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Electromagnetic metamaterials

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ABSTRACT

This paper proposes a review of electromagnetic metamaterials based on the idea that these are composite materials, their properties depending of the type and dimensions of the structural elements as well as the dimensions of unit cell. From the multitude of structural elements, only few that could present negative permittivity and negative or very high permeability in the range of radio and microwave frequency were chosen. The method of determination for the constitutive parameters (μ_{eff} and ε_{eff}) of metamaterials based on the *S* parameters or transmission and reflection coefficients is presented. Moreover, some applications of metamaterials are described, the attention being focused on perfect lenses and novel structures, namely conical Swiss rolls, electromagnetic cloaks and sensors for nondestructive evaluation of materials. Given that the spatial resolution of these sensors can be substantially improved in comparison to classical sensors, the metamaterial lenses are used for the manipulation of evanescent waves.

1. Introduction

One of the remarkable aspects of the human civilizational development is the intention to create or construct something that is not available in natural surroundings [1]. Initially, people attempted to rearrange objects around them. Then, they started to modify the shape and structure of the objects, to split them into parts, to combine different ones, the humanity reaching then to make their first tools. Useful substances started to be extracted from natural resources, the complexity of procedures increasing together with the aim of obtaining materials with specified properties. Further on, the materials have been synthetized due to the development of manipulation methods at molecular and atomic levels respectively. Furthermore, spectacular properties of materials can be also obtained by manipulation of certain structures, various composites being thus created.

Somehow, every material is a composite, even if the individual components are atoms and molecules [2]. Therefore, it is only a small step to replace the atoms of the original concept with structures on a larger scale and to pass from materials to metamaterials.

Metamaterials are an arrangement of artificial structural elements designed to achieve advantageous and unusual properties. A detailed consideration of the terminology is presented in [3].

In most cases, metamaterials consists of a periodical lattice of identical elements (or sets of elements), being analogy to crystals, as showed in Fig. 1. The constitutive elements of a metamaterial are named metaatoms or metamolecules. Through the metaatoms presented in Fig. 1, detailed analyzed in the paper, we can identify wire meshes, splitter ring resonators, conical Swiss rolls, Swiss rolls, further development of this fascinating domain allowing other types of constitutive elements.

An amorphous substance consists of random or irregular arrangement of artificial structural elements. We shall consider periodic structures defined by a unit cell of characteristic dimensions *a*, defined by [2]

$$a \ll \lambda$$

where λ is the wavelength of incident electromagnetic waves.

In this limit an effective permittivity and permeability is a valid concept.

Metamaterials have various applications, starting from perfect lenses [4–6] and invisible cloaks [7,8], antennas [9,10] and different types of sensors [11–13].

This paper aims to be a review in the domain of electromagnetic metamaterials, focusing on the state of the art in sensing technologies using metamaterials.

2. Metamaterials structural elements

Nowadays, a multitude of metamaterials structural elements types are known, giving special electromagnetic properties. In principle, the structural elements of metamaterials might be classified into two categories: those with negative dielectric permittivity and, in a certain frequency range, those with negative magnetic

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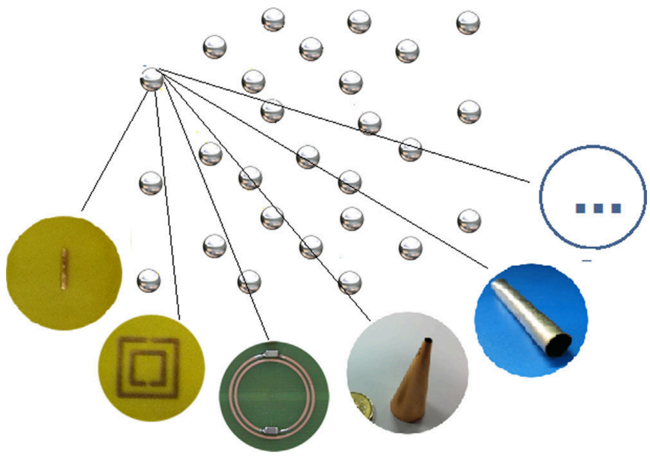

Fig. 1. Metamaterial concept.

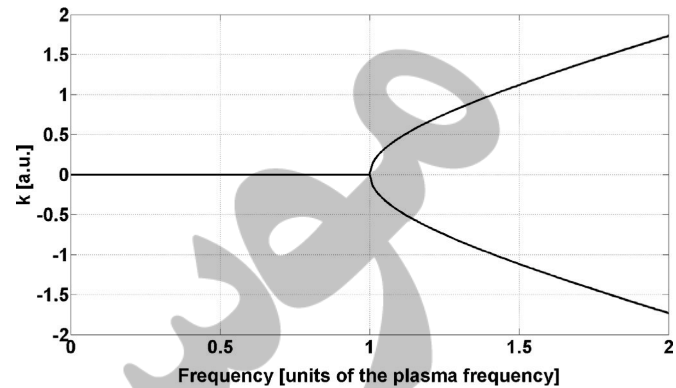

Fig. 2. Dispersion equation for light in an ideal metal.

permeability or very high magnetic permeability, although the elements are made from paramagnetic materials.

2.1. *Materials with negative permittivity*

2.1.1. *Metals and plasmons at optical frequencies*

At optical frequencies, many metals have a negative dielectric permittivity when the conductive electrons in metals can be assumed reasonably free. It is the plasma-like behavior that is responsible for a negative dielectric permittivity at frequencies smaller than the plasma frequency. The dielectric permittivity of the metals is

$$\varepsilon(\omega) = 1 - \frac{\omega_p^2}{\omega(\omega + j\gamma)} \tag{1}$$

where ω_p is the bulk frequency, γ is the damping constant and ω is the angular frequency of the incident planar electromagnetic wave. The bulk plasma frequency depends on the electron density, n, the electron mass, m_e and charge e respectively

$$\omega_p^2 = \frac{ne^2}{\varepsilon_0 m_e} \tag{2}$$

This is the Drude theory for the dispersion characteristics of a plasma [14], the dispersion equation gaining the form

$$k = \frac{\omega}{c}\sqrt{1 - \frac{\omega_p^2}{\omega^2}} \tag{3}$$

and is represented in Fig. 2.

Below the plasma frequency, in a metal only evanescent modes (with imaginary wave vector) can exist. Two degenerate modes emerge at the plasma frequency as shown in Fig. 2.

Consider the interface between an ideal metal (characterized by ε_m) and a dielectric (ε_d), for example vacuum, “illuminated” with an electromagnetic wave, p polarized as is presented in Fig. 3. Here, the frequency has been chosen so that $\varepsilon_m < 0$ and $\varepsilon_d \geq 1$ (($\varepsilon_d = 1$ for vacuum), Fig. 3.

The fields between two media, as is presented in Fig. 3, can be written

$$\begin{aligned} \bar{E}_d &= \bar{E}_0 \exp(j(k_x x + k_y y - \omega t) - K_{z+} z), \quad z > 0 \\ \bar{E}_m &= \bar{E}_0 \exp(j(k_x x + k_y y - \omega t) - K_{z-} z), \quad z < 0 \end{aligned} \tag{4}$$

Using the continuity equations for the tangential components of the electrical fields at the interface, it is obtained

$$\begin{aligned} k_x^2 + k_y^2 - K_{z+}^2 &= \frac{\varepsilon_d \mu_0 \omega^2}{c^2} \\ k_x^2 + k_y^2 - K_{z-}^2 &= \frac{\varepsilon_m \mu_0 \omega^2}{c^2} \end{aligned} \quad \text{or} \quad \frac{K_{z+}}{\varepsilon_d} + \frac{K_{z-}}{\varepsilon_m} = 0$$

There are collective excitations of electrons with the charges displaced parallel to the real part of the wave vector. Therefore, there is a mode with the amplitude of the longitudinal component of the fields decaying exponentially between the metal and the dielectric. Hence, this charge density wave lines on the surface of the metal and is called a surface plasmons, characterized by the dispersion equation

$$k_x = \frac{\omega}{c}\left(\frac{\varepsilon_m \varepsilon_d}{\varepsilon_m + \varepsilon_d}\right)^{1/2} \tag{5}$$

for a metal with $\varepsilon_m(\omega)$, given by Eq. (1) and setting $\varepsilon_d = 1$ for vacuum, $k_x > \omega/c$ for the surface plasmons [15]. Hence it will not be possible to excite the surface plasmons on a perfectly flat surface using propagating modes of light. For the surface plasmons excitation are necessary some mechanisms such as the surface roughness, a metallic strip grating structure or a dielectric coupler to vacuum such as a prism or a hemisphere [16].

2.1.2. *Wire-mesh structure*

Metal-dielectric structures have long been studied for their rich electrodynamics response [2]. It has been demonstrated in [16] that the metallic wire-mesh structures have low frequency stop band from zero frequency up to the cut-off frequency which can be attributed to the motion of electrons in metal wires. This

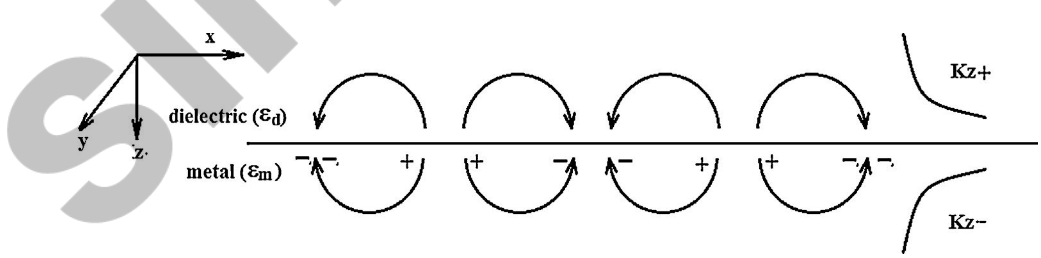

Fig. 3. Surface plasmon on an interface between a dielectric ($\varepsilon_d > 0$) and a metal ($\varepsilon_m < 0$).

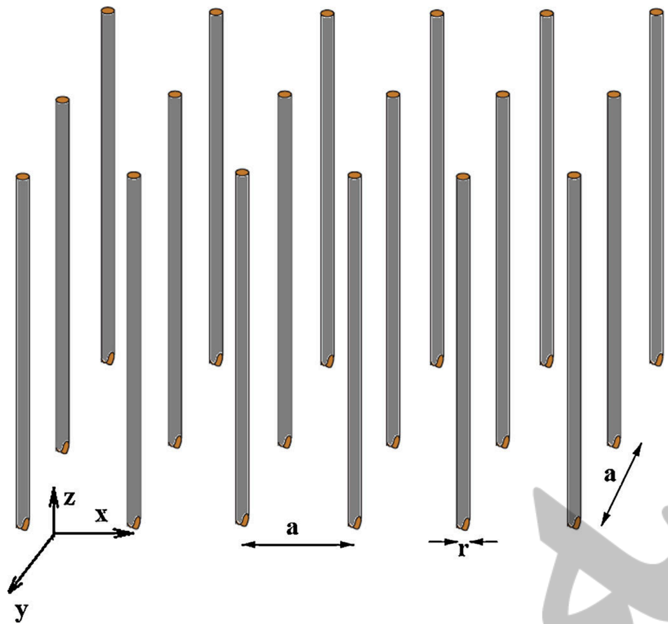

Fig. 4. An array of infinitely long thin metal wires of radius *r* and *a* lattice period *a*.

structural element consists of very thin wires structures on truly sub-wavelength scale, as is presented in Fig. 4

The electric field is considered to be applied parallel to the wires and $\lambda \gg r$, *a*. The electrons are confined to move within the wires only, which reduces the effective electron density [2].

The plasmons frequency, from the longitudinal plasmonic mode for the system is [16]

$$\omega_p = \frac{2\pi c^2}{a^2 \ln(a/r)} \tag{6}$$

If $r = 1\,\mu\text{m}$, $a = 10\,\text{mm}$ and aluminum wires, the plasma frequency is about 2 GHz and the complex dielectric permittivity is

$$\varepsilon(\omega) = 1 - \frac{\omega_p}{\omega(\omega + j(\varepsilon_0 a^2 \omega_p^2/\pi r^2 \sigma))} \tag{7}$$

where, for aluminum, $\sigma = 3.65 \times 10^7$ S/m

In Fig. 5a and b is presented the dispersion equations for this structure: the frequency dependency (expressed in plasma frequency units) of real component (Fig. 5a) and imaginary component (Fig. 5b) of the wavenumber.

According to Eq. (7), it can be seen that the wire structure described above has a negative value of the real component of ε up to a value of approximately 0.5 ω_p, after which it became positive taking the asymptotic trend toward 1 for high frequencies. The imaginary component of ε has a maximum for very small values of frequency and after that it will asymptotically decrease toward 0. The dependency of complex dielectric permittivity for the wire structure is presented in Fig. 6a and b.

A specific property of wire-mesh structure is the strong spatial dispersion of the dielectric permittivity, manifested as the formation of TEM modes in addition to the TE and TM modes of an ordinary uniaxial structure [17].

Due to a finite value of the dielectric permittivity of wires, TEM modes acquire hyperbolic dispersion [18]. In this regards, the wire medium represents a particular class of metamaterials with hyperbolic isofrequency surfaces.

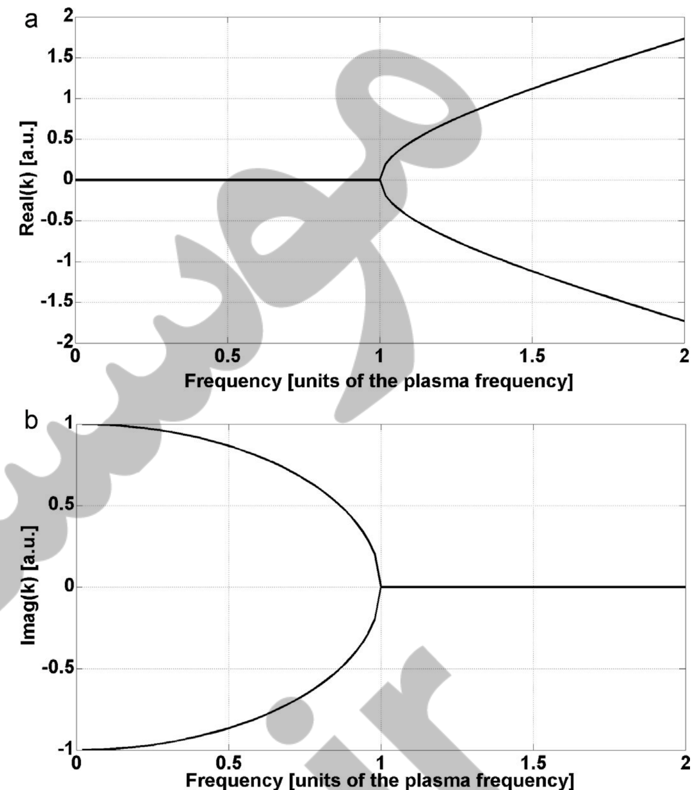

Fig. 5. The dispersion equation for aluminum thin wires of radius 1 μm, and a lattice period of 10 mm, the plasma frequency is about 2 GHz: (a) real part; (b) imaginary part.

2.2. *Metamaterial with negative permeability or with positive extremely large permeability*

The magnetic activity in most materials tends to fail off at high frequencies of even a few hundred megahertz or a few gigahertz. So it is indeed a challenge even to obtain magnetic activity, let alone negative magnetic permeability, at microwave frequencies and beyond. There are metamaterials which in certain range of frequencies in the above mentioned domain present high positive magnetic permeability, and in other ranges, can have negative magnetic permeability.

From these, only two types extremely used will be presented, namely split ring resonator (SRR) [19–21] and Swiss rolls [2,22,23], with its special variant conical Swiss roll [24].

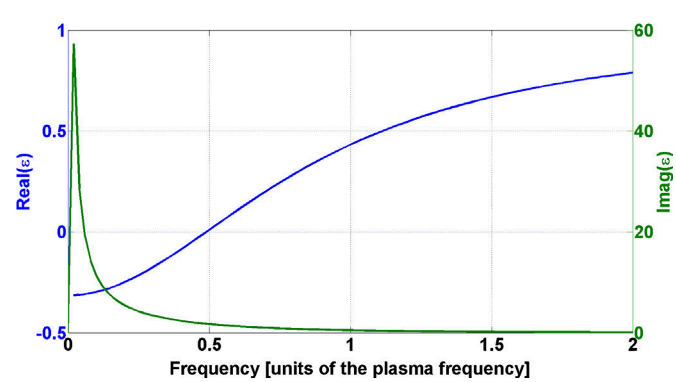

Fig. 6. The dependency by frequency of complex permittivity of aluminum thin wires of radius 1 μm, and a lattice period of 10 mm.

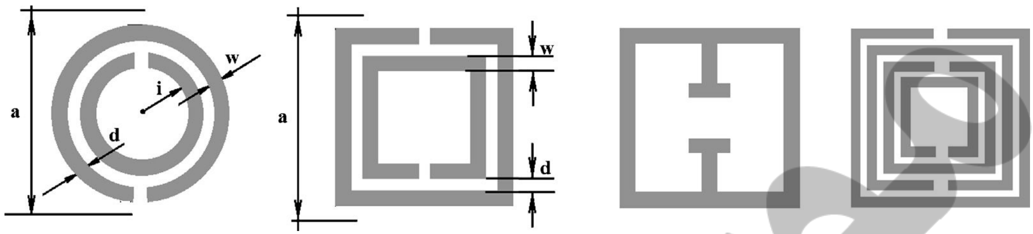

Fig. 7. Split ring resonator: (a) circular structure; (b) squared structure; (c) single ring structure; (d) multiple rings structure.

2.2.1. Split ring resonators

This type of metamaterial has the advantage to be planar, such that its practical realization can be made via photo-lithography for relatively large dimensions and nanolithography for nanometric dimensions, and due this reason, it has been intensively studied. A multitude of variants have been realized, few of them being presented in Fig. 7.

A split ring resonator (SRR) is a highly conductive structure in which the capacitance between the two rings balances its inductance (Fig. 7a). In Fig. 7 b, the circular shape of metallic structure is replaced by a rectangular one of the same structure. In Fig. 7d, multiple split ring resonators are shown, whereas in Fig. 7c other physical realization of SRR is presented.

A time-varying magnetic field applied perpendicularly to the rings surface induces currents which, depending 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 μ. In other words, the operation of a SRR represents an "over-screened, under-damped" response of metamaterial to electromagnetic stimulation [25].

For a circular double SRR (Fig. 7a), in vacuum and with a negligible thickness of metallic layer, the following approximate expression for μ is valid [19]

$$\mu_{eff} = 1 - \frac{\pi r^2/a^2}{1 + (2\sigma j/\omega r \mu_0) - (3dc^2/\pi^2 \omega^2 r^3)} \tag{8}$$

where σ is the metal resistivity and c is the speed of light in vacuum, μ_{eff} has a resonance form presented in Fig. 8.

Examining Fig. 8, the existence of two angular characteristic frequencies, namely the resonance angular frequency of μ_{eff}, ω_0, and "magnetic plasma frequency", ω_{mp}, can be observed. These frequencies can be defined as

$$\omega_0 = \sqrt{\frac{3dc^2}{\pi^2 r^2}}$$
$$\omega_{mp} = \sqrt{\frac{3dc^2}{\pi^2 r^3 (1 - (\pi r^2/a^2))}} \tag{9}$$

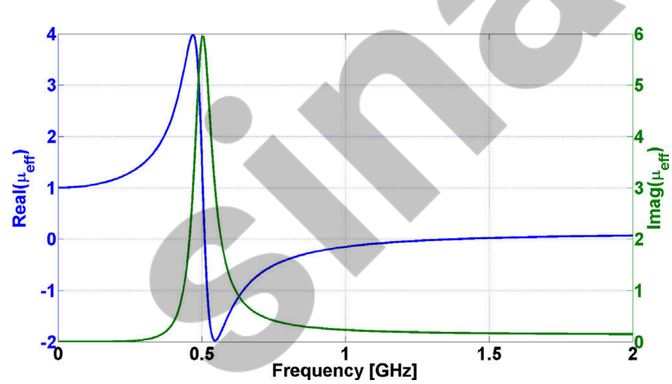

Fig. 8. The effective magnetic permeability for circular double SRR with dimensions: a = 30 mm, r = 16 mm, d = 1.5 mm. w = 1 mm, the metal being copper.

Below the resonant frequency, μ_{eff} is enhanced, and between ω_0 and ω_{mp}, the real component of μ_{eff} is negative. For a circular SRR with dimensions as mentioned above, $f_0 \cong 0.51$ GHz and $f_{\text{mp}} \cong 1.42$ GHz.

In Fig. 9 is presented the dispersion equation for circular double SRR described above. The two vertical dotted lines correspond to f_0 and f_{mp} frequencies. For $f < f_0$, the circular SRR behavior shows the existence of a transversal mode, followed by a gap between $f_0 < f < f_{\text{mp}}$; for higher frequencies, a longitudinal magnetic plasma mod appears, lacking dispersion.

2.2.2. Swiss roll

A Swiss roll consists of a central cylindrical mandrel, upon which is wound a spiral of conductor with an insulated backing, so that there is no electrical contact between the layers. When an alternating magnetic field is applied along the axis of the cylinder, it induces a current in the conducting sheet. However, the current cannot flow freely, because the sheet is not continuous; it can only flow by virtue of the self-capacitance of the structure which allows the alternative current circuit to be completed [26].

In Fig. 10 is presented the principle scheme of a Swiss roll.

For this type of material, the effective permeability was described in [2]

$$\mu_{eff} = 1 - \frac{F}{1 + (2\sigma i/\omega r \mu_0 (N-1)) - (dc^2/2\varepsilon \pi^2 r^3 (N-1)\omega^2)} \tag{10}$$

where r is the radius of the mandrel, d is the layer's thickness and N is the number of turns in the spiral. The conductor has a conductivity σ and the insulator between the conductive layers has a permittivity ε. F is the filling factor, the fraction of the material volume which is magnetically active; ideally, this is given as $\pi r^2/a^2$ where a is the lattice spacing. In practice, F is an empirically determined parameter [26].

For the case of Swiss rolls, the resonance frequency f_0 can be defined, as well as for magnetic plasma mode f_{mp}.

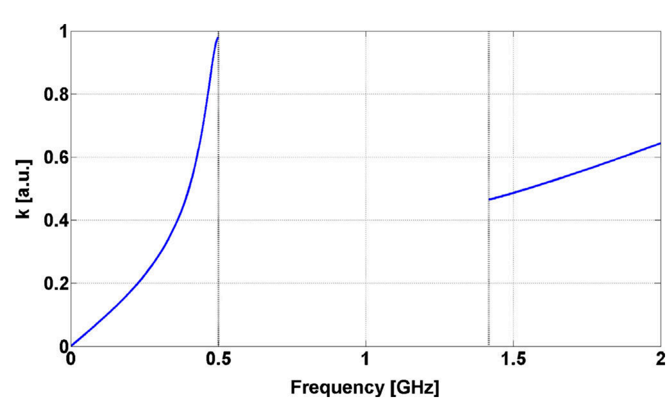

Fig. 9. The dispersion equation for circular double SRR.