Progress In Electromagnetics Research, PIER 69, 117–125, 2007

CONTROLLABLE ABSORBING STRUCTURE OF METAMATERIAL AT MICROWAVE

Z. X. Xu and W. G. Lin

Institute of Electronic Engineering
University of Electronic Science and Technology of China
Chengdu, Sichuan 610054, China

L. D. Kong

The First Aeronautical Institute of the Air Force of China
Xinyang, Henan 464000, China

Abstract—A kind of controllable metamaterial absorbing structure is presented in this paper, both transmission coefficient and single radar cross section (RCS) are electrically controlled. This structure is composed from split ring resonators (SRRs) and metallic wire arrays including pin diodes, pin diodes are periodically inserted at these wire arrays discontinuous, and they can be either in an on state or in an off state depending on the voltage to realize the electronic control. We use the metallic wave-guides theory, ANSOFT HFSS, high impedance surface (HIS), radiation boundary conditions, and a master-slave (M/S) relationship between each of the periodic boundary conditions (PBC's) pairs, to simulate the transmission coefficient and single radar cross section (RCS), and simulation proves that this method and technology can absorb vertical incident microwave. This is very useful for getting zero-reflected power and better aircraft stealth performance in the future.

1. INTRODUCTION

In 1968, Veselago theoretically investigated materials with simultaneously negative permittivity and permeability. Since the E, H fields and the wave vector k of a propagating plane EM wave form a left-handed system in these materials, Veselago referred to them as "left-handed" media, or metamaterial media, and pointed out that the Snell's law, the Doppler shift, and the Cherenkov radiation are reversed, and in designing improved microwave absorbing materials [1–4]. Microwave absorbing materials may be divided into two main types, one is that employ one or more thin resistive sheets separated by dielectric spacers, such as the Salisbury screen, or the multiple layer Jaumann absorber, another one is that are comprised of one or more lossy layers such as the Dallenbach absorber. The Salisbury screen and Jaumann are examples of passive radar absorbers as their reflectivity characteristics are fixed at the time of manufacture. However, if the electromagnetic properties of one or more of the constituent layers of the absorber can be varied in response to an applied electrical or optical control signal, then it is possible to realize an active, or adaptive, absorbing structure [5]. One approach to this problem is to construct a variable impedance layer using a grid of semiconductor pin diodes [6]. A similar approach is described by Dittrich and Wulbrand, in which a variable resistance layer is formed from parallel strips of series connected pin diodes [7, 8]. But people is not satisfy above absorbing effect for aircraft stealth. In 2006, J. B. Pendry, D. Schurig and D. R. Smith published paper of metamaterial electromagnetic fields, and A. Djermoun et al. published a negative refraction device, these are based on left-handed materials [9, 12]. In this paper, we report a study of a kind of metamaterial absorbing structure, which bases on left handed material properties, both the transmission coefficient and RCS of the structure are electrically controlled at microwave. Such is very useful for getting zero-reflected power and better aircraft stealth performance in the future, because Veselago pointed out that achieving effective permittivity $\varepsilon_{eff} = -\varepsilon_0$, effective permeability $\mu_{eff} = -\mu_0$ would be very desirable, as electromagnetic waves at any angle of incidence would be entirely transmitted into such a material, with nearly zero-reflected power [1].

2. METAMATERIAL ABSORBING STRUCTURE

2.1. Metallic Wires

Thin metallic wires were described as one of the earliest structures with negative permittivity ε, and the media with embedded thin metallic wires can be as artificial dielectrics for microwave applications. The structure with $\varepsilon < 0$ described by Pendry [13] consists of a square matrix of infinitely long parallel thin metal wires embedded in dielectric medium. In the situation the medium is air or vacuum, and the radius of a single wire is very thinner than the distance between two wires, the effective dielectric permittivity can be written as [14]

$$\varepsilon_{eff} \approx 1 - \frac{\omega_p^2}{\omega^2} \tag{1}$$

where ω_p is the plasma frequency for the longitudinal plasma mode. Clearly, it becomes negative for $\omega < \omega_p$.

2.2. Split Ring Resonators (SRRs)

A double split ring resonator (SRR) is a highly conductive structure in which the capacitance between the two rings balances its inductance. A time-varying magnetic field applied perpendicular to the rings surface induces currents which, in dependence on the resonant properties of the structure, produce a magnetic field that may either oppose or enhance the incident field, thus resulting in positive or negative effective μ. For a circular double split ring resonator in vacuum and with a negligible thickness the following approximate expression is valid [14]

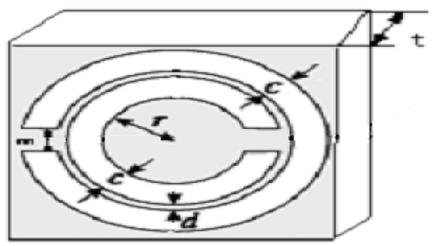
$$\mu_{eff} = 1 - \frac{\pi r^2/a}{1 + \dfrac{2\sigma i}{\omega r \mu_0} - \dfrac{3d}{\pi^2 \mu_0 \omega^2 \varepsilon_0 \varepsilon r^3}} \tag{2}$$

where a is the unit cell length, and σ is electrical conductance. It becomes negative for $\omega_{0m} < \omega < \omega_{pm}$, where ω_{0m} is the resonant frequency (for which $\mu_{eff} \rightarrow \pm\infty$); ω_{pm} is the magnetic plasma frequency (for which $\mu_{eff} \rightarrow 0$). Usually, there is a narrow frequency range where the $\mu_{eff} < 0$.

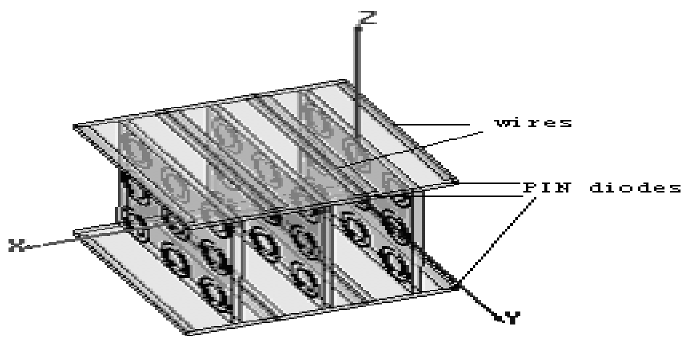
Hollow metallic wave-guides can support TE and TM modes, and a hollow metallic wave guide can be regarded as a "one-dimensional plasma" with respect to the EM propagation along the axial direction. The square wave-guide can model a "one-dimensional plasma", this reasoning can be extended to predict that the behavior of a EM wave in a left-handed material can be simulated by placing a periodic array of SRRs inside the square wave-guide. To keep the modeling of the system as simple as possible and to enhance the interaction SRR-EM field, the SRR array should be placed at the plane of symmetry of the square wave-guide, with a spacing between the SRRs equal to the wave-guide lateral side walls dimension. This "left-handed pass band" should coincide with the frequency band at which the composite SRRs and wave-guide device simulates a left-handed material [15].

2.3. Metamaterials Absorbing Structure Cell

Metamaterial structure unit cell is as shown as Fig. 1, split-ring resonators layers are realized with printed on a commercial substrate of dielectric constant $\varepsilon = 3.6\varepsilon_0$, and thickness $t = 0.4\,\text{mm}$. The metallic split ring resonators have an external diameter of 1.85 mm for the internal disk and 2.85 mm for the external one. These wires are discontinuous, 1 mm wide and 4 mm spaced, and pin diodes are inserted at these discontinuities, each 10 mm, in order to control the electrical continuity of the wires.



(1). Split ring resonator (SRR) cell.



(2). Left-handed material unit cell

Figure 1. The left-handed material unit cell (split ring resonators (SRRs) and metallic wires) used in this work. Structural parameters are $r = 0.8\,\text{mm}$, $c = 0.125\,\text{mm}$, $d = 0.375\,\text{mm}$, $t = 0.4\,\text{mm}$, $m = 0.5\,\text{mm}$ and $\varepsilon = 3.6\varepsilon_0$.

3. SIMULATION AND RESULTS

First we use ANSOFT HFSS (High Frequency Structure Simulator), a commercial solver of Maxwell's equations, to simulate the electromagnetic fields inside a SRRs, and then to the material composed from wires and SRRs. The complete simulation

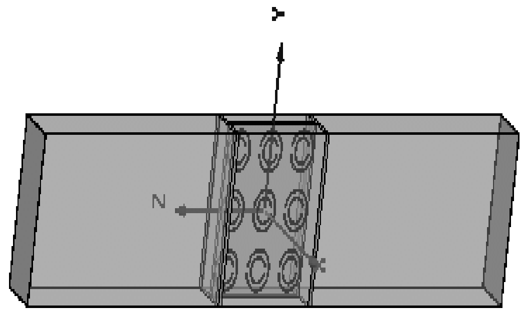


Figure 2. Setup: a unit cell (nine SSRs cells and four wires cells) in the propagation direction.

arrangement, shown in Fig. 2, consists of a metamaterial section (one unit cell) composed of an array of nine SRRs cells and four wires cells in the propagation direction placed between two regions filled with air. In order to simulate infinite media in the transverse direction, a master-slave (M/S) relationship is defined between each of the periodic boundary conditions (PBC's) pairs. Wave ports at $z = -12.5\,\mathrm{mm}$ and $z = 12.5\,\mathrm{mm}$. Calculated the transmission of the lattice of split-ring resonators is done, see Fig. 3. For metallic wire arrays and SRRs with pin diodes, shown in Fig. 1, pin diodes are inserted in these wires at the discontinuous, depending on the voltage, which is applied to them, the diodes can be either in an on state or in an off state. When these diodes are switched on (the diodes are a short circuit), the diodes are conducting and the metallic wires are continuous. When the diodes are switched off (the diodes are an open circuit), the properties of the arrays are the same as those of a structure consisting of discontinuous wires with dielectric inserts, the metallic wires become discontinuous. Fig. 4 shows the transmission spectra calculated for metallic wires where pin diodes are periodically inserted at these discontinuous each 10mm in order to control the electrical continuity of the wires. The measured transmission coefficients are as shown as Fig. 5 that comes from document [11], our simulation result is that transmission coefficients are smaller than $-12\,\mathrm{dB}$ when pin diodes are either in an on state or in an off state and shows a good fit with their measured transmission coefficients.

The single radar cross section (RCS) of such structure (suppose infinite) is simulated with which a master-slave (M/S) relationship is defined between each of the periodic boundary conditions (PBC's) pairs of HFSS, and the diodes are assigned of high impedance surface (HIS) when they are in an off state. Result is as shown as Fig. 6, it

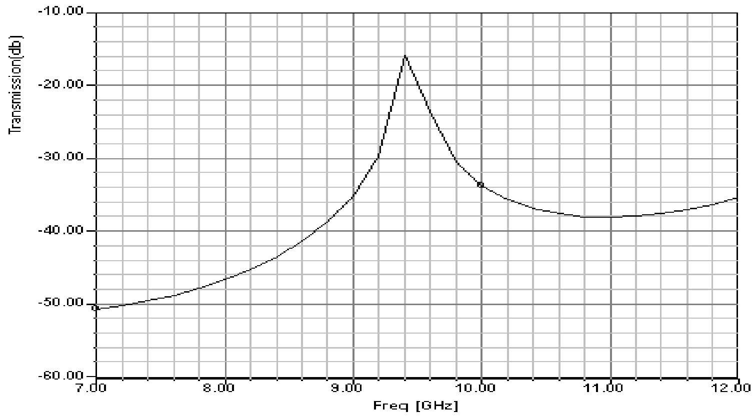
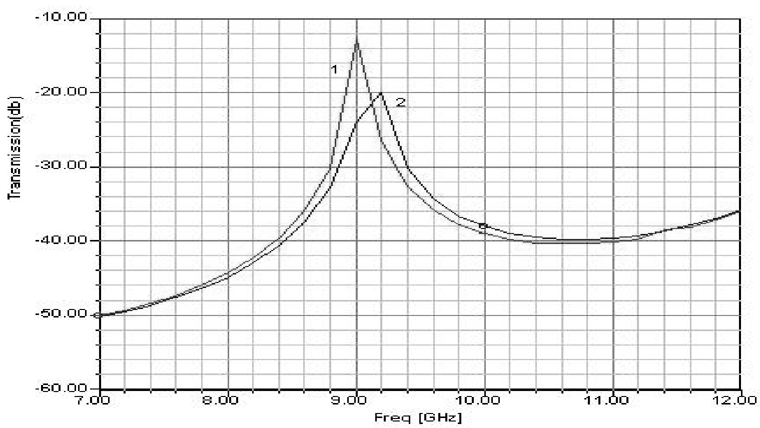


Figure 3. Transmission of the lattice of split ring.



(1). Diodes are in the on-state. (2). Diodes are in the off-state.

Figure 4. Metallic wire arrays and SRRs with pin diodes.

is clear that such structure has reduced RCS with the largest scope of -6 dBm at a resonance frequency around 9.0 GHz when pin diodes in an on state comparing of in an off state.

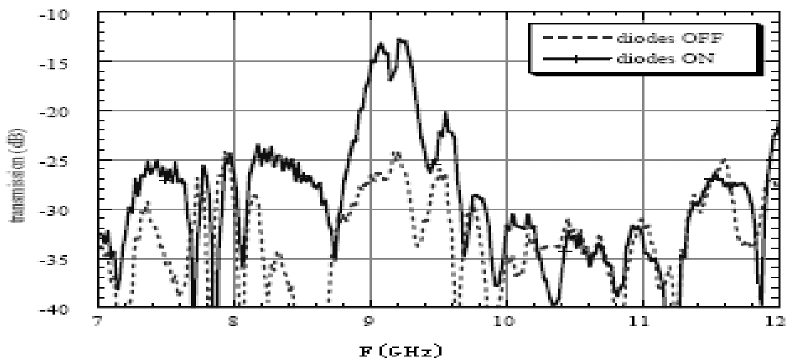
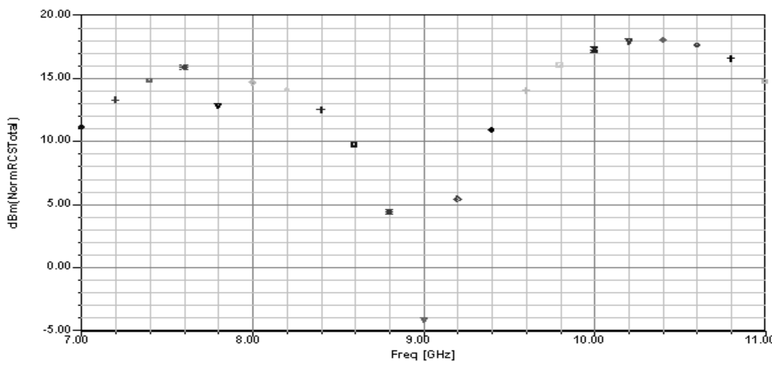
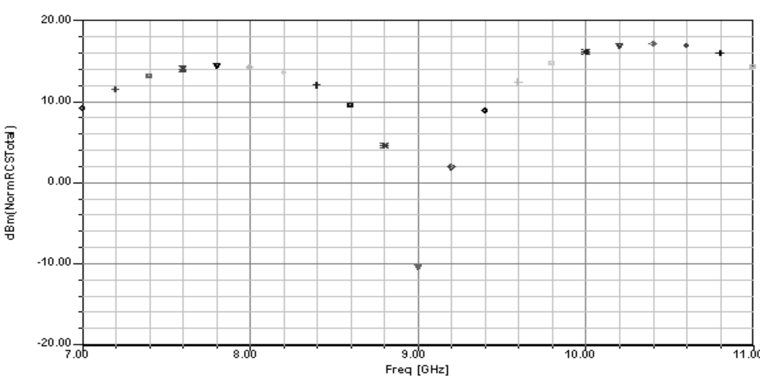


Figure 5. Measured transmission of metallic wire arrays and SRRs with pin diodes.



(1). Diodes are in the off-state.



(2). Diodes are in the on-state.

Figure 6. RCS of metallic wire arrays and SRRs with pin diodes.

4. CONCLUSION

We have presented a kind of a controllable metamaterial absorbing structure and simulated it at microwave between 7 and 12 GHz, both transmission coefficient and RCS can be electrically controlled. This structure is composed from split ring resonators (SRRs) and metallic wire arrays including pin diodes, and these diodes can be either in an on state or in an off state depending on the voltage to realize the electronic control. ANSOFT HFSS and some boundary conditions are used in simulation, our simulation result coincides with test of document, and shows that such structure would reduce RCS effectively. Above work maybe very useful for getting better aircraft stealth performance in the future.

REFERENCES

1. Veselago, V. G., "The electrodynamics of substances with simultaneously negative values of μ and ε," *Sov. Phys. Usp.*, Vol. 10, 509–514, 1968.
2. Poilasne, G., "Antennas on high impedance ground planes: on the importance of the antenna isolation," *Progress In Electromagnetics Research*, PIER 41, 237–255, 2003.
3. Shu, W. and J.-M. Song, "Complete mode spectrum of a grounded dielectric slab with double negative metamaterials," *Progress In Electromagnetics Research*, PIER 65, 103–123, 2006.
4. Sihvola, A., "Metamaterials and depolarization factors," *Progress In Electromagnetics Research*, PIER 51, 65–82, 2005.
5. Chambers, B., "A smart radar absorber," *Smart Materials and Structures*, Vol. 8, 64–72, 1999.
6. Ruck, G. T., *Radar Cross Section Handbook*, Vol. I, Plenum Press, 1970.
7. Dittrich, K. W. and W. Wulbrand, "Radar absorbing structure with integrated PIN diode network," *Proc. IO"European Electromagnetic Structures Conference*, 101–110, Oct. 1–4, 2001.
8. de Lustrac, A., et al., "Experimental demonstration of electrically controllable photonic crystals at centimeter wavelengths," *Appl. Phys. Lett.*, Vol 75, No. 11, 1625–1627, 1999.
9. Pendry, J. B., D. Schurig, and D. R. Smith, "Controlling electromagnetic fields," *Science*, April 10, 2006, www.sciecemag.org.
10. Djermoun, A., et al., "Negative refraction device with electrically controllable permittivity and negative permeability," *Electronics Letters*, Vol. 42 No. 4, 223–225, February 16, 2006.

11. Djermoun, A., A. de Lustrac, F. Gadot, and E. Akmansoy, "Design and characterization of a controllable left-handed material at microwave frequencies," *2005 European Microwave Conference*, Vol. 2, 4, Oct. 4–6, 2005.
12. Cummer, S. A., B.-I. Popa, D. Schurig, and D. R. Smith, "Full-wave simulations of electromagnetic cloaking structures," *Physical Review E*, Vol. 74, 036621, 2006.
13. Pendry, J. B., A. J. Holden, D. J. Robbins, and W. J. Stewart, "Low frequency plasmons in thin wire structures," *J. Phys.: Condens. Matter*, Vol. 10, 4785–4788, 1998.
14. Jakšić, Z., N. Dalarsson, and M. Maksimović, "Electromagnetic structures containing negative refractive index metamaterials," *Proc. 7th Internat. Conf. on Telecommunications in Modern Satellite, Cable and Broadcasting Services TELSIKS 2005*, Vol. 1, 145–154, Niš, Sep. 28–30, 2005.
15. Marques, R., J. Martel, F. Mesa, and F. Medina, "Left-handed-media simulation and transmission of EM waves in subwavelength split-ring-resonator-loaded metallic waveguides," *Phys. Rev. Lett.*, Vol 89, 183–901, 2002.