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# Metamaterials: Theory, Classification and Application Strategies (Review)

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The review of the design, principles and operation of artificial composite structures with peculiar electromagnetic properties (metamaterials) is presented. Physical preconditions of metamaterials have been considered in order to explain how exciting properties of such structures can be achieved. A detailed classification scheme and a comparative description of the most proven and wide-used metamaterial structures for microwave technologies have been presented. In addition, the most successful examples of metamaterial application in waveguides, resonators and their derived components as well as in antennas technology have been considered and systematized.

**Keywords:** Microwave, Metamaterials, Negative refraction, Resonator, Transmission line, Waveguide, Coupler, Metamaterial absorber, Antenna.

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## 1. INTRODUCTION

Nowadays millimeter and submillimeter wave devices are used in variety of fields such as spectroscopy, satellite applications, communications, radio astronomy, etc. [1]. Despite of these, significantly less weight, better and well controlled output characteristics of microwave devices are new requirement and challenge for the researchers and developers. The novel approaches to design microwave components and elements has been intensified recently. Among of them is implementing into microwave devices construction a new class of materials with exclusive properties which are called metamaterials [1-2]. A production and improvement structures with controlled electromagnetic properties has a significant impact on the development of advanced microwave devices [1-3]. An amount of publications devoted to artificial materials with new physical phenomena has been rapidly growing [4-6]. Hence, materials and media with unusual electric and magnetic properties have a great deal of research interest now.

Metamaterials form a wide class of composite structures constituting artificial inclusions are named unit cells. Inclusions have certain forms and are embedded into the base medium, typically dielectric substrate. Extraordinaire and even paradoxical features of metamaterials are difficult to achieve technologically and undetectable practically in natural materials [6]. They achieved due to properties of base substrate and rightly selected unit cells parameters. The latter include dimensions, form and shape of individual cells. The size and the period of unit cells of most metamaterials are much smaller than operating wavelength (a separate class of photonic crystals with structure dimensions that can be equal to wavelength is not take into account currently). Therefore, such a materials can be represented as a homogeneous media with effective values of permittivity and permeability. This constants can be changed by manipulation individual inclusions with getting the required values. In other words, one can interact with the separate "atoms" of whole material. Permittivity and permeability of metamaterial composites can take not only much large or small values including zero, but also can be negative in certain frequency band. The latter case makes possible to implement a medium with negative refractive index. Thus, we can directly affect electrophysical properties of the material by modifying material constants. In our paper we have classified metamaterials from different points of view what should help the researchers to do a right material choice depending of the target.

The following section of the paper presents physical preconditions to forming metamaterial structures. The classification of microwave metamaterials and the properties of the most wide-used structures with their comparison are discussed in Section 3. The metamaterial applications in microwave technology including waveguides, resonators, couplers, filters, absorbers and antennas are considered in Section 4.

## 2. PHYSICAL PRECONDITIONS

It is appropriate to consider the classification of materials represented on Fig. 1 before turning to specific types and designs of metamaterial structures.

Almost all isotropic materials existing in nature have positive values of permittivity and permeability more than unity. They thus are determined as DPS (double positive) materials. Materials with negative $\varepsilon$ or $\mu$ only are termed as SNG (single negative) materials and divided into two classes depending on negative effective parameter: ENG (epsilon-negative) and MNG (mu-negative). It should be noted that if one constant takes on a negative value, the refractive index of incident beam becomes imaginary and only damped (evanescent) electromagnetic waves can propagate in such

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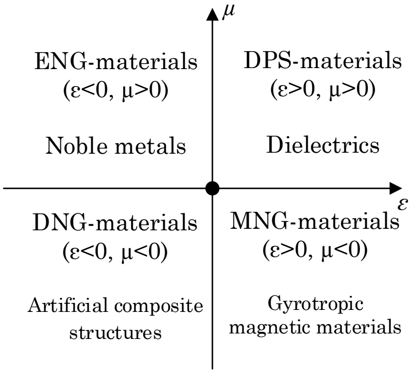


**Fig. 1** – The general classification of physical materials depending on values of permittivity and permeability

material. Considered that material is opaque to radiation if its thickness is greater than the characteristic attenuation length of the electromagnetic wave.

The most known natural ENG-material is the plasma, which dielectric constant is negative in a certain frequency range. Typical ε-negative materials are metals since their dielectric constant is described as a function of frequency in the Drude model and below the plasma frequency of metal permittivity is negative [7]. For instance, the noble metals behave like ε-negative materials in infrared and optical frequency ranges therefore the propagation of light is impossible in such media.

In MNG-materials, accordingly, permittivity is greater than zero and permeability is less. Some gyrotropic materials exhibit such characteristic in certain frequency range.

Materials with simultaneously negative values of ε and μ doesn't exist in nature, so they are produced artificially. Over the last two decades the research and experiments with these materials and finding ways of application became a widespread. Such artificial media are named in different sources left-handed materials [8, 9] double negative metamaterials (DNG) [10], backward wave media [11]. As indicated above, negative material constants lead to negative value of the refractive index of an electromagnetic wave passing through the media. Refracted beam disposed is not as usual, but in the “left” direction, symmetric relative to normal to the usual direction, as shown on Fig. 2. It is proceed from fact that a wavevector and Poynting vector are parallel if the refractive index is positive and antiparallel if vice versa. Hence an incident beam to the interface between the conventional DPS-medium and DNG-material will be refracted to the same side it came from.

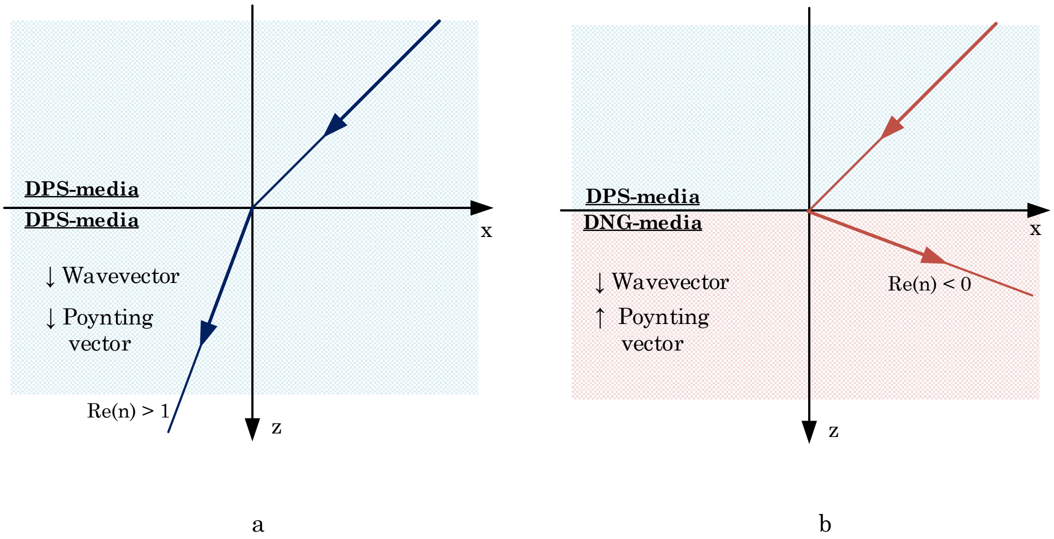


**Fig. 2** – Refraction in DPS-medium (a) vs. refraction in material with simultaneous $\varepsilon < 0$ and $\mu < 0$ (b)

The physical foundations of the left-handed media were laid in the pioneer paper [12]. In particular, the author theoretically proved that existence of materials with simultaneously negative $\varepsilon$ and $\mu$ is not denied by Maxwell's equations. Also have been predicted that the group and phase velocity of an electromagnetic wave passing through the left-handed medium have an opposite signs. Additional possible characteristic of DNG-materials is inversion of Doppler shift [8]. The detected shift in an approaching object made from DNG-material is red, while in receding is blue, in contrast to behavior in the DPS-medium. Another effect is the inversion of Vavilov-Cerenkov radiation [13]. In DNG-material Cerenkov radiation is emitted in backward direction to the conventional angle cone. It should be noted that due to preservation of causality principle any real DNG-material must be lossy and dispersive.

The earliest material with left-handed properties in the centimeter wavelength range have been presented and studied in [14-16]. It is the combination of thin metal wires grid and split ring resonators. The first set is artificially produced ENG-material while the the second belongs to MNG-materials. Periodic placement of unit cells leads to both negative values $\varepsilon$ and $\mu$ of obtained composite structure. Anomalous refraction on the edge of the material have been demonstrated experimentally [14].

## 3. MICROWAVE METAMATERIAL STRUCTURES

### 3.1 Classification Scheme

According to [1] metamaterials can be divided into two major classes due to approaches to a mathematical description. The first class includes DNG and SNG-structures, whereas the second is PBG-structures or photonic crystals that also termed as photonic bandgap materials.

As were mentioned above, the linear size of internal inclusions in DNG and SNG-materials is much smaller than the operating wavelength. Thus such media generally are lead to homogeneity and described with the concept of effective medium. The distance between the constituent elements in PBG-structures is equal to about half the wavelength or more. Therefore, photonic crystals cannot be considered as homogeneous media. They are usually described by Bragg reflection, which don't have an important role in DNG and SNG-structures, and other approaches to periodic media are used.

After analyzing papers and monographs, which highlighting the basic metamaterial strategies for microwave applications, classification scheme shown in Fig. 3 have been made.

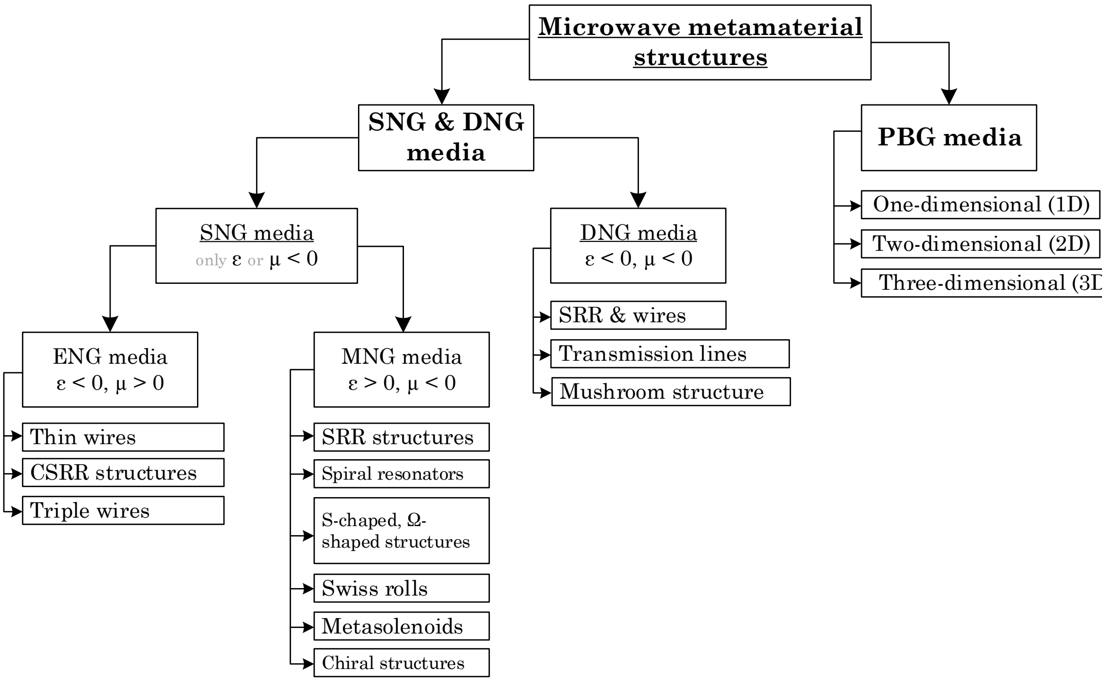


**Fig. 3** – Classification of microwave metamaterials constructions

### 3.2 Epsilon-negative Metamaterials

The first and the most-known ENG-material for microwave applications are thin metal wires. The structure consists of a square matrix of infinitely long parallel thin metal wires, embedded in a dielectric medium, it have been considered in [17]. Propagation of electromagnetic waves in such a structure is similar to propagation in plasma. Permittivity of composite material is negative at frequency $\omega < \omega_p$, where $\omega_p$ is the plasma frequency of the structure. Its value depends on the radius and placement period of wires, therefore plasma frequency of such structure is controlled. Effective permittivity can be written as

$$\varepsilon_{eff} = 1 - \frac{\omega_p^2}{\omega\left[\omega - i(\omega_p^2 a^2 \varepsilon_0)/\sigma\pi r^2\right]} \tag{3.1}$$

where $r$ is the radius of individual wire, $a$ is the period between the wires with $r << a$, $\sigma$ is electrical conductivity.

Another example of wire ENG-structures is three-dimensional structure proposed in [18]. A lattice of infinitely long connected wires forms triplet element (Fig. 4). Using effective medium approach, the attenuation and phase constants of modes that propagating in the triple wire medium have been calculated both below and above the plasma frequency. It have been discovered that the wave propagates below the plasma frequency along all the spatial directions with the same attenuation coefficient. So the triple structure is characterized by the isotropy relative to the direction of electromagnetic waves.

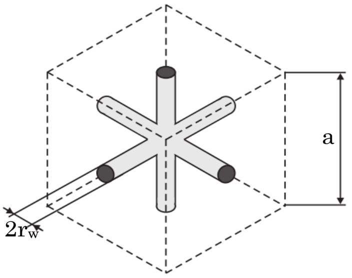


**Fig. 4** – Triple wire isotropic structure [18]

### 3.3 Mu-negative Metamaterials

The first and the most widely-used MNG-structure is split-ring resonator (SRR) [3]. SRRs can be both round and square geometrically, are characterized as high-conductive resonant structure, in which the capacitance between the two rings balances the inductance.

A time-varying magnetic field applied perpendicular to the rings surface induces currents that produce the secondary magnetic field. In dependence on the resonant properties of the structure, it can either oppose or enhance the incident field, thus resulting in positive or negative $\mu_{eff}$.

A few unit cells geometries of MNG-material based on the SRR are shown on Fig. 5.

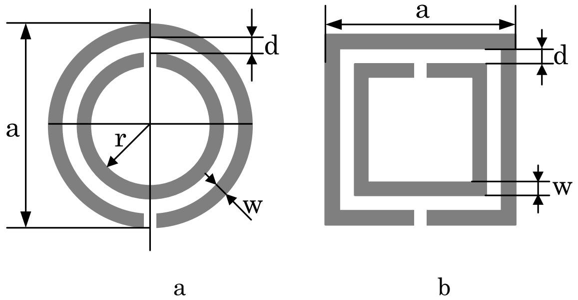


**Fig. 5** – The first MNG-material unit cells: a) round, b) square

For a circular double split ring resonator in vacuum the following approximate expression with a negligible thickness is [7]:

$$\mu_{eff} = 1 - \frac{\pi r^2 / a}{1 + \frac{2\sigma i}{\omega r \mu_0} - \frac{3d}{\pi^2 \mu_0 \omega^2 \varepsilon_0 \varepsilon r^3}} \qquad (3.2)$$

where $a$ is the unit cell length, $d$ is the interval between the rings, $r$ is the radius of the inner ring, and $\sigma$ is the electrical conductance.

Main disadvantages of the first metamaterials based on circular or rectangular SRRs are narrow frequency band where $\mu_{eff} > 0$ and high levels of electromagnetic losses. Moreover, SRR is actually anisotropic structure. If the vector of magnetic field of the incident plane wave is perpendicular to the SRR, as a result we will observe the negative permeability. However, if the magnetic field vector is parallel to the SRR, it cannot influent on the induced currents and does not affect the $\mu_{eff}$, so the first SRR is characterized as one-dimensional unit cell [1]. In order to overcome such anisotropy a few ways have been presented [19-23]. The simplest method is to placing the same planar SRRs in three orthogonal space directions and thus forming a group matrix of unit cells and achieving an anisotropy [20].

Alternative topologies of the structure have been proposed as well. Unit cell variations of the rectangular SRR are shown in Fig. 6. In whole, electrophysical properties of various modifications of microwave SRR are sufficiently studied [20-27]. Numerical study performed using the finite integration technique (FIT) and transfer matrix method (TMM) on the Microwave Studio software has shown that the most promising and potentially successful structures for microwave technique are SRRs from the second row on Fig. 6 [23]. It have been determined that more symmetrical structure (for instance, on Fig. 6, c) than the original (Fig. 6, b) allows to distribute the capacity in the rings equivalently between the two gaps. It reduces the cross-polarization effects that lead to electromagnetic losses in the overall system. The summarizing of theoretical and experimental studies of ring resonators is the broadside-coupled SRR (Fig. 6, h), which is constituted of two identical rectangular or round microresonators located on both sides of the dielectric substrate with the gaps on opposite sides. Such approach to forming unit cells leads to the isotropy of obtained composite structure as well reduces its electrical size in the resulting DNG-material at the operating frequency. Consequently, the further material description as a homogeneous media is simplified and thus makes its using in practical microwave applications more convenient.

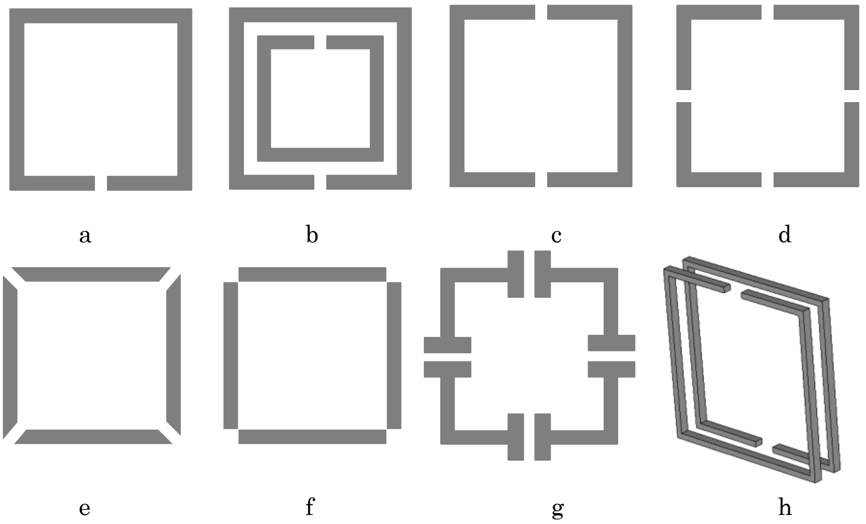
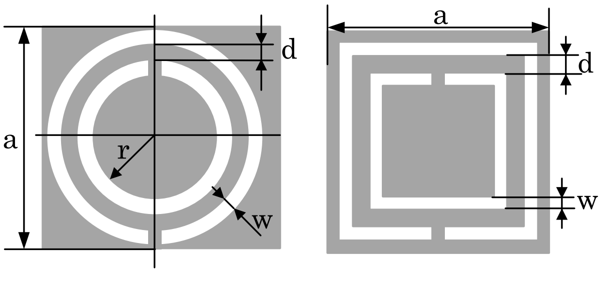


**Fig. 6** – The basic modifications of rectangular SRRs

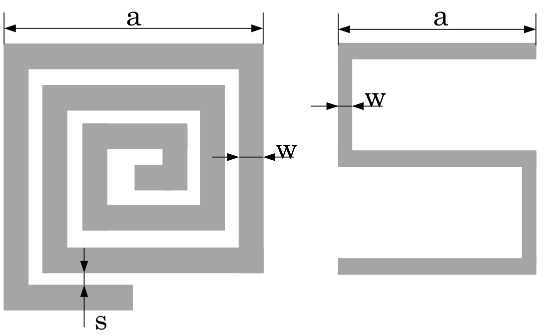
With applying the Babinet principle to convenient SRRs the complementary structures (Fig. 7) abbreviated CSRRs were engineered and manufactured [28]. CSRR unit cells are the holes of corresponding form in the metal surface. Such a structures belong to the ENG-materials and negative $\varepsilon_{eff}$ is obtained in a narrow frequency range near the resonance.



a b

**Fig. 7** – Unit cells of ENG-material based on complementary split ring resonators: a) round, b) square. Grey – thin metal surface

According to the classification scheme (Fig. 2) the MNG-structures class includes helical structures [29-30] and S-shaped [31] resonators as well (Fig. 8). They have been also constructed in order to improve the characteristics of original split ring resonators. The main advantages of its unit cells compared to SRRs is compactness, easy manufacture with obtaining the homogeneous DNG-material with the same resonant frequency.

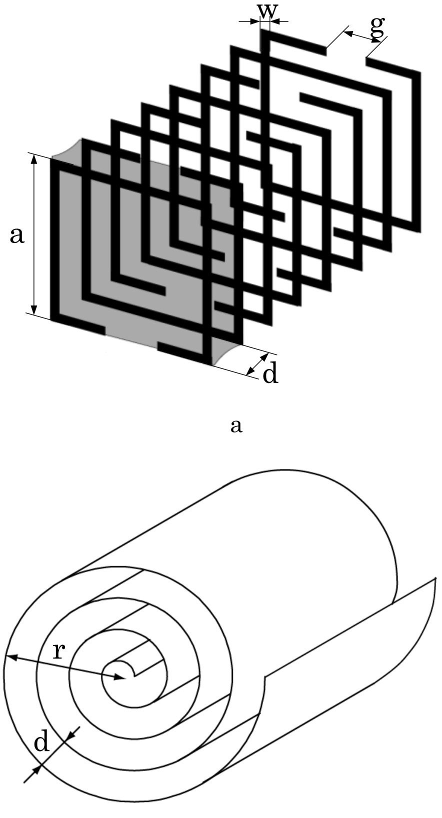


a b

**Fig. 8** – Unit cells of alternative MNG-structures: a) spiral resonator, b) S-shaped resonator

Generally, the anisotropy of metamaterial structures is undesirable effect. Nevertheless, in the paper [32] bianisotropic Ω-shaped mu-negative structured have been presented and its potential applicability in microwave technique have been thoroughly considered. The properties of metamaterials composed of Ω-structures are appreciably different in comparison with the conventional SRR metamaterials. The resonance frequency, according to [32], directly depends on an electric field orientation on the structure plane. Omega-structures are claimed as the most suitable for applications where interaction with linearly polarized plane waves with storing the maximum of energy is used, such as antennas, absorbing devices and lenses [33]. With partial changing the geometrical parameters of Ω-structure one can directly control the resonance frequency and thus optimize electromagnetic characteristics of the overall system, i.e. corresponding unit cells have additional degrees of freedom.

Rolling MNG-structures, termed as Swiss rolls, and metasolenoids are similar to each other in unit cell construction and operation principles. However, they are designed in order to operate at different frequency ranges. A detailed comparative description of such structures is presented in [34]. The schematic representations of the corresponding unit cells are shown on Fig. 9.



a

b

**Fig. 9** – Metasolenoid [34] (a) and Swiss roll structure (b) [6]

Swiss rolls is manufactured practically as metal-dielectric layer material that is wounded in form of spiral onto a dielectric rod. For array of such unit cells an effective permeability is equal:

$$\mu_{eff} = 1 - \frac{\pi r^2 / a}{\left(1 - \frac{dc_0^2}{2\pi^2 \varepsilon r^3 (N-1)\omega^2}\right) + i\frac{2\rho}{\omega r \mu_0 (n-1)}} \qquad (3.3)$$

where $N$ is the number of spiral turns, $r$ is the diameter of each roll, $\varepsilon$ is the permittivity of dielectric rod and $\rho$ is the conductor resistivity.

A number of conductor layers affects the self-inductance of such rolls while thickness and rod permittivity affects the self-capacitance. The Swiss rolls are entirely suitable for low frequency applications. In particular, they are widely used in magnetic resonance imaging [2], where the operating frequency has values to about 100 MHz.

Metasolenoids is proven as MNG-structures with noticeably high magnetic activity at microwave regime. The unit cell of metasolenoid can be characterized as a set of discrete cuts of the Swiss roll structure. An array of single SRRs with one gap are located with a small period along the axis of electromagnetic waves propagation. The bandwidth of metasolenoid isn't widen as compared with SRR-structures. Nevertheless, high values of $\mu_{eff}$ over a wider range of frequencies far away from the resonance was obtained [34].

The MNG-structures, as seen from Fig. 2, also include complicated isotropic or anisotropic chiral structures of various configurations: G-shaped and U-shaped structures, asymmetric rings etc. [35-38]. They are characterized by significant optical activity, i.e. the ability to rotate the polarization plane of linearly polarized electromagnetic wave. The circular dichroism is also discovered. It means that there is a significant difference between the absorption coefficients for the left- and right-polarized waves in such materials. A procedure for accurate placing chiral structures, such as asymmetric rings, into the base substrate in order to obtain a negative index of refraction have been studied and prescribed. The chiral structures are widely used in the technique of infrared and submillimeter wavelengths, as well as optical devices.

### 3.4 PBG-metamaterials

Before turning to the main principles of designing DNG-materials we shortly consider a separate class of composite structures, characterized by the presence of so-called forbidden frequency gaps [39-41]. Photonic crystals or photonic bandgap materials (PBG) are artificially fabricated structures that can control the propagation of electromagnetic waves. Properly designed photonic crystals are able to prohibit the electromagnetic waves propagation (including light waves), or allow waves to propagate only along defined directions. They can also localize an electromagnetic energy in certain areas.

The ability to control electromagnetic radiation arising from photonic band structure, which concept is similar to the electronic band structure in semiconductors [1]. The latter have permitted and forbidden bands for energies of charge carriers and in turn, photonic crystals have similar bands for photon energies at different frequencies [41]. In other words, the permittivity of the photonic crystal varies periodically in space with a period that allows Bragg diffraction of light [42]. Electromagnetic field concentrates in the structure inhomogeneity, defined as photonic crystal defects.

An advantage of the photonic crystals is that the periodicity of permittivity changing can be changed at will, hence choosing the frequency range of the PBG-material. Photonic crystals are constructed of dielectric and/or metallic materials and can be one-dimensional, two-dimensional and three-dimensional depending on the number of spatial directions in which a change of the refractive index can be realized. Properties of photonic crystals' defects are widely used in microresonators and waveguides based on PBG-structures. The prevalent applications in microwave technology also include photonic integrated circuits, microwave filters with high selectivity, GPS-antennas etc. [1].

### 3.5 DNG-metamaterials

We divided the most prevalent approaches to design metamaterials with negative refractive index into three main classes:

- Thin wires & SRR
- Transmission lines
- Mushroom structure

The pioneer structure, already mentioned in the part 2 of present paper, is the combination of split ring resonators and thin metal wires. It have been proposed in [14] and schematic is represented on Fig. 10.

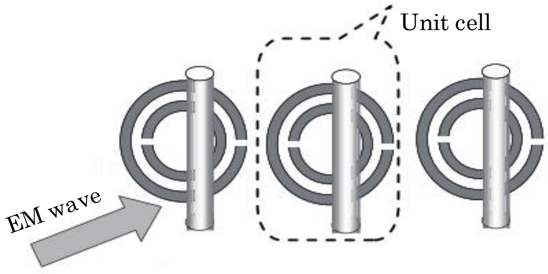


**Fig. 10** – The array of unit cells for ring & wire structure

Negative values of effective permittivity and permeability of corresponding composite structure have been confirmed by experiments in the waveguide chamber [43]. Fundamental properties of structure also have been tested by numerical simulations [44]. Because of resonance properties of the unit cell, an anomalous electromagnetic radiation and thus negative index of refraction have been observed in a very narrow frequency range, which restricts the applicability of such structures. One can partially expand the frequency range by using other planar MNG-structures in place of SRRs, such as improved modification of split rings (Fig. 6), S-shaped and spiral resonators and metasolenoids for several application.

An alternative approach to forming DNG-metamaterial is transmission line structures [45-46] that are extensively used in microwave technique. In contrast to thin ring and SRRs structure, transmission lines are non-resonant and mostly planar. The most convenient approach to describe unit cells and total systems based on metamaterial transmission lines is the method of equivalent circuits [47]. It is based on represent metamaterial structures coupled to planar transmission lines of different types by lumped-element circuit models. As well, it allows determining the main circuit parameters for these models.

As known from transmission line theory, the voltage and the current in transmission line and its components are in agreement with components of the electromagnetic field. For isotropic homogeneous medium the impedance and admittance can be written as

$$Z = i\omega\mu \tag{3.4}$$

$$Y = i\omega\varepsilon \tag{3.5}$$

Whereas those variables for left-handed transmission line are defined as

$$Z' = 1/j\omega C \tag{3.6}$$

$$Y' = 1/j\omega L \tag{3.7}$$

So, such transmission line is similar to the dual distributed network with a sequence of parallel capacitors and inductance. Actually, it can be characterized as high pass filter that supports the propagation of backward waves. A unit cell of transmission line DNG-material with parasitic series inductance and shunt capacitance is shown on Fig. 11.

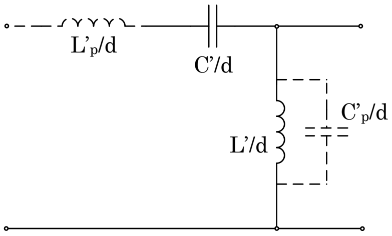


**Fig. 11** – An equivalent circuit for the transmission line unit cell. L'$_p$ and C'$_p$ are accordingly parasitic inductance and capacitance

A wave propagation through the metamaterial transmission line is described by the telegrapher's equation [45]. DNG-properties of obtained composite structure are observed at frequencies below the cutoff frequency. In turn, structure behaves like a conventional material above the cutoff frequency, hence it have been defined as CRLH-structure – composite right/left-handed structure [48]. Planar metamaterial transmission lines are typically implemented as combination of SRRs and complementary structures coupled by microstrip technology or by embedding it to the structure of planar waveguide. In order to obtaining larger bandwidths and lower losses, the lumped circuit elements can be added in unit cells.

The third mushroom structure (Fig. 12) termed in such manner because of unit cells' shape, which resemble a mushroom caps and stems. It is similar to previous structure and relates to the CRLH-structures as well.

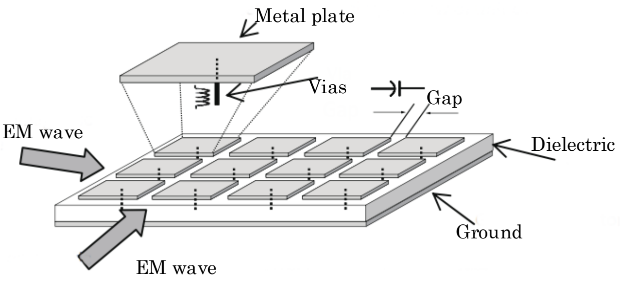


**Fig. 12** – Mushroom metamaterial structure [49]

In order to form the metamaterial unit cells a metal patches are periodically arranged in a matrix over the lower conductive layer. The gaps between the patches form capacitances and the vias form inductances. Mushroom structure has properties of both right and left-handed material depending on frequency as the previous one; hence it is a CRLH-structure as well. Such a structure has features, which are suitable for low-and-high-pass filter implementation for frequency range around those in which the structure has left-handed properties [49]. Different types of MNG-materials can be used as metal cells in mushroom structure: SRRs and derived configurations, Ω-shaped and chiral structures. The successful example is mushroom metal-dielectric structure with PIN diodes placed along the direction of the vias proposed in [50]. Such structure with multi-diode switch allow minimizing the undesired transmission for a certain incident angle. The mushroom structure with diodes can be applied in dual-band subwavelength imaging where the operation frequency can be controlled by changing the states of diodes. Electrodynamic characteristics of planar variants of metal-dielectric structures operating in millimeter and submillimeter wavelength ranges can be experimentally measured by methods described in [51].

## 4. METAMATERIALS IN MICROWAVE TECHNIQUE

Peculiar electrophysical properties of composite artificial structures lead to successful utilization in microwave technique. Most of metamaterials, such as single negative, double negative, epsilon-near-zero structures and DPS-DNG combinations, are actively implemented in waveguides, resonators, power dividers, absorbers, filters, couplers, isolators, antennas and their constructive elements. One can design a multiband waveguide arrays and systems based on metamaterials, microwave component with improved bandwidth, distributed amplifiers, zero-order resonators, advanced microwave filters etc. In this part of paper we will briefly summarize some trends of applications.

### 4.1 Waveguides and Derived Devices

Media combined in pairs with different signs of effective $\varepsilon$ and $\mu$ have found a special place in design devices with improved characteristic. Discovered that the unconventional electromagnetic properties of metamaterial are observed when one material are paired with other material with at least one oppositely signed effective material constant [1]. For example, DNG and DPS-materials can be combined or left-handed media formed of ENG and MNG-material can be paired with a conventional DPS-material.

The general geometry of parallel-plate waveguide formed of such structures is showed on Fig. 13. The peculiar electromagnetic properties of such bilayer structures are caused by behavior of surface electromagnetic waves at the junction between two paired materials with corresponding material parameters ($\varepsilon_1$, $\mu_1$) and ($\varepsilon_2$, $\mu_2$). The interaction with the external field lead to so-called interface resonance along the junction and the characteristics of such resonance is not depend on the thickness of each material layer $d_1$ and $d_2$. Due to interface resonance the compensation of amplitude of the damped wave in the first plate is performed by increasing the amplitude in the second plate.

It have been shown in [52] that the correct selection the parameters of paired structures and its placing opens up new opportunities for creating waveguides with no cutoff mode.

There is a correlation between the lateral dimensions and support propagation the modes of certain types in conventional waveguide designs. A waveguide constructed with DPS-DNG pairs can support the dominant mode if the value of $d_1/d_2$ is approximately equal to $\mu_2/\mu_1$. It opens possibilities to engineer the waveguides and cavities with extremely reduced lateral dimension i.e. subwavelength waveguides and cavity resonators.

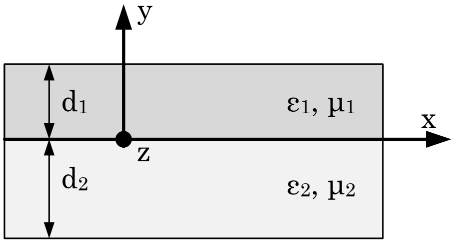


**Fig. 13** – Schematic representation of parallel-plate waveguide formed of pairs of DPS-DNG or ENG-MNG materials [1]

A rectangular waveguide filled with DNG-metamaterial or formed of paired structure can behave as coaxial and support the TEM-waves propagation. The waveguides based on metamaterials with propagation of fast and slow waves, forward, evanescent and backward waves and those configurations that support a greater range of propagation constants have been designed. The concept of the paired metamaterial structures has been theoretically considered and confirmed by experiments for the case of closed plane-parallel, rectangular and cylindrical waveguides [1].

A similar trend have been observed for the case of open waveguides (Fig. 14). If the thickness of conventional slab dielectric waveguide is much smaller than the operating wavelength, much of an energy of transverse component of the electromagnetic field spreads in the space around the slab. While in the open waveguide designed with DNG-slab the dominant mode can propagate along the surface regardless of the slab thickness.

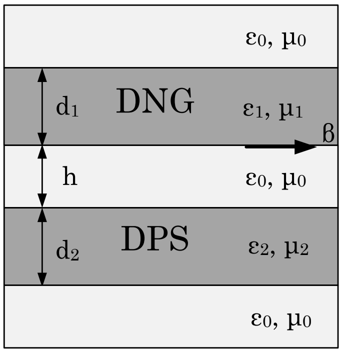


**Fig. 14** – Geometry of the open slab waveguide with DPS and DNG materials

A reducing the thickness of DNG-slab confined the order of the odd propagating mode, thus ultrathin open waveguides for optical applications with overcoming the standard diffraction limit can be designed [53].

The phenomenon of phase compensation as characteristic of CRLH-structures is complete or partial removal of the phase shift of electromagnetic wave passing through an appropriate structure. It have been used for design transmission lines with controlled phase. By replacing conventional transmission lines in couplers by CRLH-structures a dual-band branch coupler have been manufactured [54]. By setting the dc offset of the CRLH-transmission line in such the coupler, the design frequency and the dual frequency can be directly controlled. In turn, directional couplers based on transmission line metamaterials (Fig. 15) considered in [55] demonstrate improved coupling and extended operating frequency range with simultaneous greater compactness compared with conventional ones.

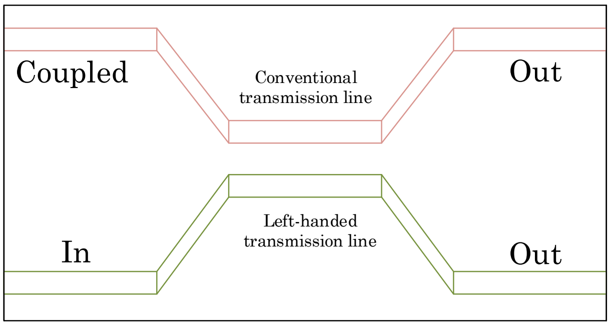


**Fig. 15** – Schematic of directional microstrip coupler on metamaterials

A wideband phase shifters based on CRLH-lines have been presented. They demonstrate a small error of phase shift due to switching segments of transmission line from right ones to left. Compact low-and-high-pass filters with low losses, particularly microstrip implementation coupled with CRLH-lines placed under the strip on the backside of the metallized substrate, also have been manufactured [2]. Electromagnetic energy of the wave that passed through the filter at resonance, concentrates in CRLH-line, which leads to attenuation in the microstrip line. Thus rejection band is forming within the resonant characteristic of CRLH-line. The required bandwidth obtained by applying unit cells with slightly different sizes and therefore different resonant frequencies. Desired rejection bands are achieved with maintaining low electromagnetic losses outside the band. Coplanar waveguides with periodic thin wire & SRR inclusions can be applied as well [56].

Epsilon-near-zero (ENZ) materials are proved to show such effects as tunneling of electromagnetic waves and “squeezing” in the channel with subwavelength lateral dimensions [57-59]. The waves characteristics are independent on channel geometry. Practically such metamaterials can be applied in transitional waveguide channels. They provide almost perfect coupling between separate waveguide lines with proportional phase distribution while having compactness and possibility to choose a desired geometry.

### 4.2 Metamaterial Absorbers

A particular branch of applications is electromagnetic absorbers for microwave and terahertz bands. As usual, they constitute of metamaterial layer and a metal slab separated by dielectric [60-62]. SRR and their modifications, such as S-shaped and spiral resonators, are widely used as metamaterial parts of microwave absorbers. The main advantages of such absorbers are compactness and easy manufacturing with polarization independence at the broad frequency band. High absorption coefficient for wide angles of incidence and possibility of dynamical tuning have been obtained. The main aim of such studies is to design i.e. perfect metamaterial absorbers, which provide absorption coefficient equal unity in a wide range of frequencies.

Devices that can absorb electromagnetic energy at certain points and transfer it into heat have been developed as well. Such a property can be applied in high-selective thermal emitters. Absorbers with the possibility of tuning operating frequency can be used as spectrally sensitive detectors or sensors, particularly in microbolometers and pyroelectric detectors [63]. Microwave metamaterial absorbers are used in order to reduce the radar cross-section (RCS) of conducting object in military applications.

### 4.3 Antennas and Elements

The most prevalent antennas applications include metamaterial substrates for miniaturized printed antennas and improved electrically small antennas, leaky-wave antennas and complicated implementations such as antenna cloaking due to corresponding artificial structures [64].

One of the most successful approach for improving electrically small antenna is covering the monopole radiator by metamaterial which matched in impedance with surrounding space (Fig. 16). Antennas with improved efficiency and greatly increased radiating power in comparison with conventional implementations have been considered in [65].

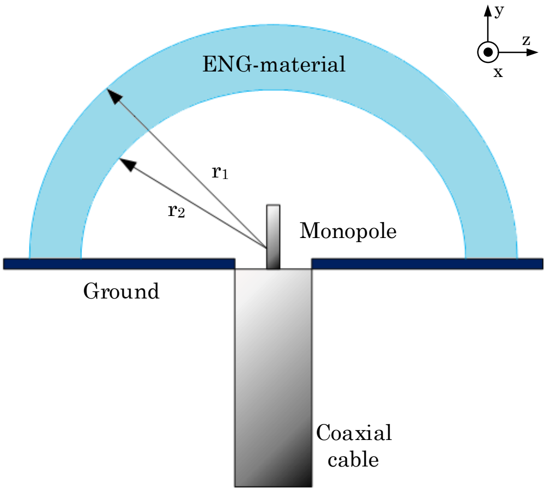


**Fig. 16** – A design of electrically small antenna with metamaterial: schematic representation

High-efficient radiators with quality factor greater than fundamental limit related to physical size of antenna have been designed. In order to compensate reactive power ENG-materials with high self-inductance are applied and Fig. 17 illustrates such principle of compensation. In addition, the thickness of metamaterial layer can be less than hundredth part of operating wavelength therefore noticeable attenuation in such system is prevented.

Using DNG-materials makes possible to improve the design due to further reducing the physical size and compensation the radiated power.

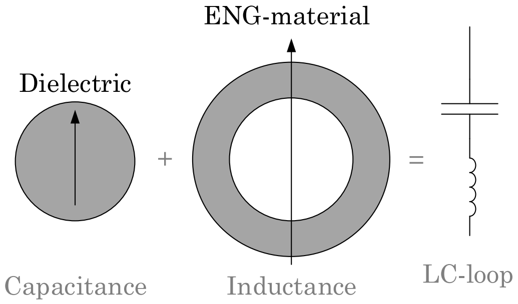


**Fig. 17** – Compensation the reactive power of electrically small antenna with ENG-material

Applying metamaterial structures in substrates for printed miniaturized antennas allow reducing sizes of conventional radiators, enhance the antenna bandwidth and improve the radiation efficiency. The substrate structure is homogeneous as usual and is made of SRRs, chiral rings or metasolenoids [66] or has several types in one structure. Metamaterials are directly applied in structure of printed radiators as well. In particular, antenna arrays based on CRLH-structures are manufactured. Noticeably reduced electrical sizes and suppressed interference of adjacent radiators are obtained. Due to correct selection of geometrical sizes of left- and right components of composite structure one can control the resonance frequency of antenna and even make it dual-band with simultaneous using the modes $TM_{010}$ and $TM_{020}$ [67].

Metamaterial transmission lines or mushroom structures are successfully applied in more complicated antennas, for instance in horn antennas. In particular, coating the horn surface by DNG-material allows shortening the horn length, improving the horn matching, increase the efficiency and reducing the parasitic cross-polarization radiation angle. However, it narrows the antenna bandwidth; therefore the optimization methods concerned with improving metamaterial structures are on study. In order to simplify the feed of leaky-wave antenna, increase its scanning angle and reduce the reactance without efficiency losses CRLH-metamaterials have been introduced as well. In general, applying metamaterials in antenna technology is promising branch with a plenty of proposed and implemented applications.

## CONCLUSIONS

There are number of articles and monographs related to metamaterial physics, designs and applications in order to conclude the present state have been reviewed. The main principles of formation artificial structures that arise from general materials classification are considered. The concept of homogeneous composite media with controlled effective permittivity and permeability and summarized peculiar electrophysical effects appearing in such media is explained. We thoroughly analyzed well-known metamaterials designs and made a detailed classification scheme. The structures, which are widely used for millimeter and submillimeter band applications are highlighted. We examined the construction, the principle of operation, applications and advantages/disadvantages of such structures. Finally, a compact overview of implement metamaterials in waveguide technique, absorbers and antennas applications are presented.

It should be noted that scaling metamaterials to infrared and optical frequencies are relevant branch of up-to-date researches. However, the question of further improvement microwave-band technique, such as waveguides and resonators, in order to achieve compactness, cheapness and easy manufacturing with upgrading electrophysical parameters is under study for today.

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