Shielding of electromagnetic waves at microwave frequencies with the split-ring resonator metamaterial.

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***Abstract*—In this work, the shielding efficiency of a split ring resonator (SRR) formed by a periodic structure built from concentric copper rings printed on a dielectric material has been studied.**

These artificial materials called metamaterials can be represented as a homogeneous material that has effective constitutive parameters that could not be obtained from naturally occurring materials, such as magnetic permeability and electrical permittivity simultaneously negative.

Simulations of the effective magnetic permeability of the material were performed by varying the geometry of the metamaterial. This analysis enables the design and construction of structures with properties that make them an attractive candidate for shielding applications in the range of microwave frequencies. This material is an alternative to massive metallic materials and can lower costs in electromagnetic absorbers.

The metamaterial has been built with 100 unit cells on each dielectric slab, stacking 5 slabs. We have made experimental measurements of the shielding effectiveness of these materials when subjected to an electromagnetic plane wave with an magnetic field polarized in the direction perpendicular to the dielectric slabs.

***Index Terms*—metamaterials, split ring resonator , magnetic permeability , shielding efficiency**

I. Introduction

Due to the proliferation of mobile electronic systems operating at microwave frequencies, such as tablets, cell phones, and laptops, which generate electromagnetic pollution, there is an interest in developing a material or electromagnetic structure design capable of absorbing electromagnetic energy at these frequencies.

The physical concept of Metamaterial was developed by Viktor Veselago, who in 1968 speculated about the possibility of creating materials with simultaneously negative electric permittivity and magnetic permeability, leading to a negative refractive index. The behavior of radiation when passing through such a material would be very different from anything known at the time [7].

Electromagnetic metamaterials (MTM) are generally defined as artificially constructed electromagnetic structures that exhibit unusual properties not readily available in nature [1], [2]. These properties originate from the geometric structure of the design rather than its chemical composition and are characterized by periodic repetitions of a pattern (unit cell). The contents of the unit cell define the effective response of the system as a whole. Electromagnetic properties can be controlled since they depend on the design of the structure. An example of a metamaterial can be observed in the Fig. 1 [5].

This significant scientific discovery is leading to the development of new devices in the fields of optics and telecommunications, both at the micrometer and nanometer scales [3], [4].

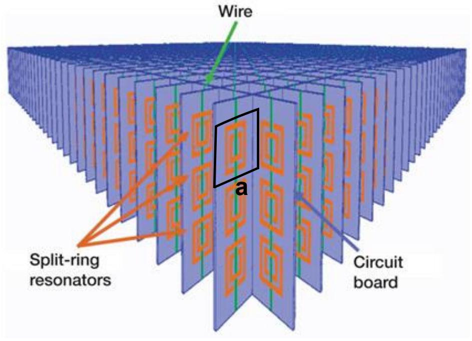

Fig. 1. Metamaterial.

If the wavelength of the incident radiation, λ, is much larger than the material's unit cell length a, i.e., if the condition of "effective homogeneity" is satisfied:

$$a << \lambda = \frac{c_0}{f} \tag{1}$$

with f representing the frequency of the incident radiation wave, the structure behaves as a homogeneous material in the sense that electromagnetic waves do not detect the internal structure. In this limit, the effective permittivity and permeability (ϵ_{eff} and μ_{eff}) are defined, which depend on the nature of the unit cell. Thus, the structure is considered electromagnetically uniform along the propagation direction for the frequency of interest.

$$\overrightarrow{D} = \epsilon_0 \epsilon_{eff} \overrightarrow{E} \qquad \overrightarrow{B} = \mu_0 \mu_{eff} \overrightarrow{H} \tag{2}$$

where $\overrightarrow{E}$ is the electric field vector of the incident wave, $\overrightarrow{H}$ is the magnetic field vector, $\overrightarrow{D}$ is the electric displacement vector, and $\overrightarrow{B}$ is the magnetic flux density vector.

Metamaterials find various applications, including antenna design, the construction of highly efficient absorbers, superlenses to enhance microscopes, the design of structures to cloak or render electric and magnetic fields invisible, and in the field of medicine, such as in the acquisition of medical images through magnetic resonance imaging, among others [8], [9], [10].

A. Development of the Effective Electric Permittivity Model for the Split-Ring Resonator (SRR) System

In the metamaterial model presented in [6] and [12], an artificial material is demonstrated to produce interesting magnetic effects within the GHz frequency range.

Starting from a structure of conductive cylinders, as shown in Fig. 2,

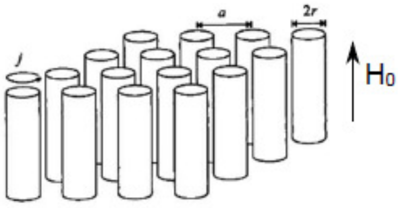

Fig. 2. Square array of metallic cylinders designed to exhibit magnetic properties parallel to the axes of the cylinders.

If an external magnetic field H_0 is applied parallel to the cylinders, a current per unit length J flows across their surface, as depicted in the figure.

The magnetic field inside the cylinders is:

$$H = H_0 + J - \frac{\pi r^2}{a^2} J \tag{3}$$

donde:

- J: Field induced by the current.
- $\frac{\pi r^2}{a^2} J$: Depolarizing field at the endcaps.

Result the effective magnetic permeability in this structure:

$$\mu_{eff} = 1 - \frac{\pi r^2}{a^2} [1 + i \frac{2\sigma}{\omega r \mu_0}]^{-1} \tag{4}$$

where σ is the resistivity of the material of the cylinders, and a and r are geometric parameters of the structure.

Since this structure exhibits a relatively narrow magnetic range, capacitive elements are added to it, thus expanding the range of magnetic properties. The same cylinder arrangement is used in an identical square structure as the simple model, except that the cylinders are now constructed as shown in Fig. 3, with a metal sheet wrapped around each cylinder. This structure is referred to as a “Swiss Roll Capacitor”. In this model, it is evident that for certain geometric parameters of the structure, the real part of magnetic permeability takes on negative values in the microwave range, a necessary condition for using the material as an electromagnetic wave absorber.

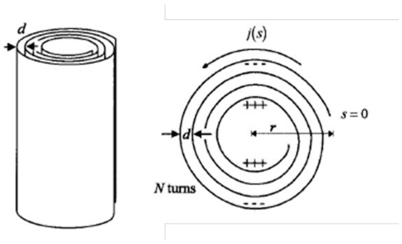

Fig. 3. Swiss Roll Capacitor Structure: A metal sheet is wrapped around each cylinder.

In this Swiss Roll Capacitor model, if the magnetic field is not precisely parallel to the cylinders, the system partially responds as a metal because current can flow freely along the cylinders. For some applications, this behavior may be undesirable. Therefore, the system is redesigned with the aim of minimizing purely electrical effects. In [12], Pendry et al. propose an adaptation of the structure in which the cylinder is replaced by a series of flat disks, each of which retains the “split-ring” configuration, as shown in the Fig. 4 and Fig. 5.

A square array is assembled using disks printed with metallic inks on a solid dielectric plate, and these plates are stacked with a small separation distance between them. In this structure, by eliminating the continuous conductive path provided by the cylinders, most of the electrical activity along this direction is eliminated.

This model is referred to as the Split Ring Resonator (SRR).

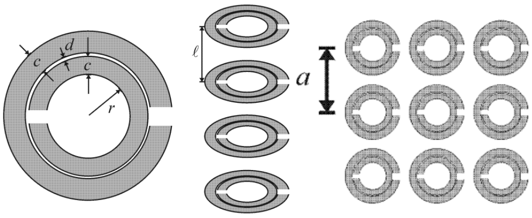

Fig. 4. SRR and plate formed by the rings

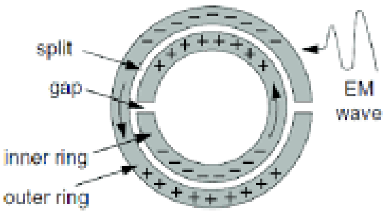

Fig. 5. Current generated in the SRR

The effective magnetic permeability as a function of the angular frequency (ω) for the SRR, as expressed by Pendry in [12], is:

$$\mu_{eff}(\omega) = 1 - \frac{\dfrac{\pi r^2}{a^2}}{1 + \frac{2l\sigma_1}{\omega r \mu_0} i - \frac{3lc_0^2}{\pi\omega^2 ln(\frac{2C}{D}) r^3}} \tag{5}$$

Where r, l, d, C, and a are geometric parameters of the structure, c_0 is the speed of light in vacuum, and σ_1 is the resistance per unit length of the SSR.

B. *Shielding efficiency*

When a plane electromagnetic wave impinges upon a material, as illustrated in Fig. 6, a portion of the incident wave is reflected, while the other part propagates through the material [14].

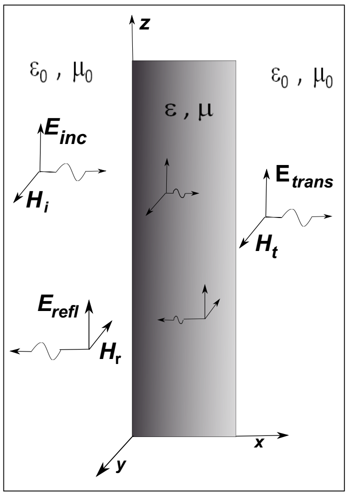

Fig. 6. Transmission through a material.

The efficiency of a shield can be specified in terms of field intensity attenuation in decibels (dB). Thus, the shielding effectiveness (SE) is calculated as the incident electric field intensity divided by the electric field intensity that passes through the structure.

In this study, the shielding efficiency of the metamaterial will be evaluated using coefficients known as “scattering parameters or S-parameters”, which are commonly employed in radio frequency (RF) and microwave measurements. The parameter S21, referred to as the transmission coefficient, will be measured [13]:

$$|S_{21}|^2 = \frac{Transmitted\ power}{Incident\ power\ at\ the\ network\ input} \tag{6}$$

II. SIMULATION OF THE ELECTROMAGNETIC BEHAVIOR OF THE SRR

With the aim of designing a material that can be used as electromagnetic shielding in the frequency range near Wi-Fi frequencies, an SRR was simulated by varying the geometric parameters to obtain the design of a metamaterial with a real negative magnetic permeability at microwave frequencies close to Wi-Fi frequencies.

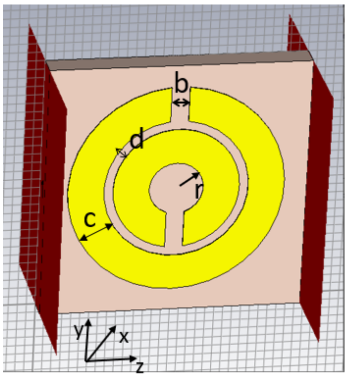

Fig. 7. Simulated SRR unit cell.

The simulation of the unit cell depicted in Fig. 7 was realized for various values of geometric parameters. An electromagnetic field simulator (CST) based on finite differences in the frequency domain (FDFD) with a tetrahedral mesh was employed.

The rings are made of copper with a resistivity of $\sigma = 200\Omega/m^2$ and a thickness of 50 μm, applied onto FR4 epoxy material with a thickness of 1300 μm and a dielectric constant of 4,4. The transverse electromagnetic (TEM) wave was directed along the z-axis, with the magnetic field propagating in the x-direction and the electric field in the y-direction.

Electromagnetic properties were measured within the frequency range of 2 to 6 GHz.

The simulation results are presented in Fig. 8, showing the real part of the magnetic permeability for various geometric parameters of the SRR.

In Table I, the values of C, D, and r for each structure are detailed. It can be observed that for certain geometric parameters of the SRR, there is a frequency range in which the magnetic permeability is negative.

TABLE I
GEOMETRIC PARAMETERS OF THE SRR CELL FOR THE MAGNETIC PERMEABILITY SIMULATIONS.

Fig.	**Geometric parameters**		
	r(mm)	***D(mm)***	***C(mm)***
(a)	1,5	1,00	1,00 1,50 2,00
(b)	1,00 1,50 2,00	1,00	2,00
(c)	1,50	0,50 1,00 2,00	2,00

The structure with parameters $C = 2000\mu m$, $D = 1000\mu m$, and $r = 1500\mu m$ was chosen for subsequent construction since, at Wi-Fi frequencies, the real part of the magnetic permeability is negative and of significant value.

III. EXPERIMENTAL PROCEDURE AND RESULTS

A prototype of the metamaterial consisting of 5 slabs, each with 100 rings, was constructed using the geometric design based on simulation, as depicted in Fig. 9.

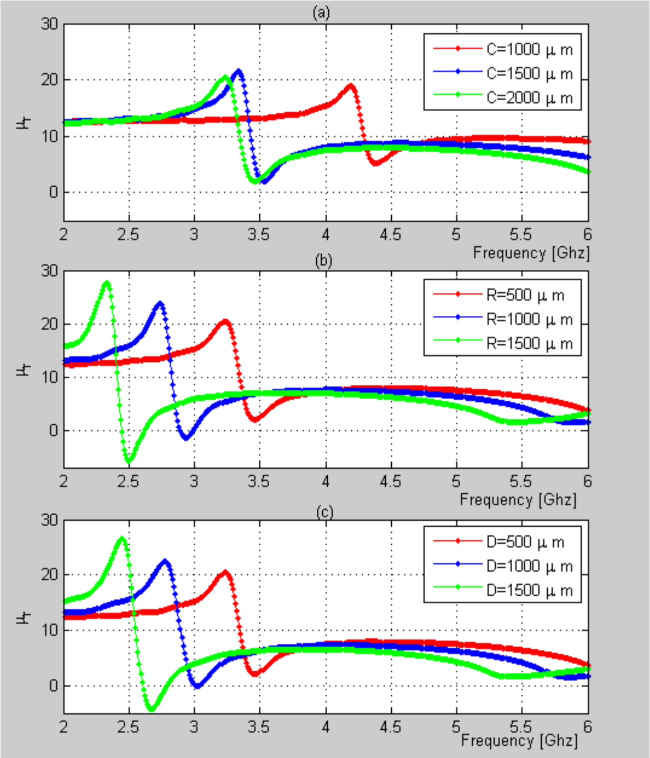

Fig. 8. Simulation Results: Real part of the magnetic permeability for different geometries. In (a), variation of the magnetic permeability with the value of C. In (b), variation with the value of r, and in (c), variation with the value of D.

Experimental measurements of the shielding efficiency of the structure were performed over a frequency range that includes the Wi-Fi frequency.

Fig. 9. Metamaterial plate

To evaluate the shielding efficiency of the metamaterial, a measurement setup was prepared, as shown in Fig.10, consisting of two horn antennas, one transmitting and one receiving, connected to a Vector Network Analyzer (VNA) of Agilent brand, model Field Fox N9932A.

The experiment involves transmitting a plane wave using the network analyzer through the transmitting antenna and measuring the response at the receiving antenna. The power ratio between the emitted power at the transmitting antenna and the received power at the receiving antenna is evaluated, first without any material present to establish a reference level, and then with the prototype placed between the antennas. In each case, the source output level is kept constant. The ratio of the two received powers indicates the power loss due to the shielding effect provided by the metamaterial [15]. The distance between the antenna and the metamaterial corresponds to the far-field approximation. The VNA was calibrated, taking into account the effects of the cables and connectors used.

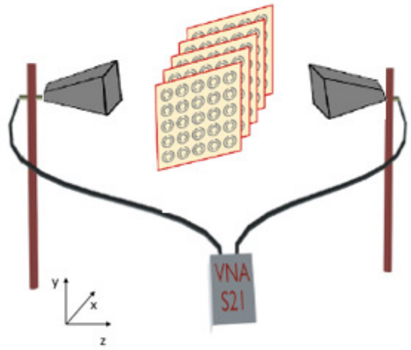

Fig. 10. Schematic diagram of the experimental setup for measuring transmission through the SRR.

The direct transmission coefficients S21 (expressed in dB) were measured, first without the metamaterial between the antennas and then with the metamaterial. The difference between the S21 coefficients results in the shielding effectiveness (SE).

The results of the shielding effectiveness can be observed in the graph in Fig.11, where the S21 coefficients of the scattering matrix with and without the metamaterial between the transmitting antenna and the receiving antenna are plotted for a plane electromagnetic wave with the magnetic field polarized in the x-direction, over a frequency range from 2 to 7 GHz. As mentioned above, the subtraction of the S21 coefficients indicates the shielding efficiency of the metamaterial.

Shielding effectiveness ranging between 10 and 20 decibels is observed within the evaluated frequency range.

IV. CONCLUSIONS

In this work, a metamaterial model known as Split Ring Resonator (SRR) was investigated for its potential use as electromagnetic shielding in microwave frequencies, including WiFi frequencies. Magnetic permeability of the metamaterial was simulated by modifying the structure's geometry, and it was observed that negative real parts of magnetic permeability were present in the frequency range of 2 to 6 GHz. This condition is essential for utilizing the material as electromagnetic shielding.

A prototype of the metamaterial consisting of 5 plates, each containing 100 rings, was fabricated based on the geometric design derived from simulations. Coefficients of direct transmission, S21 (expressed in dB), were measured by emitting a plane wave through a transmitting antenna and recording the response at the receiving antenna. Measurements were first

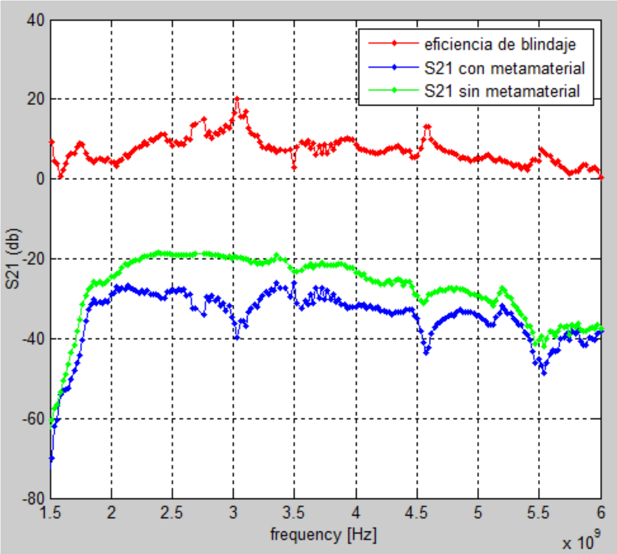

Fig. 11. Experimental measurements

taken without the metamaterial placed between the antennas and then with the metamaterial in place. The difference between the S21 coefficients yielded the shielding effectiveness (SE).

It was found that within the evaluated frequency band, the shielding effectiveness of this metamaterial falls within the range of 10 to 20 decibels, as predicted from the simulations.

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