Letters*. 6: 401-404, 2007.

[29] Thomas H. Hand y Steven A. Cummer. "Controllable magnetic metamaterial using digitally addressable split-ring resonators". *Antennas and Wireless Propagation Letters, IEEE*, 8: 262-265, 2009.

[30] Thomas Henry Hand. "Design and Applications of Frequency Tunable and Reconfigurable Metamaterials". Doctoral Thesis: Department of Electrical and Computer Engineering - Duke University.

[31] Zelada Rivas, Fabricio "Apantallamiento Electromagnetico empleando metamateriales". Engineer Thesis: Telecommunication Engineering department – Pontificia Universidad Catolica del Peru.