Electromagnetic Structures Containing Negative Refractive Index Metamaterials

Zoran Jakšić[1], Nils Dalarsson[2], Milan Maksimović[3]

Abstract – **We review different structures for microwave and optical range containing 'left-handed' metamaterials – artificial composites with simultaneously negative effective permittivity and permeability. Special attention is dedicated to their fundamentals, design strategies and main applications which include subwavelength resonant cavities, superlenses, etc.**

Keywords – **Metamaterials, left-handed materials, negative refractive index, superlenses, subwavelength resonant cavities.**

I. Introduction

The advent of microsystem technologies and nanotechnologies enabled breakthroughs in many different areas of science and technology, offering functionalities well beyond the natural ones. It enabled structuring of materials for electromagnetic and optical applications in manners previously unimaginable. Among probably the best known examples of novel electromagnetic structures are photonic crystals (e.g. [1]) and the negative refractive index materials, popularly known as 'left-handed' materials [2], [3]. These enabled extension of the operation of passive and active elements for microwave and optical applications beyond the limits which were previously deemed possible. Another result was an extreme miniaturization of components, sometimes even three to four orders of magnitude.

Negative refractive index metamaterials (NRM) are artificial composites characterized by negative effective value of refractive index [2], [3]. These materials were theoretically predicted in 1967 by Veselago [4] (in English translation of his text it is erroneously stated that the first results on this topic were published in 1964). However, most ideas connected with negative refraction appeared even earlier. L.I. Mandelshtam described negative refraction and backward propagation of waves in his textbook published in 1944 [5]. Backward-wave transmission lines were described by Malyuzhinets in 1951 [6]. The early history of the field is described in some detail in [7]. The main problem with all of the early works was that due to the technological limitation these ideas remained only a scientific curiosity and did not attract much attention.

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With the arrival of micro- and nanofabrication, new possibilities opened for practical implementation of different metamaterials and the field became intensely studied by a number of research teams. Extremely influential were seminal texts by Pendry [8], [9], [10]. A further boost to the field came when the existence of NRM was experimentally confirmed by Smith, Shelby et al [11], [12], [13], [14]. The applicability of NRM for lensing which avoids the diffraction limit by utilizing both periodic and evanescent electromagnetic waves, as proposed by Pendry in 2000 [15] even further increased the interest for NRM. The field continued to expand owing to the fact that the Maxwell equations are scalable, thus practically the same strategies can be used for the microwave and the optical range, including the transmission line approach.

Today the number of the teams studying NRM and the number of published treatises on this topic are both increasing exponentially (see e.g. [2], [3] and references cited therein). The *Science* journal included these materials among the ten most significant breakthroughs of the recent years [16].

The aim of this paper is to present a comprehensive review of the state of the art in the rapidly expanding field of NRM. We examine electromagnetics and physics of these materials, focusing our attention to some issues which may appear counter-intuitive. We systematize the most important approaches to the design and application of the NRM.

The text is organized as follows. In the first part fundamentals of materials with negative refractive index are reviewed from the phenomenological point of view. The second part handles electromagnetic and optical design strategies to reach negative effective refractive index, i.e. describes the basic building blocks of NRM while putting an accent to the structures for the optical range and their nanofabrication. Finally, the third part shortly describes the most interesting proposals for practical applications.

II. Fundamentals of Negative Refraction

A. Some Definitions

Since one often encounters slightly dissimilar, but sometimes even outright contradictory descriptions of different structures and phenomena connected with negative refraction, we start this Subsection by giving some definitions to be used throughout this paper.

First we define metamaterial as an artificially structured material furnishing properties not encountered in nature.

Electromagnetic metamaterial is a metamaterial furnishing tailored electromagnetic response which surpasses that of natural structures. It may be an ordered structure (periodic, quasiperiodic, aperiodic, fractal) or disordered (random) structure. Artificial dielectrics [17]were historically the first electromagnetic metamaterial. Examples of periodic electromagnetic metamaterials include electromagnetic and photonic crystals and left-handed metamaterials.

Electromagnetic metamaterials intended for ultraviolet, visible or infrared range are termed optical metamaterials.

Materials that can achieve negative effective value of their refractive index were historically first termed left handed metamaterials (LHM). These can be defined as artificial composite subwavelength structures with effective electromagnetic response functions (permittivity and permeability) artificially tuned to achieve negative values of their real part. They are also denoted as negative refractive index materials (NRM), to make a distinction between these and chiral materials, which are also sometimes called 'left-handed'. Another name often met in literature is double negative materials (DNG), to stress the difference between these and the so-called single negative materials (SNG), i.e. structures characterized either by negative effective permeability or permittivity, but not both at the same time. Other names encountered in literature include Veselago media, backward media and negative phase velocity media. In this text we will stick to the term negative refractive index materials (NRM).

B. Negative effective refractive index

The complex refractive index of a given medium is defined as the ratio between the speed of an electromagnetic wave through that medium and that in vacuum and can thus be written as $n^2 = \mu\varepsilon$, where μ is complex relative magnetic permeability and ε complex relative dielectric permittivity. If both ε and μ are negative in a given wavelength range, this means that we may write $\mu = |\mu| \exp(i\pi)$ and in an equivalent fashion $\varepsilon = |\varepsilon| \exp(i\pi)$. It follows that

$$n = \sqrt{|\mu||\varepsilon|\exp(2i\pi)} = \sqrt{|\mu||\varepsilon|}\sqrt{\exp(2i\pi)} = -\sqrt{|\mu||\varepsilon|} \quad (1)$$

i.e. the refractive index of a medium with simultaneously negative μ and ε must be negative. A more detailed consideration based on causality may be found e.g. in [18].

Since no known material inherently possesses negative permeability and permittivity, NRM metamaterial is a composite of two materials which individually show $\varepsilon<0$ and $\mu<0$. This raises a question when it is permissible to describe such a composite as a medium with negative effective index.

Starting from the Maxwell equations in their integral form (Gauss and Ampere law)

$$\int_C \vec{H}d\vec{l} = \frac{\partial}{\partial t}\int_S \vec{D}d\vec{S} \quad (2)$$

$$\int_C \vec{E}d\vec{l} = -\frac{\partial}{\partial t}\int_S \vec{B}d\vec{S} \quad (3)$$

one can define average fields in quasistatic approximation as

$$\left\langle H\right\rangle_{x_i} = \frac{1}{a_{x_i}}\int_0^{x_i} \vec{H}d\vec{r}, \quad \left\langle B\right\rangle_{x_i} = \frac{1}{a_{x_i}}\int_0^{x_i} \vec{B}d\vec{S}, \quad x_i = x, y, z \quad (4)$$

so that the effective μ across the considered volume is

$$\left(\mu_{eff}\right)_{x_i} = \frac{\left\langle B\right\rangle_{x_i}}{\mu_0\left\langle H\right\rangle_{x_i}} \quad (5)$$

Analogously, the effective permittivity can be written

$$\left(\varepsilon_{eff}\right)_{x_i} = \frac{\left\langle D\right\rangle_{x_i}}{\varepsilon_0\left\langle E\right\rangle_{x_i}} \quad (6)$$

A practice often met in literature when investigating NRM is to analyze the cases with frequency-independent ε and μ [19]-[22]. However, any real NRM must be dispersive and lossy in order to preserve causality principle [23].

An often utilized form for effective ε and μ is the lossy Drude model [2] according to which polarization is

$$\varepsilon_{eff}(\omega) = 1 - \frac{\omega_{pe}^2}{\omega(\omega + i\Gamma_e)} \quad (7)$$

and magnetization

$$\mu_{eff}(\omega) = 1 - \frac{\omega_{pm}^2}{\omega(\omega + i\Gamma_m)} \quad (8)$$

where plasma frequency ω_p and dumping constant Γ are usually assumed to be equal for both polarization and magnetization, $\omega_{pe} = \omega_{pm} = \omega_p$, $\Gamma_{pe} = \Gamma_{pm} = \Gamma_p$. For low-loss model ($\omega_p >> \Gamma$) the refractive index becomes

$$n_{eff}(\omega) = 1 - \frac{\omega_p^2}{\omega(\omega + i\Gamma)} \approx 1 - \frac{\omega_p^2}{\omega^2} + i\Gamma\frac{\omega_p^2}{\omega^3} \quad (9)$$

An approximation often met in NRM is that dumping is negligible, which is an acceptable approximation even from the experimental point of view [11]. Finally, if lossy metamaterial is explicitly considered, a common assumption is that the dumping factor is given as a fraction of plasma frequency [24].

Another model often encountered in literature is the Lorentz model [25], applicable for some of the experimental implementations of negative permeability structures.

A more detailed consideration of constitutive relations in NRM can be found in [26].

C. Basic Properties of NRM

Many interesting phenomena not appearing in natural media are observed in double negative materials. These are shortly reviewed below.

The most important and probably the most thoroughly considered effect in NRM is the modification of the Snell's law, i.e. negative refraction [2], [4]. Fig. 1 shows the refraction of electromagnetic plane wave incident from vacuum (or air) onto an electromagnetically thicker medium with its real part of effective refractive index positive (Fig. 1 top) or negative (bottom). The range of refractive index values which are positive, but < 1 is also shown in top figure.

Wavevector and Poynting vector are parallel in the positive index case and antiparallel in the NRM case. Thus a beam arriving at the interface between positive and negative index material will be refracted to the same side it came from. At first sight this may appear counter-intuitive. A consequence is that a plane parallel slab of a NRM, rather to scatter beams arriving from a distance d_1, will focus them at a distance d_2 if $d_1 + d_2 = d$, where d is the thickness of the slab. In other words, a convex NRM lens will diverge a plane wave, while a concave lens will converge it. This is one of the basic processes leading to perfect lensing, to be handled in more details further in this text.

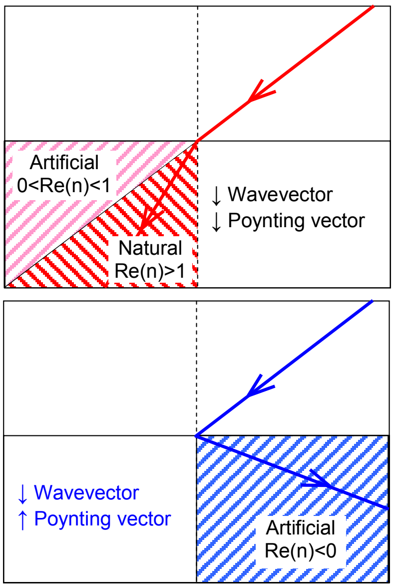

Fig. 1. Refraction in conventional material (top figure, wavevector and Poynting vector parallel) versus that in NRM material (bottom figure, wavevector and Poynting vector antiparallel).

It should be mentioned that the angle of the reflected beam remains unaffected by the NRM.

Another effect in NRM is the reversal of Čerenkov radiation [27]. It is known that a charge moving through a medium at a speed larger than the speed of light in that medium emits Čerenkov radiation in a certain angle cone. In NRM this radiation is emitted in backward direction, i.e. at an obtuse angle.

The Doppler shift in NRM will also be reversed in a NRM medium [2]. This means that the detected shift in an approaching NRM object will be red, and that in a receding blue, counter to the behavior in a conventional medium.

If a beam is incident to optically rarer medium, there is a critical angle beyond which its propagation is evanescent and a beam is then reflected with a certain shift of the beam in the transverse direction – the so-called Goos-Hänchen shift. It has been shown that the Goos-Hänchen shift is negative for reflection from NRM [28].

Since phase and group velocity have opposite signs, a NRM medium is described by the backward propagation. One should note, however, that under no circumstances the causality is violated and that in that respect the propagation through NRM corresponds to that in positive index media.

D. Mesoscopic Versus Subwavelength Negative Refraction

A misconception is that negative refraction of electromagnetic waves is equivalent to the existence of negative refractive index. The former may occur in electromagnetic and photonic crystals (the superprism effect) [29], but also in conventional diffractive gratings and generally in holographic optical elements. In that case it is a mesoscopic phenomenon entirely due to diffractive effects, i.e. Bragg scattering, and the phase velocity and wavevector have the same direction as the Poynting vector, the same as in conventional dielectric case.

However, in metamaterials with negative refractive index the wavevector and the Poynting vector have the opposite directions, the process is due to the subwavelength nature of the structures and a plethora of different effects occur which do not take place in diffractive structures [30].

Another important question is that of homogenization. Although there have been attempts to describe photonic crystals by effective refractive index, especially near the photonic band edges, a NRM-like homogenization is difficult to apply [31], thus negative refractive index cannot be even formally introduced. Still, PBG can be utilized for all-angle negative refraction and one may expect devices based on it.

E. Reversal of Fermat Principle

An interesting consideration of refraction in NRM from the point of view of the Fermat's principle [32] can be done by analyzing a propagating wave using ray tracing. The optical path length is $OPL = \int_A^B n(\vec{r})ds$, where $n(\vec{r})$ is an arbitrary dependence of refractive index on the position vector $\vec{r} = \vec{r}(x, y, z)$ and ds is a differential element of the path length. The time taken by light to travel from a point A to B is proportional to the optical path. The least action principle [33] states that the most probable path is determined by the path of stationary phase, which corresponds to an extremum in the spatial derivative of the total travel time through all possible paths. An extremum means that the variation in optical path is zero, $\delta\int_A^B n(\vec{r})ds = 0$. Generally, this extremum could be a minimum, a maximum, or a point of inflection [33]. The Fermat principle states that it must be a minimum [33], .

Consider the path for a ray incident from medium with an index of refraction n_1 to an medium n_2 (a derivation can be found in [34], [35]). For $n_2 > 0$, the curvature is positive, indicating that Fermat's result indeed gives the minimum time and distance. For $n_2 < 0$, the curvature is negative, pointing to an apparently counter-intuitive conclusion that a maximum travel time is necessary for a wave to cross a path in NRM material. In terms of the least action principle, such a solution for the path is adequate after recognizing that negative index materials are causal in an energy sense but not in a temporal sense [34], [2]. Thus for the case of NRM the Fermat principle has to be reformulated.

III. Design Strategies for NRM

A. Basic 'Particles' of NRM

It is known that highly conductive metals with permittivity dominated by plasma-like behavior (as described by Drude model) show negative dielectric permittivity in a narrow range at UV/visible frequencies. However, typical materials with negative permeability or negative permittivity are composites consisting of a large number of the basic building blocks described as unit cells (to retain correspondence with single crystals of natural materials). These building blocks are also referred to as electric ($\varepsilon<0$) or magnetic ($\mu<0$) 'particles' [2] and are often composed of dielectric with metal inclusions.

The characteristic dimensions of NRM particles have to be much smaller than the operating wavelength (in order for the effective medium approach to be applicable), but still macroscopic, i.e. much larger than the atomic or ionic dimension of their constituent materials.

All NRM structures fabricated until now were highly dispersive and dissipative. The main cause of dissipation is large absorption due to conduction losses in the metal parts of the NRM.

The main structures utilized to obtain NRM include thin metallic wires, metal cylinders, 'Swiss roll' structures, split ring and complementary split ring resonators (SRR), omega structures, broadside-coupled or capacitively loaded SRRs, capacitively loaded strips, space-filling elements, etc. Of these, only the most important ones will be presented here.

A. Thin Metallic Wires

Thin metallic wires were described as one of the earliest structures with negative permittivity. The media with embedded thin metallic wires as an artificial dielectrics for microwave applications were reported in 1953 [17].

The structure with $\varepsilon < 0$ described by Pendry [9] consists of a square matrix of infinitely long parallel thin metal wires embedded in dielectric medium (Fig. 1)

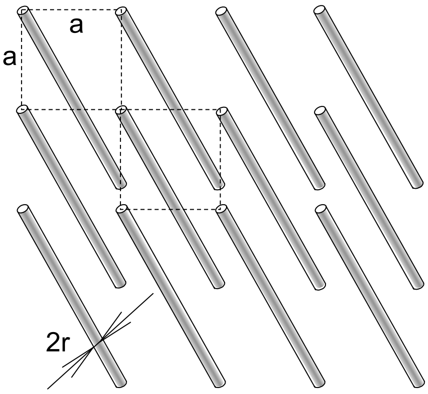

Fig. 3. Metallic wire mesh with negative dielectric permittivity

In the situation shown in Fig. 1 the medium is vacuum or air, the unit cell length is a and the radius of a single wire is $r<<a$. If plasma frequency for the longitudinal plasma mode is

$$\omega_p^2 = \frac{2\pi c^2}{a^2 \ln(a/r)} \tag{10}$$

the effective dielectric permittivity can be written as

$$\varepsilon_{eff} = 1 - \frac{\omega_p^2}{\omega\left[\omega - i\left(\omega_p^2 a^2 \varepsilon_0\right)/\sigma\pi r^2\right]} \approx 1 - \frac{\omega_p^2}{\omega^2} \tag{11}$$

i.e. it becomes negative for $\omega<\omega_p$. The approximate value at the right-hand side of the above expression is valid if conductance $\sigma\rightarrow\infty$.

B. 'Swiss Roll' Structures

The induced currents in a particle (both real and displacement ones) contribute to its effective magnetization through their magnetic moments. This contribution is non-negligible if at the same time their electric polarizability is small. For instance, if the effective permeability of the structure of metal cylinders is considered, similar to that shown in Fig. 3, one obtains that its effective permeability cannot reach negative values. However, the introduction of capacitive elements into the structure furnishes $\mu<0$.

This can be practically done by rolling up a metal sheet into spiral coils which assume the form of a cylinder [10] (Fig. 4). This is the popularly know Swiss roll structure.

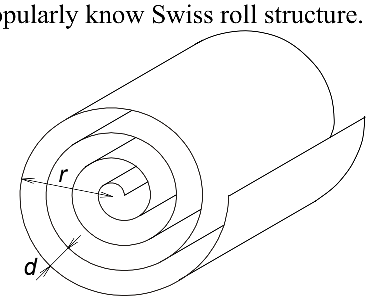

Fig. 4. Swiss roll structure with negative permeability

The sheets in the Swiss roll coils are separated by an insulator with a thickness d. If the number of coils is N and their per unit length resistance is ρ, the effective μ becomes

$$\mu_{eff} = 1 - \frac{\pi r^2 / a^2}{1 - \left[\frac{da^2}{2\pi^2 r^3}(N-1)\omega^2 + i\frac{2\rho}{\mu_0 \omega r (N-1)}\right]} \tag{12}$$

Swiss roll structures are especially convenient for low frequency operation.

C. Split Ring Resonators

For decades, and starting in the early 1950s, different ring or ring-like structures with negative permeability were of interest as building blocks for artificial chiral materials in microwave. A split ring was described in this context in the textbook by Schelkunoff and Friis [36].

A double split ring resonator (SRR) (Fig. 5) 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. In other words, the operation of a SRR represents an 'over-screened, under-damped' [2] response of material to electromagnetic stimulation.

For a circular double split ring resonator (Fig. 5a) in vacuum and with a negligible thickness the following approximate expression is valid [2]

$$\mu_{eff} = 1 - \frac{\pi r^2 / a}{1 + \dfrac{2\sigma i}{\omega r \mu_0} - \dfrac{3d}{\pi^2 \mu_0 \omega^2 \varepsilon_0 \varepsilon r^3}} \tag{13}$$

where a is the unit cell length, and σ is electrical conductance.

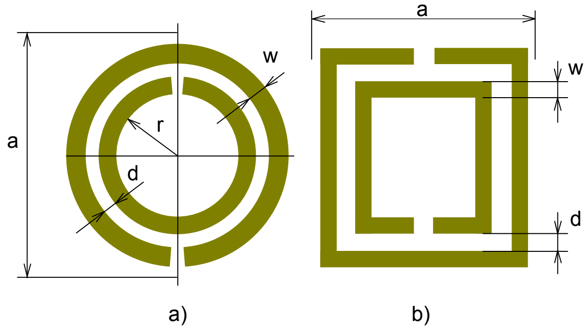

Fig. 5. Planar geometries of negative permeability material unit cells based on the split ring resonator; a) circular structure; b) square structure. Dark: thin metal film.

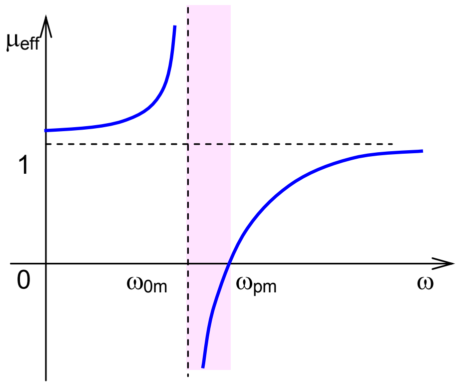

Fig. 6. Frequency dependence of effective permittivity for a split ring resonator. Shaded area denotes negative μ range

An detailed calculation of the effective magnetic permeability of split ring resonators can be found e.g. in [13].

The shape of the frequency dependence of (6) is shown in Fig. 6. It can be seen that there is a narrow frequency range where the effective permeability is below zero.

The resonant frequency (for which $\mu_{eff} \rightarrow \pm\infty$)

$$\omega_{0m} = \sqrt{\frac{3dc_0^2}{\pi^2 r^3}}, \tag{14}$$

while the magnetic plasma frequency (for which $\mu_{eff} \rightarrow 0$)

$$\omega_{pm} = \sqrt{\frac{3dc_0^2}{\pi^2 r^3 \left(1 - \pi r^2 / a^2\right)}}. \tag{15}$$

For a dielectric with ε and a ring width w

$$\omega_{0m} = \sqrt{\frac{3dc_0^2}{\pi \varepsilon r^3 \ln(2w/d)}}. \tag{16}$$

Split ring resonator is probably the most often used and analyzed negative permeability building block for the NRM.

D. Complementary Split Rings

Structures complementary to double split rings were designed and produced by applying the Babinet principle to the split rings [37]. In this way structures with apertures in metal surface are obtained, as shown in Fig. 7. These complementary split rings (CSRR) create negative ε instead of μ in a narrow range near the resonance frequency.

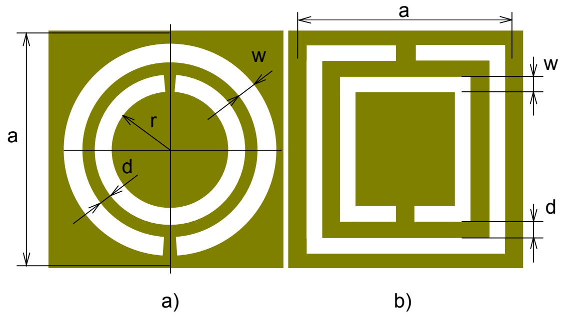

Fig. 7. Planar geometries of negative permittivity material unit cells based on the complementary split ring resonator; a) circular structure; b) square structure. Dark: thin metal film.

E. Transmission Line NRM

An alternative approach to using NRM 'particles' was proposed in [38] and [39] and subsequently elaborated in [40], [41]. It utilizes the well-known duality between filters and distributed networks to produce the so-called transmission line metamaterials (TLM). There is a direct analogy between the voltage/current in a transmission line and the components of the electric and magnetic fields. A name coined for NRM-positive index TLM composites was CRLH (composite Right/Left Handed) materials [42]. Such transmission lines behave as NRM at low frequencies and as conventional TLM at high frequencies.

In an ideal case, conventional material multilayer filters are equivalent to distributed L-C networks with series inductance and parallel capacitance. A transmission-line based NRM is equivalent to a dual distributed network with series capacitance and shunt inductance (Fig. 8) – actually a high-pass filter supporting backward wave propagation. [40]. A unit cell of a realistic lossless TLM CRLH structure includes parasitic series inductance and shunt capacitance.

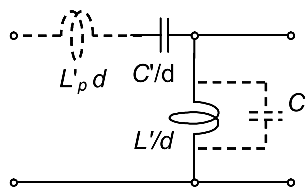

Fig. 8. Equivalent circuit for a lossless CRLH unit cell with a length d. Index "p" denotes parasitic inductance and capacitance (dashed lines). Per unit length parameters are shown (primed)

The per-unit length impedance Z' and admittance Y' for the 1D unit cell in Fig. 1 are

$$Z'(\omega) = j\left[\omega L'_p - \frac{1}{\omega C'}\right], \quad Z'(\omega) = j\left[\omega C'_p - \frac{1}{\omega L'}\right] \tag{17}$$

The propagation along the CRLH is described by the well-known telegrapher's equation (e.g. [40]). The complex propagation constant γ is

$$\gamma = \alpha + j\beta = (Z'Y')^{1/2} \tag{18}$$

where β is the real propagation (attenuation) constant. For $L'_p C' = L'C'_p$, we have the so-called balanced case. The dispersion of β for the balanced case is

$$\beta(\omega) = \omega\sqrt{L'_p C'_p} - \frac{1}{\omega\sqrt{L'C'}} \tag{19}$$

Since the propagation constant of a material is defined as $\beta = \omega(\mu\varepsilon)^{1/2}$, the refractive index of a TLM is given by

$$n = c / v_p = c\beta / \omega \tag{20}$$

Besides offering larger bandwidths and lower losses, the unit cells of TLM can be equipped with lumped circuit elements, allowing an additional degree of freedom in design, and are suitable for e.g. filtering applications [43].

F. Scaling to Optical Frequencies

An important issue to be considered is the high frequency scalability of the electric and magnetic particles for NRM. The thickness of the metal layers for the SRR/CSRR must not be smaller than the skin depth [24] (approx. 20 nm for silver at 100 THz). Moreover, at wavelengths approaching the optical range there is an additional inductance determining the plasma frequency, termed inertial inductance, which is a consequence of the electron mass and the currents through the SRR being almost purely ballistic [2]. For the scaled-down dimensions the inertial inductance becomes prevailing and the negative permeability/permittivity effect completely disappears. Several methods were proposed to overcome this problem [24]. The simplest one is to add more capacitive gaps to the original SRR design. An implementation of this principle to the square geometry SRR and CSRR is shown in Fig. 9.

Although experimental NRM structures with near-infrared response have been demonstrated (e.g. [24], [44], [45]), practically utilizable NRMs at optical frequencies remain yet to be implemented.

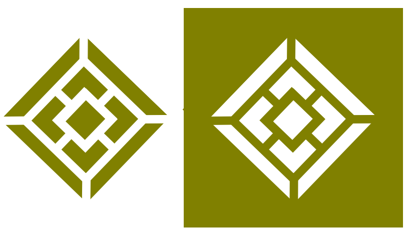

Fig. 9. Magnetic particles modified for high frequency design by adding capacitive gaps. Left: double SRR; right: double CSRR

G. Anisotropy and Homogenization Issues

The negative ε and the negative μ parts of a NRM are assumed to be electromagnetically independent. However, in reality they may interact and thus affect the performance of the composite, or even completely remove its NRM properties. A solution to this problem is to model the composites of negative μ and ε simultaneously when performing electromagnetic modeling to determine when the approximation of independence of its parts hold. In this way one can maximize NRM effects and remove undesired interference.

Another issue of interest for the existence of NRM is that of homogenization. The magnetic and electric elements of NRM are typically strongly anisotropic and with a very narrow bandwidth. The simplest and the most straightforward method to obtain a spatially isotropic effective medium is to repeat the same planar element in all three orthogonal orientations in space. Thus the obtained structure is approximately isotropic (although it would be best described by a band structure). Basic structures utilized to homogenize negative permittivity and negative permeability [10] are depicted in Fig. 1.

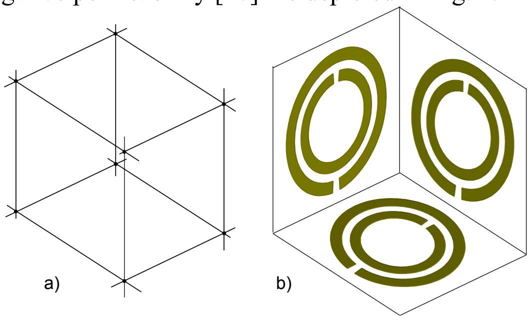

Fig. 1. Unit cells of three-dimensional isotropic structures. a) thin wire spatial mesh structure for negative permittivity; b) double split ring 3D structure for negative permeability

IV. Perfect Lens and Superlens

A. Principles of Perfect Lensing

It was shown in Subsection II C that the very fact that Snell's law is reversed in NRM must result in focusing properties of a plane-parallel metamaterial slab. However, due to the interaction of plasmons at the NRM surfaces with evanescent (near-field) components of objects located near the surface and the ensuing resonant enhancement, the NRM slab also focuses these evanescent waves. Thus a NRM slab acts as a lens focusing all components of electromagnetic radiation originating from the object and therefore surpasses the diffraction limit. Such a lens enables subwavelength resolution and is referred to as the perfect lens.

The concept of perfect lens was introduced in the classic paper by Pendry [15]. A perfect lens may be described as an optical or electromagnetic element which enables imaging in both near and far field, i.e. it forms image using both propagating and evanescent modes, resulting in an almost perfect image of the original.

The dispersion relation in free space can be written as

$$k_x^2 + k_y^2 + k_z^2 = \varepsilon_0\mu_0 \frac{\omega^2}{c^2} = k_0^2 \tag{21}$$

since $k_i = 2\pi / \Delta_i$ (where Δ_i is spatial distance over the coordinate *i*), if Δ_x, Δ_y are small, this means that the corresponding k_x, k_y must be large. If k_x, $k_y > k_0$, then k_z must be imaginary and thus the wave in *z* direction must be evanescent, i.e. decay exponentially with *z*. If the lens is at a distance larger than the operating wavelength, it will be unable to "see" this k_z. Therefore k_0 (and thus λ) remains the basic limitation in the far-field approximation – this is the well-known diffraction limit.

Let us further consider the transmission and reflection of a slab with $\varepsilon = -1$, $\mu = -1$ (which exactly compensates the positive permittivity and permeability of the surrounding free space). One can apply the well-known relations for transmission and reflection in case of multiple reflections

$$T = \frac{t_{21} t_{32} \exp(ik_{z2} d)}{1 - r_{12} r_{21} \exp(2ik_{z2} d)} \tag{22}$$

$$R = \frac{r_{21} + r_{32} \exp(2ik_{z2} d)}{1 - r_{12} r_{21} \exp(2ik_{z2} d)} \tag{23}$$

where t, r are the complex Fresnel transmittance and reflectance coefficients. The incident medium is denoted by 1, the slab material by 2, and the exiting medium is 3.

The wavevector k_{z2} can be written as

$$k_{z2} = \pm\sqrt{\frac{\varepsilon\mu\omega^2}{c^2} - k_x^2 - k_y^2} \tag{24}$$

where + sign is used for propagating, – sign for evanescent waves. In case of propagating waves one obtains $R = 0$ and $T = \exp(-ik_{z1} d)$, identical to the positive material case. However, if one replaces the expression for evanescent waves, the result is that $R = 0$ and $T = \exp(+ik_{z1} d)$. This means that NRM increases exponentially the amplitude of the evanescent wave and thus completely restores it, acting as a perfect complementary medium.

B. Losses and Active Compensation

It was mentioned before that to satisfy the causality principle a NRM must be lossy (α>0). A perfect lens with losses is referred to as superlens. The existence of absorption and dissipation significantly impairs the resolution of the superlenses and may completely remove the desirable effects. Ramakrishna [46] proposed a method to remove absorption losses and dissipation by optical amplification, e.g. by introducing lasing medium instead of dielectric into NRM-positive material composite and to utilize alternating NRM-amplifying layers instead of bulk NRM. Although there are problems with this approach (for example, regarding the influence of surface plasmons and extreme localization of fields to optical amplification), it appears that it could furnish improved results.

C. "Poor Man's" Superlens

It is well known that metals have negative dielectric permittivity in a range of frequencies in UV or visible spectrum. If the distances are much smaller than the wavelength, then the quasi-static (or extreme near-field) limit is observed and single-negative materials can be used as superlens (negative ε material will be applicable for p polarization, and negative μ for s polarization).

It was proposed to use very thin sheets of silver (a fraction of the wavelength) to obtain near-field lensing to p-polarized radiation [2]. In this way one avoids the diffraction limit in ultraviolet/visible part of the spectrum, where this feature is potentially the most applicable.

D. Experimental

The existence of the superlensing effect has been much debated, since the possibility to overcame the diffraction limit does appear counter-intuitive. However, the debate is over now, and a number of theoretical and experimental works confirm the existence of focusing with subwavelength resolution. The results on experimental fabrication of superlenses were published in e.g. [47]-[49].

V. Phase Compensators and Subwavelength Resonators

Phase compensation may be defined as partial or complete removal of phase shift of electromagnetic wave propagating through a structure containing both positive and negative refractive index material.

The simplest structure to be considered as phase conpensator consists of two slabs, one of them positive index material with a thickness d_1 and refractive index n_1, the other NRM, described by d_2 and n_2. If $\vec{k}_0$ is the wave vector in free space, then wave vector in the material is $\vec{k}_i = \vec{k}_0 n_i$ (i=1,2) if impedance-matched to free space. After passing through both slabs, the phase is $\phi = \vec{k}_1 d_1 + \vec{k}_2 d_2 = \vec{k}_o \left(n_1 d_1 + n_2 d_2\right)$ and thus the phase difference introduced by the structure is $\phi = k_o \left(n_1 d_1 - |n_2| d_2\right)$. Since n_1>0 and n_2<0, the total phase difference becomes zero if

$$\frac{n_1}{|n_2|} = \frac{d_2}{d_1} \tag{25}$$

In the case of materials with complex refractive index $N_i = n_i - ik_i$ (the extinction coefficient $k_i < 0$ for lossy structures and $k_i > 0$ for amplification), the condition for phase compensation is

$$\phi = k_o \left(n_1 d_1 - |n_2| d_2\right) - i\left(k_1 d_1 + k_2 d_2\right) = 0\,. \tag{26}$$

If the first material is conventional material with gain and second material is metamaterial with losses, the phase compensation conditions are [50], [51]

$$\frac{n_1}{|n_2|} = \frac{d_2}{d_1}\,,\ \frac{k_1}{|k_2|} = \frac{d_2}{d_1}\,. \tag{27}$$

An important conclusion is that the phase compensation in NRM-positive material composite is not dependent on the absolute value of slab thickness d_1, d_2, but only on their ratio. Such a structure is denoted as a phase compensator. It is also called beam translator, because it does not introduce any phase changes in the beam, and only "translates" it in space.

If a phase compensator/beam translator is placed between two perfect reflectors, the structure behaves as a resonator.

However, due to the fact that the phase compensator behavior depends on NRM-positive slab thickness ratio only, the structure will act as a subwavelength resonator [52], i.e. it will possess nonzero modes even for the case d_1, $d_2 << \lambda/2$. Obviously, this property is extremely useful for long-wavelength applications, where their dimensions may be extremely reduced in comparison to the conventional ones.

The extension of the concept of subwavelength resonators was done from 1D to different other geometries, including spherical and cylindrical one [3].

VI. Some NRM-Based Components and Devices

A number of concrete components and devices utilizing backward propagation and negative index media have been proposed. It should be mentioned, however, that the number of applications lags behind the theoretical descriptions encountered in literature. The reason is that although NRM approach is valid for the whole electromagnetic spectrum (the main applications are expected in the optical range,) due to technological limitations only components in microwave are currently being experimentally fabricated. However, since the field itself is very new – Pendry's landmark paper [15] which initiated the interest in NRM was published in 2000, while the majority of the published papers appeared in the last two years – it could be expected that this will change soon. The current trends surely point to that direction.

It should be mentioned that only the most important proposed applications are described in the further text.

A. Electrically small antennas

Analyses of the applicability of NRM-containing resonant structures to improve the performance of antennas were published in [53] The idea was to enclose a small emitting dipole into a shell of NRM-containing material which would match it to the surrounding free space (i.e. act as a matching network), thus obtaining an electrically small antenna with large radiated power (the “super-gain” effect) [53]. Here the compensating behavior of NRM is utilized, which reduces to zero the potential barrier and thus the reactive power near the antenna. The effect is that the antenna appears to have a larger aperture than its physical size.

An important case of steerable leaky wave antenna utilizing NRM metamaterials has been introduced in Sievenpiper's patent [54]. Antennas with single negative materials are described in [55], and multi-horn antennas in [56]. Highly directive antennas using the superlens principle have also been described [57].

B. Subwavelength Waveguides

As described by Alu and Engheta [58] and Grbic and Eleftheriades [59], the concept of sub-wavelength cavity resonators can be applied to parallel-plate waveguides and generally guided-wave structures to obtain functional structures with lateral dimensions smaller than the diffraction limit. Such waveguides incorporating NRM support a larger range of propagation constants, even very high ones. They offer a tighter confinement of waves compared to the conventional ones. The concept has also been described for the case of cylindrical guides [60]. In practical NRM-based subwavelength guides the main limitation to a decrease of their dimensions are losses.

C. Directional Couplers

The NRM-based subwavelength guide structures offer a possibility for the “backward” coupling between such guides and the conventional ones. Such directional couplers were described in [61] and [62]. A high efficiency directional coupler is described in [63]. If one of the coupled carries power in one direction, the second waveguide, placed in its vicinity, will send some of this power in the opposite direction. The coupling efficiency of the redirected power increases exponentially as the distance between the two guides decreases. The two power flows are isolated each in its channel and flow separately.

D. Dispersion Compensators

The idea for dispersion compensation in transmission lines using NRM was described in [64]. Elimination of dispersion can be done by adjusting the NRM part to match the frequency dependence of the effective permittivity of any particular type of transmission line. A partial dispersion compensation has been done experimentally for microstrip lines [3], and full dispersion compensation appears theoretically possible.

E. Active NRM filters

Amplifying media in NRM-containing structures have been described as the main way to overcome the absorptive and dissipative losses. Their use as active filters was described in [65]. The problem of tailoring the spectral response of the active medium is proposed to be dealt with by using compound semiconductors with continuously tunable bandgap [66].

F. Beam Shaping and Directing

The use of superlenses and generally complementary media has been proposed for near-field applications in microwave where a beam should be focused or simply shifted, but also for efficient channeling of beams with different shapes onto a pre-defined surface [15], [67]. An advantage of this approach is that the utilized element can simultaneously act as a phase compensator. It can be either with curved surfaces (if a collimated/flat beam is used), or, in many situations, even plane parallel, which is an advantage in certain geometries. Further, NRM-based beam shapers can bend incident waves to a greater extent although only small absolute values of the refractive index are used compared to the conventional refractive and diffractive shapers. Finally, NRM shapers are by definition impedance-matched to the incident medium and offer subwavelength resolutions.

G. Antireflection and High Reflection coatings

Antireflection (AR) and high reflection (HR) coatings based on NRM were proposed in [19]. One of their greatest advantages is their relative insensitivity to the incident angle and a much wider bandwidth than in the conventional AR and HR layers and structures. Their applicability both in microwave and in optical range has been described.

H. Gradient, Quasiperiodic and Fractal NRM Filters

NRM structures with a gradient of refractive index have been described in the context of improved filtering applications [68], [69]. Similar approach is used as that in conventional filters where graded structures enable a wider range of high-reflection or antireflection properties. Here these are coupled with flatter response and omnidirectional behavior, a trait characteristic for NRM. The use of NRM-containing composites for passive filters with fractal or quasiperiodic periodicity was described in [70], [71].

VII. Conclusion

In this paper we shortly reviewed the basic properties and applications of the popular 'left-handed' metamaterials. Over a very short period the field has rapidly developed into a state where the knowledge of its fundamental processes reached its maturity. This enabled a host of different applications to be proposed, while NRM physics slowly transits to technology. Currently the focus is shifting from microwave applications to terahertz and optical frequencies. The endeavor to create optical NRM metamaterials and applications will require a number of innovative techniques, including intensive use of micro- and nanofabrication. The speed of the development of the NRM and the number of highly motivated research teams participating its research anticipates fruitful results and a bright future for the field.

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Dear Professor Dalarsson,

I would like to take this opportunity to introduce myself as the Chairman of the 7th International Conference on Telecommunications in Modern Satellite, Cable and Broadcasting Services - TELSIKS '05 that will be held from 28 to 30 September 2005, at the Faculty of Electronic Engineering, University of Nis, Serbia and Montenegro.

The Conference TELSIKS '05 strives to attract high quality papers in the field of telecommunications. That is the reason why I kindly invite you, as one of the world-leading scientific authorities, to prepare an invited paper on one of the conference topics (First Announcement and Call for Papers is enclosed) for presentation at the TELSIKS '05 Conference.

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I will be very pleased if you inform me, as soon as possible, about your decision. If you accept to be our invited speaker I am free to ask you to send: title of the paper, names of co-authors (if you decide to write your paper in collaboration with some other authors) and short abstract (up to 300 characters).This information should be sent no later than January 31 2005. I truly hope that you will take part at the Conference.

Thanking you in advance, I am looking forward to hearing from you soon.

Yours sincerely,

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