České vysoké učení technické v Praze, Fakulta elektrotechnická

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Recent Progress in Metamaterials

Současný vývoj v metamateriálech

SUMMARY

The permittivity, permeability and conductivity of a material characterize its ability to interact with an electromagnetic field. In nature, the magnitudes of these three quantities are restricted mostly to positive values. In contrast, metamaterials are artificially produced composite media exhibiting electromagnetic responses that natural materials do not provide. They enable the three constitutive parameters to be cast down to negative values. Nowadays, electromagnetic metamaterials is a rapidly growing research domain involving electromagnetism, microwave and millimeter wave technology, optics, material technology, nanotechnology and quantum physics. There are prospects for many challenging practical applications. A historical survey of the evolution of metamaterials from the earliest assumptions until the current state of the art introduces a discussion of metamaterials, and a description of their characteristics and behavior.

Metamaterials are known in two forms. An inherent metamaterial is a real 3D solid volumetric medium. 1D or 2D planar circuits are the second version of metamaterials. The first form is characterized by field theory, while the second form utilizes transmission line theory.

Manifold applications of guided waves, radiated waves, new microwave circuits, devices and structures will be discussed from the engineering point of view. There is a brief report on the authors' own innovative findings. This involves both theoretical and experimental results that have been achieved in recent years. In particular, we have used split ring resonators in negative permeability metamaterials, and have developed and produced an isotropic negative permeability medium, an isotropic negative permittivity medium, CPW supporting propagation of a left-handed wave, and wire media exhibiting negative permittivity. The main aim was to build a real 3D isotropic metamaterial. Two kinds of 3D isotropic single negative metamaterials are reported. The first material consists of unit cells in the form of a cube bearing on its faces six equal planar resonators with tetrahedral symmetry. In the second material, the planar resonators boxed into spherical plastic shells and randomly distributed in a hosting material compose a real 3D volumetric metamaterial with an isotropic response. In both cases the metamaterial shows negative permittivity or permeability, according to the type of resonators that are used. The experiments prove the isotropic behavior of the cells and of the metamaterial specimens. Finally, the prospects for further developments in this interesting field are presented.

SOUHRN

Schopnost materiálů reagovat na elektromagnetické pole je charakterizována jejich permitivitou, permeabilitou a vodivostí. V přírodních materiálech jsou tyto veličiny ve většině případech kladné. Na rozdíl od toho, jsou metamateriály uměle připravené kompozitní materiály, které vykazují odezvy, jaké nejsou přírodní materiály schopny. Uvedené parametry mohou u nich dosahovat záporných hodnot. V současné době představují metamateriály rychle se rozvíjející multidisciplinární oblast výzkumu zahrnující elektromagnetismus, mikrovlnnou technologii, technologii milimetrových vln, optiku, materiálové inženýrstí, nanotechnologie a kvantovou fyziku. Výhledově existuje celá řada jejich velmi zajímavých aplikací. Práce shrnuje historii vývoje a současný stav, jsou stručně charakterizovány vlastnosti metamateriálů.

Jsou známy dvě varianty metamateriálů. Vlastním metamateriálem je objemové médium, které je charakterizováno vlnovou teorií. Druhá verze je reprezentována jedno nebo dvourozměrnými planárními obvody, které se charakterizují pomocí postupů známých z teorie vedení.

Jsou diskutovány jednotlivé aplikace pro vedené vlny, vyzařující vlny (antény), nové mikrovlnné obvody a prvky. Je stručně uveden původní přínos autora k této problematice, jak v teoretické, tak i experimentální oblasti. Zejména je uvedeno použití dělených kruhových rezonátorů pro metamateriály se zápornou permeabilitou. Bylo navrženo a zhotoveno isotropní médium se zápornou permitivitou. Dále je zmíněno koplanární vedení podporující přenos zpětné vlny, drátové prostředí vykazující zápornou permitivitu a isotropní odezvu. Základním cílem bylo vytvořit reálný třírozměrný objemový metamateriál s isotropní odezvou. Jsou prezentovány dvě varianty objemových isotropních metamateriálů s jedním záporným parametrem (permitivitou, nebo permeabilitou). První z nich je tvořen periodickým uspořádáním základních buněk ve formě krychliček. Tyto mají na svých šesti stěnách umístěno šest planárních rezonátorů splňujících vhodnou symetrii. Ve druhé variantě jsou tyto planární rezonátory umístěny v kulových schránkách z umělé hmoty, keré jsou náhodně umístěny v prostoru a vytvářejí tak reálný objemový metamateriál s isotropní odezvou. V obou případech metamateriál vykazuje zápornou permitivitu nebo permeabilitu podle typu použitých rezonátorů. Experimentálně bylo ověřeno isotropní chování vytvořených vzorků metamateriálů. Závěrem jsou stručně ukázány směry vývoje této zajímavé oblasti.

Klíčová slova:

Koplanární vedení, disperzní charakteristika, elektrický dipól, isotropní chování, metamatriál, polarizovatelnost, dělený kruhový rezonátor, přenosová charakteristika, teorie přenosových vedení, drátové prostředí.

Key words:

Coplanar waveguide, dispersion characteristic, electric dipole, isotropic response, metamaterial, polarizability, split ring resonator, transmission characteristic, transmission line theory, wire medium.

 ISBN

CONTENTS

1. INTRODUCTION

Metamaterials belong to the group of artificial media that have become one of the most important topics in classical electromagnetic theory in the last two decades. In fact, pioneering work on artificial media goes back much further. The first attempt to produce an artificial medium was carried out by Winston E. Kock in 1946 [1]. Kock suggested a dielectric antenna lens with a dielectric made of a mixture of metal spheres embedded in a matrix. In 1962, Rotman [2] showed artificial 1D electric plasma using a parallel plate medium that embodies the frequency band with negative permittivity, simulating the properties of natural ionospheric plasma. Six years later, Veselago [3] published his paper on the electrodynamics of media with simultaneously negative permittivity and permeability. This entirely theoretical paper included predictions of strange electromagnetic effects in such media, e.g., anomalous refraction, inverted Cherenkov radiation and Doppler shift, see [4] for more details. It was demonstrated that if both permittivity and permeability are negative, vectors **E**, **H**, **k** form a left-handed (LH) system as opposed to the system in ordinary natural materials. That is how the name for LH media was established. In Veselago's times no practical realization of such a medium was known. Negative permittivity could be achieved with electric plasma, however negative permeability was missing. In contrast to electrical plasma, there are no magnetic monopoles in classic electrodynamics and thus natural magnetic plasma is not achievable. After the work of Veselago was published, the issue of LH media was almost forgotten for nearly 30 years. The main reason was the unachievability of such media. The return of artificial media theory came in 1992, when Mamdouh *et al.* [5] proposed an omega particle as a unit cell of an artificial chiral medium. Unfortunately, the authors did not realize that such a medium can also embody negative permittivity and permeability. In those years, interest in Veselago's work began to rise, mainly in the papers written by J. B. Pendry *et al.* Pendry's first paper [6] showed how to make a negative permittivity medium at microwave frequencies. For this purpose, the authors proposed a "wire medium", a 2D matrix of thin wires which simulates the plasmon behavior of metals at optical frequencies. In [7], Pendry's working group extended this idea to a 3D wire net, by which isotropic behavior was achieved. Negative permeability was however still unknown. It was first presented in [8] in 1999. This paper, probably the most important publication in metamaterials, was a proposal for a small resonant particle, a split ring resonator (SRR), the basic constituent of artificial negative permeability media.

After this seminal work, Smith *et al.* [9] manufactured an artificial medium by superposing SRRs (negative permeability) and metallic wires (negative permittivity). This was the first implementation of an LH medium. Subsequently, Shelby *et al.* [10] experimentally demonstrated negative refraction, previously predicted by Veselago.

In 2000, the first application of an LH medium was presented in Pendry's paper on a perfect lens [11]. This paper gave a detailed analysis of the wave refraction on the boundary between an ordinary medium and an LH medium. Afterwards it was shown that in order to map point to point, thus to focus, it is enough to use a slab of LH medium with permittivity and permeability equal to minus one. In such a situation, the incident wave is ideally transmitted and the system is able to focus even without a curved boundary, as in an ordinary lens. The possibility of avoiding a curved lens surface was interesting in itself, but Pendry also showed that unlike an ordinary lens, this new slab-lens is able to amplify evanescent waves of the source in such a way that their amplitude is recovered in the place of the image in the same magnitude as it is in the source plane. This fact opened up the possibility of focusing by a lens with arbitrarily fine resolution (the resolution of an ordinary lens is limited to one half of the operating wavelength).

This work presents metamaterials of two different types. The first is denoted as a volumetric metamaterial. It consists of basic elements, much smaller than the operating wavelength, which are assembled randomly or periodically in the host medium, forming a bulk artificial material with given effective material parameters.

The second type of metamaterials, called planar, is represented by 1D or 2D transmission lines (TL) operating with backward waves. These have been known for more than 60 years, and were described by Brillouin [12] and by Pierce [13] utilizing the equivalent circuit model shown in Fig. 3c dual to the model of a standard TL. Applying this concept, the first practically applicable LHTLs were introduced by Caloz *et al.* [14] in a 1D version and in a 2D version in [15], simultaneously with Eleftheriades *et al.* [16, 17] and Oliner [18]. In all cases these TLs are based on a line periodically cut by series capacitors and shortened by parallel inductors. The main advantage is the planar structure of the LHTLs, which makes them compatible with microwave integrated circuits. Their behavior can be easily controlled by *L, C* parameters. A number of novel devices have already been proposed based on the LHTL concept [4]. Most of these circuits utilize the LHTL in the form of the composite right/left-handed (CRLH) TL first introduced by Caloz and Itoh [19].

The resonant elements composing a volumetric metamaterial themselves are anisotropic. Consequently, the medium composed by them is generally also anisotropic. However, there are several ways leading to isotropy of a 3D metamaterial. A specific form of the unit cell satisfying symmetry of the selected crystallographic group [20], and its periodical arrangement in space were utilized in [20-23]. Another way leading to isotropy is based on randomly located unit cells in the volume of the host [24]. A double-negative isotropic medium, i.e., a medium with both negative permittivity and permeability, can be designed as a 3D structure consisting of a set of dielectric spheres of high permittivity, having two different radii located periodically [25-27] or randomly [28] in a hosting material. A single sphere can be used, but has to consist of a core and a casing of different materials [29]. Dielectric spheres of one kind can be used for building an isotropic double-negative metamaterial using mutual coupling between them, or they are placed in an epsilon-negative medium [30]. An isotropic epsilon-negative metamaterial was achieved by a 3D triple wire medium consisting of connected wires just below the plasma frequency, as presented in [31]. An isotropic metamaterial was designed using a circuit approach as a rotated transmission line matrix scheme [32,33].

Our objective is to design and fabricate a 2D or 3D volumetric single-negative metamaterial using inexpensive, easily-accessible technology. We have adopted the concept of a cubic unit cell consisting of six planar resonant elements on its faces, or alternatively the concept of single resonant elements randomly placed in a hosting material. This involves designing the structure of the resonant element, analyzing its responses to the excitation by an electromagnetic wave, fabricating the medium and measuring its electrical parameters. A unit cell of this medium is isotropic if its polarizability tensor is invariant to any rotation. This fact, expressed in terms of the scattering parameters, means that the transmission of such a unit cell does not depend on the angle at which the illuminating wave is incident on the cell. Using this method, we evaluate the degree of isotropy of the final products of both concepts mentioned above. We investigate a magnetic single-negative metamaterial and an electric single-negative metamaterial in parallel, but separately. These new composites may then be combined, resulting in a left-handed, i.e., a double-negative isotropic medium. Our results offer a real medium for designers of microwave devices and systems. It is only necessary to recalculate the proportions of the resonant element and unit cell by scaling in order to meet the specific requirements for each application. Technological limitations must, however, be taken into account here.

The planar resonators were designed by the CST Microwave Studio, then fabricated and measured. The effective permittivity and permeability were calculated according to [19], though it is senseless to define these quantities for a single resonant element. Our code therefore provides the effective parameters of the volume between the ports where the resonant element is located, so that they serve as some measure of the electric and magnetic polarizability of the element.

The two kinds of metamaterials will now be presented, first theoretically and then through particular implementations carried out by the author together with the team of his coworkers.

1.1 Volumetric Metamaterial

Let us now see how we can modify the material parameters, i.e., the permittivity and permeability, of a volumetric medium. Let us assume a space filled by a medium subdivided by a rectangular mesh into particular cells in the shape of a prism with dimensions *dx*, *dy*, *dz*, as shown in Fig. 1. An artificial particle as an inclusion is located in the middle of each cell. The dimensions of the cell must be considerably smaller than the wavelength, in order for the medium to be treated as continuous. There are two basic kinds of particles, electric dipoles and current loops, or the magnetic dipoles shown in Fig. 2. Let us assume that these two particles are loaded by impedance Z_L. The electric dipole is sensitive to the electric field **E** parallel to the strips, and the current loop is sensitive to the magnetic field **H** perpendicular to the plane of the loop. We will first calculate the electric moment of the dipole and the magnetic moment of the loop. These quantities define the vector of polarization and magnetization, respectively, and subsequently the effective permittivity and permeability of our medium can be determined. For simplicity we do not assume bi-anisotropic particles, where both their electric and magnetic moments depend on both electric and magnetic fields. Moreover we assume that particles of one kind do not interact.

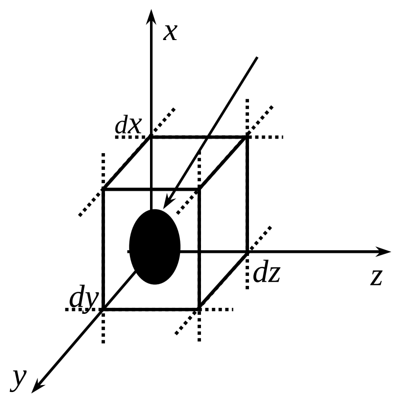
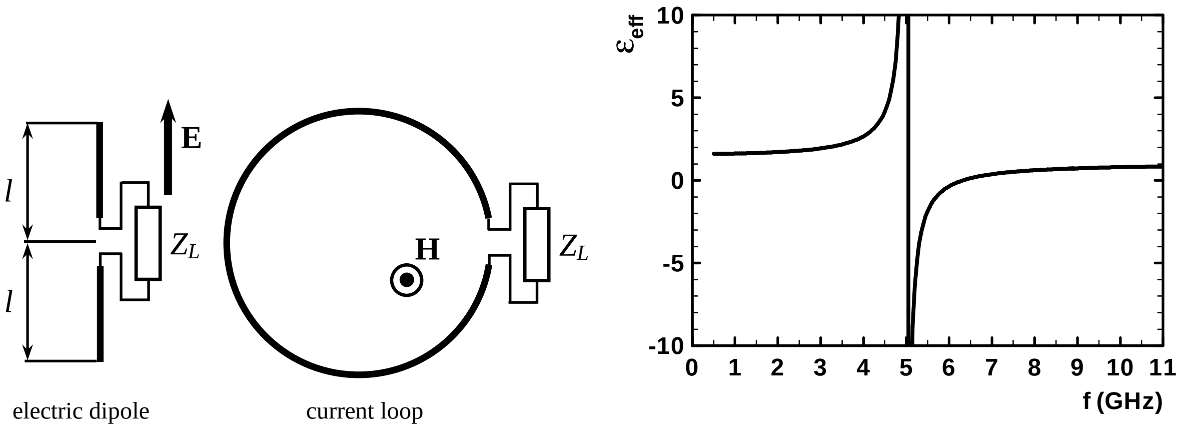


Fig. 1. Elementary cell with an inclusion.



(a) **(b)** **(c)**

Fig. 2. Sketch of an electric dipole (a), a current loop (b), and the dependence of the effective permittivity of the electric dipole loaded by a loop inductor on frequency (c).

Assuming an electric current I passing the arms of the electric dipole, we can express its moment as

$$p = \frac{I\, l_{eff}}{j\omega} = \frac{U\, l_{eff}}{j\omega(Z_e + Z_L)} = \frac{E\, l_{eff}^2}{j\omega(Z_e + Z_L)}\ , \tag{1}$$

where l_{eff} is the effective length of the dipole, Z_e is the dipole input impedance, U is the voltage received by the dipole and E is the incident electric field oriented according to Fig. 2. The magnitude of the polarization vector is

$$P = \frac{p}{V} = \frac{1}{dxdydz}\,\frac{E\, l_{eff}^2}{j\omega(Z_e + Z_L)} = \chi_e E\,, \tag{2}$$

where $V = dxdydz$ is the cell volume and χ_e is the electric susceptibility which defines the permittivity of the medium. The relative effective permittivity is

$$\varepsilon_{eff} = 1 + \frac{\chi_e}{\varepsilon_0} = 1 + \frac{1}{dxdydz}\,\frac{l_{eff}^2}{j\omega\varepsilon_0(Z_e + Z_L)}\ . \tag{3}$$

Similarly, we can get the effective medium permeability [34]. The magnetic moment of the current loop with the passing current I is

$$m = I\,S = \frac{U\,S}{Z_m + Z_L} = \frac{-\,j\omega\mu_0 H\,S^2}{Z_m + Z_L}\ , \tag{4}$$

where the voltage $U = -j\omega\phi = -j\omega\mu_0 HS$, and Z_m is the loop input impedance. The magnitude of the magnetization vector is

$$M = \frac{m}{v} = \frac{-1}{dxdydz} \frac{j\omega\mu_0 HS^2}{Z_m + Z_L} = \chi_m H \quad . \tag{5}$$

The magnetic susceptibility χ_m determines the effective relative permeability according to

$$\mu_{eff} = 1 + \chi_m = 1 - \frac{1}{dxdydz} \frac{j\omega\mu_0 S^2}{Z_m + Z_L} \quad . \tag{6}$$

The input impedance of the electric dipole is capacitive $Z_e = 1/ j\omega C_e$ while the input impedance of the current loop is inductive $Z_m = j\omega L_m$.

A number of combinations of impedances can be connected to the electric dipole and to the current loop. We will put aside the combinations with resistors representing losses. Loading the electric dipole by capacitor C_L or leaving it open, which represents a very small capacitance, or shortening its terminals, which represents infinite capacitance, or zero inductance, we get

$$\varepsilon_{eff} = 1 + \frac{1}{dxdydz\,\varepsilon_0} \frac{l_{eff}^2}{\dfrac{C_e + C_L}{C_e C_L}} \quad . \tag{7}$$

The medium created by the system of these electric dipoles has artificially increased permittivity which does not depend on frequency. This is the case of an artificial dielectric material [35,36]. Loading the electric dipole by an inductor L_L we get the effective permittivity

$$\varepsilon_{eff} = 1 + \frac{l_{eff}^2}{dxdydz\,\varepsilon_0} \frac{C_e}{1 - \omega^2 C_e L_L} \quad . \tag{8}$$

This represents the classical frequency dependent Lorentz model of a dielectric [20]. The example of this dependence for a lossless material is shown in Fig. 2c.

Loading the current loop by a capacitor C_L we get from (6)

$$\mu_{eff} = 1 + \frac{1}{dxdydz} \frac{\mu_0 \omega^2 S^2 C_L}{1 - \omega^2 L_m C_L} \quad . \tag{9}$$

This relation describes the dependence of the effective permeability on frequency, which, e.g., controls the behavior of split-ring resonators [8].

A number of other combinations of elements can be loaded to an electric dipole and a magnetic loop, including active elements which can compensate for losses and nonlinear elements [37]. Combining the loaded electric dipoles and the loaded current loops multiplies the possibility of getting an artificial material with a specific character, including a metamaterial with both negative permittivity and negative permeability [9].

The theory presented above assumes orientations of the field vectors according to Fig. 2. In the case of a general orientation the resulting effective permittivity and permeability are tensors and the material behaves anisotropically. The problem of obtaining an isotropic material will be discussed later.

1.2 Planar Version of a Metamaterial

The planar version of a metamaterial can be treated as a transmission line. Here we effectively apply the circuit approach based on the equivalent circuit of the transmission line consisting of lumped elements. This circuit, shown in Fig. 3a, consists of series impedance *Z* and parallel admittance *Y*, and represents the element of the line with length *d*, which must be much shorter than wavelength λ in order to form a unit cell.

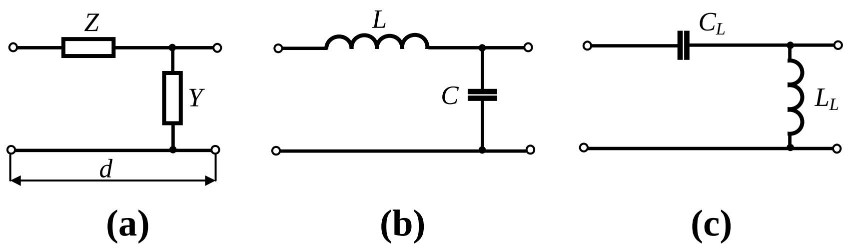


Fig. 3. The equivalent circuit of the general transmission line (a), the standard *L*-*C* line (b), *C*-*L* left-handed line (c).

The characteristic impedance of this transmission line is [38]

$$Z_o = \sqrt{\frac{Z}{Y}} \ , \tag{10}$$

the propagation constant $\gamma = \alpha + j\beta$ is

$$\gamma = \pm\sqrt{ZY} \ , \tag{11}$$

for the wave propagating in the positive *z* direction described by exp(-γz) we take + in (11), while the sign – in (11) represents the wave propagating in the negative z direction. We will now assume the positive sign. α and β are attenuation and phase constants. The phase velocity v_p is

$$v_p = \frac{\omega}{\beta} \ , \tag{12}$$

and the group velocity v_g is

$$v_g = \frac{1}{\partial\beta / \partial\omega} \ . \tag{13}$$

The standard lossless line has Z=jωL, Y=jωC, as shown in Fig. 3b, so from (10–13)

$$Z_o = \sqrt{\frac{L}{C}} \ , \tag{14}$$

$$\gamma = \mathrm{j}\beta = \mathrm{j}\omega\sqrt{LC} \ , \tag{15}$$

$$v_p = \frac{1}{\sqrt{LC}} \ , \tag{16}$$

$$v_g = \frac{1}{\sqrt{LC}} \ . \tag{17}$$

This corresponds to the propagation of the standard TEM forward wave along the line. Both velocities v_p and v_g are positive.

Now let us consider the dual case with the corresponding equivalent circuit shown in Fig. 3c, where the positions of the capacitance and inductance have been exchanged. In this way we have changed the original L-C low-pass structure into the C-L high-pass structure. The latter lines are denoted as left handed [39] and represent the planar version of a metamaterial. Now for the lossless line we have $\alpha = 0$, Z=1/(jωC_L) and Y=1/(jωL_L). Consequently,

$$Z_o = \sqrt{\frac{L_L}{C_L}} \ , \tag{18}$$

$$\gamma = j\beta = -j\frac{1}{\omega\sqrt{L_L C_L}} \ , \tag{19}$$

$$v_p = -\omega^2\sqrt{L_L C_L} \ , \tag{20}$$

$$v_g = \omega^2\sqrt{L_L C_L} \ . \tag{21}$$

There are different signs in (20) and (21). The group velocity has an opposite direction compared to the phase velocity. This features the backward wave.

The LHTL can be fabricated by inserting inductors and capacitors into a real TL with the equivalent circuit in Fig. 3b. So the hosting environment represents the series inductance L_R and parallel capacitance C_R. Therefore the equivalent circuit of the LHTL in Fig. 3c must be modified as shown in Fig. 4.

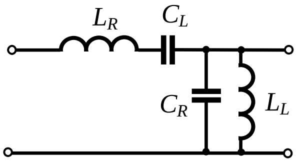


Fig. 4. The modified equivalent circuit of the lossless left-handed transmission line.

Comparing formulas (16-17) with the well-known formulas describing plane wave propagation in the free space [38], we come out with the formulas

$$L = \mu d\,, \tag{22}$$

$$C = \varepsilon d\,, \tag{23}$$

where L and C are the lumped inductance and capacitance of the line segment of length d much shorter than wavelength λ, more precisely βd << 1. In this case L=L_R, C=C_R and we have

$$Z = \mathrm{j}\omega\left(\mu - \frac{1}{\omega^2 C_L d}\right)d\ , \tag{24}$$

$$Y = \mathrm{j}\omega\left(\varepsilon - \frac{1}{\omega^2 L_L d}\right)d\ , \tag{25}$$

and we can introduce effective permeability μ_{eff} and permittivity ε_{eff}

$$\mu_{eff} = \mu - \frac{1}{\omega^2 C_L d}\ , \tag{26}$$

$$\varepsilon_{eff} = \varepsilon - \frac{1}{\omega^2 L_L d}\ . \tag{27}$$

Formulas (26) and (27) show that a transmission line can have a negative value of effective permeability and permittivity in a certain frequency band.

The transmission line with the equivalent circuit shown in Fig. 4 can be produced by various techniques, in 1D [39], or in 2D [40,41]. The simplest technique is to apply discrete capacitors and inductors [40], or these elements can be integrated into a planar structure as interdigital capacitors and shunt via holes [39]. The capacitors can be simple transversal slots in the hosting line, e.g., CPW [42], or elements in the shape of a mushroom [41]. The inductor can also be designed as an active inductor represented by a gyrator [43].

The LH wave could propagate along the line with the equivalent circuit in Fig. 3c from a certain frequency, as the circuit is a high-pass filter, up to the frequency defined by the Bragg condition $|\beta|d=\pi$ [44]. The wave on the line with the equivalent circuit in Fig. 4 has the LH character at low frequencies up to the series resonant frequency f_{os} determined by C_L and L_R. Above this frequency there is generally a band-gap where no wave can propagate till the resonant frequency f_{op} of the parallel components L_L and C_R. Above f_{op} the RH wave propagates until the Bragg condition is fulfilled. The composite right/left-handed (CRLH) TL [19], with the equivalent circuit in Fig. 4, is often designed so that $f_{os} = f_{op} = f_o$ and no gap exists. Then at f_o $\beta = 0$ and consequently $\lambda = \infty$. This gives the possibility of designing resonators of zeroth order oscillating on this resonant frequency $f_{o,}$ which does not depend on the resonator length, and even with resonances of negative orders [45].

Planar LHTLs have been applied in a number of microwave elements, mostly utilizing CRLH TLs [19]. Some of them can be found in Caloz and Itoh [4]. The new properties of these circuits include: dual-band operation, bandwidth enhancement, arbitrary coupling level and negative and zeroth-order resonance.

2. LEFT-HANDED COPLANAR LINE

A new version of a left-handed coplanar waveguide (LHCPW) has been proposed [46,47]. One cell and the layout of this line are shown in Fig. 5. The line has an entirely uniplanar structure without vias and lumped elements. The series capacitors are represented by interdigital capacitors and the parallel inductors by short-circuited CPW stubs connected to the ground metallization. The LHCPW was fabricated on the ROGERS RO4003C substrate 0.813 mm in thickness with permittivity 3.38 and metallization 0.035 mm in thickness. The measured frequency dependences of S_{21} and S_{11} agree well with the data predicted by simulation. The simple equivalent circuit of the line unit cell was set up by fitting its dispersion characteristic to the dispersion characteristic of the first left-handed mode calculated by the CST Microwave Studio. The dispersion characteristics of the basic backward wave propagating on the LHCPW are shown in Fig. 6.

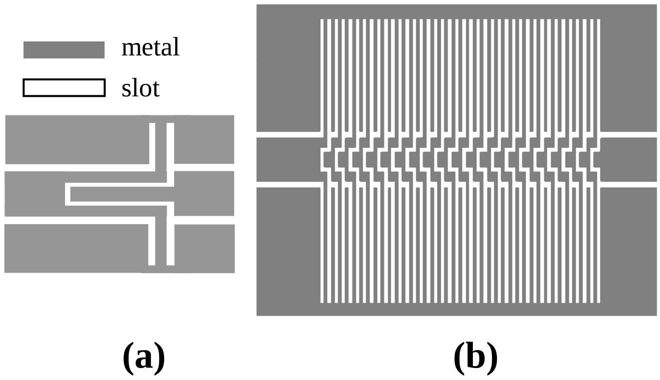


Fig. 5. Unit cell (a) and the final layout (b) of the LHCPW.

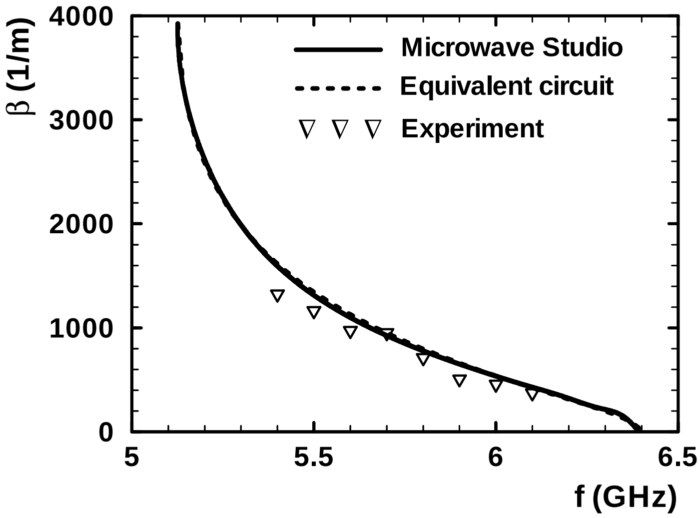
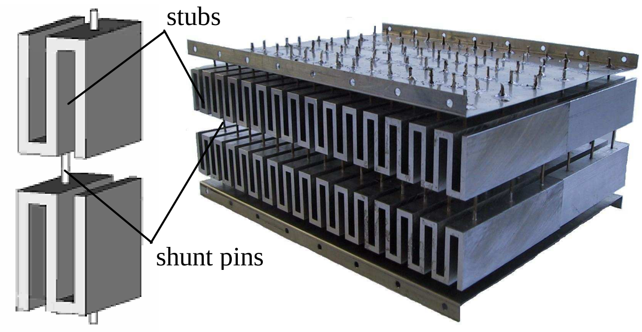


Fig. 6. The dispersion characteristics of the fabricated LHCPW calculated by the CST Microwave Studio, calculated by the equivalent circuit and measured.

3. 1D VOLUMETRIC METAMATERIAL

A new 1D volumetric LH metamaterial was proposed, designed and fabricated [48,49]. Its structure duplicates the concept of left-handed parallel strips cut by series capacitors and shunted by shunt inductors. The wave propagates inside this volumetric metamaterial as in a 1D transmission line. The shunt pins represent the shunt inductors. The input impedances of the short circuited stubs of the parallel strips represent the series capacitors. The CST Microwave Studio model of the unit cell of the proposed volumetric metamaterial is shown in Fig. 7a. This cell, containing the segment of parallel strips with the junction of two stubs, is repeated in all three directions to create a volume structure. Fig. 7a shows the central cell and the two neighbouring cells placed in the vertical direction. They are longitudinally shifted by one half of the period to fill the space completely. The incoming wave is incident to the matrix of the apertures of the particular parallel plate waveguides. The electric field vector of the propagating wave must be oriented across these parallel plate waveguides. The manufactured bulk LH metamaterial shown in Fig. 7b was milled from aluminium blocks. The inductive pins are made of cylindrical wires set in holes drilled into the aluminium body. The transmission and dispersion characteristics of this medium were calculated and measured. They fit each other very well, as shown for the transmission in Fig. 8.



a **b**

Fig. 7. A unit cell of the proposed left-handed structure (a), manufactured metamaterial consisting of six parallel rows each of 15 cells (b).

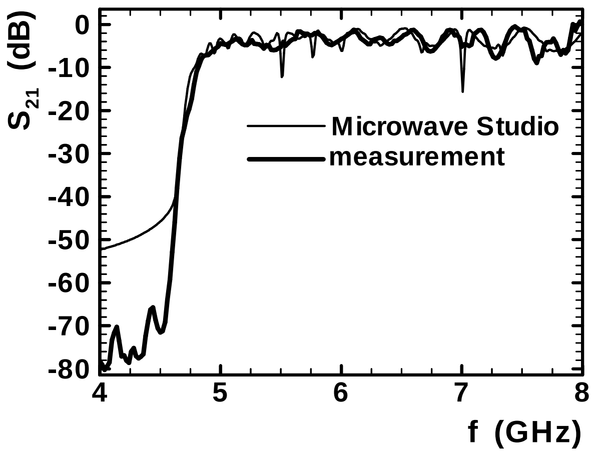


Fig. 8. Transmission S_{21} of the metamaterial from Fig. 7b.

The LH wave propagates along this structure in the range from 4.75 to 5.65 GHz. Directly above this range the standard RH wave is guided, so this structure behaves as the CRLH line described above.

4. 3D WIRE MEDIUM

The 3D wire medium [50], Fig. 12, was studied with the aim to apply it as a negative permittivity isotropic metamaterial. The derivation of the dispersion equation of modes in the 3D lattice is quite straightforward and the result is in accord with [51]. The numerical examples show that there are three eigen modes both below and above the plasma frequency in directions Γ-X and Γ-M and five eigen modes in direction Γ-R. One of the modes complies with physical intuition, i.e., it is evanescent below the plasma frequency and above it this mode becomes propagating. The other modes do not correspond to physical waves. In direction Γ-M, the attenuation and phase constants have the same value as in the case of direction Γ-X, since the propagation of the wave along one axis is equivalent to the propagation along the unit cell face. The dispersion curves both below and above the plasma frequency form a circle. This implies isotropic propagation of the plane wave along any face of the 3D cube. Taking into consideration the wave propagating in a general direction, the isotropy is now in general removed. However, a comparison of the dispersion characteristics calculated in various directions shows that in the first approximation the 3D wire medium can be considered as an isotropic material in some vicinity of the plasma frequency. The modeling by the Microwave Studio and measurement verify these theoretical results.

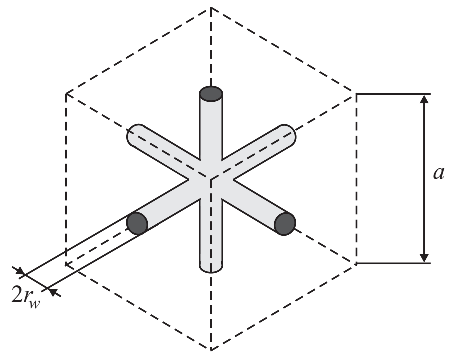
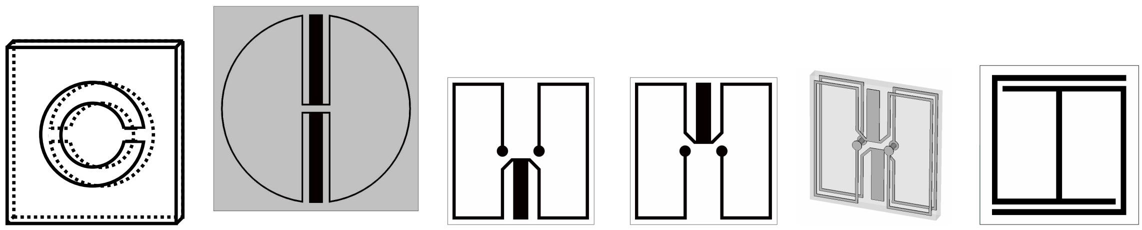


Fig. 9. 3D wire mesh structure formed by a lattice of infinitely long connected wires of radius r_w. a is the lattice period.

5. PLANAR RESONATORS

The aim of our work is to design and fabricate a real 3D isotropic single-negative metamaterial with negative permittivity or permeability using cheap, easily accessible technology. This can be achieved by using planar resonators on a dielectric substrate provided by standard planar technology. For a mu-negative metamaterial we have used broadside-coupled split ring resonators, as presented in [52,53], see Fig. 10a. The resonant elements consisting of a planar electric dipole terminated by two loop inductors connected in parallel to provide symmetry were proposed in [22] as good candidates for building an isotropic epsilon-negative metamaterial. The layout is shown in Fig. 10b. The dipole with minimized dimensions is shown in Figs. 10c-e. It was necessary to use vias in these resonators, but this drawback was removed by using a double H-shaped resonator, as shown in Fig. 10f.



(a) **(b)** **(c)** **(d)** **(e)** **(f)**

Fig. 10. Sketch of the planar resonators, not drawn to scale. Broadside-coupled SRR (a), layout of the electric dipole (b), the reduced size dipole terminated by two loop inductors, top layout (c), rear layout (d), view (e), layout of the double H-shaped resonator (f).

5.1 Split Ring Resonator

The broadside-coupled split ring resonator was designed on a Rogers RT/duroid 5880 substrate 0.127 mm in thickness with permittivity 2.20 and 0.017 mm copper cladding. Each resonator resides on a squared leaf with a 7 mm edge [24]. We measured the transmission of the R32 waveguide with this resonator located in the middle of its cross-section. The resonant response was found at around 3.1 GHz. The resonant frequencies of the individual resonators differed in a 50 MHz interval due to manufacturing imperfections. The resonator is about 13.8 times smaller in size than the resonant wavelength in free space, so a metamaterial consisting of these resonators can be assumed to be homogeneous.

5.2 Electric Dipole

An electric dipole terminated by a planar loop inductor [22] is a resonant element sensitive to an electric field. This element effectively modifies the permittivity of the hosting material under irradiation by an electromagnetic wave. The originally designed resonator, Fig. 10b, has a resonant frequency around 1.86 GHz, and the R18 waveguide was used to measure its transmission. For this resonator we obtained the ratio of the free space wavelength at resonant frequency to its total size of 28.8 mm, equal to 5.6. Such a resonant element is not small enough to produce a real homogeneous metamaterial. The size of this resonant element is limited mainly by the area occupied by the planar loops. We reduced this area by making use of the rear side of the substrate and using an inductor with two turns, see Figs. 10c,d,e. The penalty for this, however, is the presence of two vias. The dipole arms are now located on the opposite surfaces of the substrate. This reduced-size dipole resonator measured in the R32 waveguide gives a resonant-like response with resonant frequency about 3.3 GHz. The spread of the resonant frequencies of the particular resonant elements is similar as in the case of broadside-coupled split ring resonators, reported above. An example of the transmission of a single dipole located in the R32 waveguide is shown in Fig. 11.

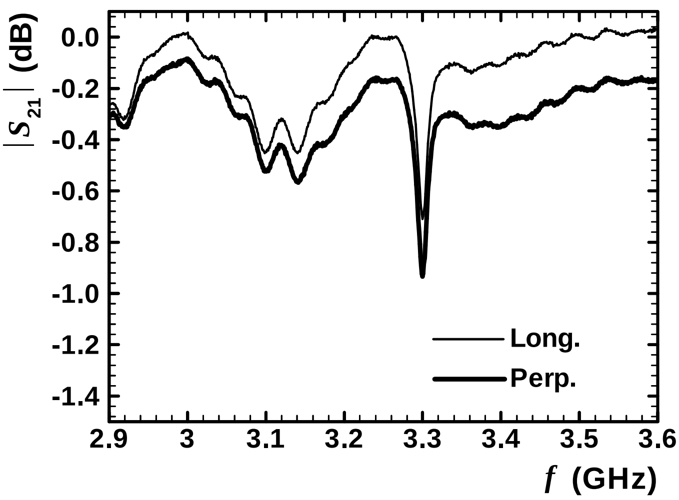


Fig. 11. Measured transmission of the R32 waveguide with one reduced-size dipole (Long.: oriented parallel to the waveguide longitudinal axis, Perp.: located perpendicular to the waveguide axis). The resonant element is located at the center of the waveguide.

5.3 Double H-shaped Resonator

Our aim was to find a new planar resonant element for composing an epsilon-negative metamaterial able to resonate at a satisfactorily low frequency and therefore compatible in size with our broadside-coupled split ring resonators. A solution was found after several iterations with a planar resonant element in the form of a folded dipole. We obtained a double H-shaped resonator, the layout of which is shown in Fig. 10f.

The double H-shaped resonator was optimized by the CST Microwave Studio using a substrate 0.2 mm in thickness, with permittivity 2.3, loss factor 0.001, and metal cladding 17 μm in thickness, finally obtaining an area of 6x6 mm and an outer strip 5.25 mm in length. Fig. 12 shows the transmission characteristics of the double H-shaped resonator located in three positions in the middle of the TEM waveguide calculated by the CST Microwave Studio. The resonant frequency is around 3.8 GHz. The ratio of the free space wavelength at resonance and the resonator size is about 13, so a metamaterial consisting of these resonant elements can be assumed to be a homogeneous medium. Position 1 denotes a double H-shaped resonator perpendicular to the side walls of the waveguide, and the central strip is in the vertical position, so there is no interaction with the magnetic field in the TEM waveguide. We have only one basic resonance at which the element shows negative effective permittivity. In positions 2 and 3, the double H-shaped resonator is located parallel to the waveguide side walls with the vertical position and with the horizontal position of the central strip, respectively. The magnetic field now interacts with the resonant element. This results in the appearance of the second magnetic resonance, Fig. 12, at which the double H-shaped resonator shows negative effective permeability, see Fig. 13. This additional resonance is, however, well separated from the basic resonance aimed as the metamaterial working resonance. The calculated effective permittivity of the TEM waveguide section with the double H-shaped resonator located in position 2 is shown in Fig. 13.

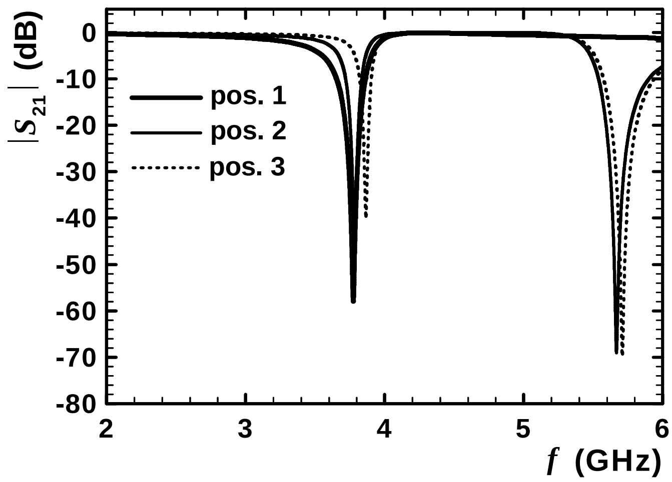


Fig. 12. Simulated transmission of the double H-shaped resonator located at the center of the TEM waveguide in three positions defined in the text.

The double H-shaped resonator was fabricated on a ROGERS RT/duroid 5880 substrate with permittivity 2.22 and thickness 0.254 mm, loss factor 0.0012 at 10 GHz and metallization thickness 0.017 mm. The outer strip is 5.25 mm in length and 0.2 mm in width, the same as the slot width. The resonator is deposited on a substrate 6x6 mm in area. The double H-shaped resonator was located in the R32 waveguide at the center of its cross-section in position 1. The measured transmission characteristic is plotted in Fig. 14. As expected, the response is weak since we have only one tiny resonant element 6x6 mm located in the R32 waveguide with a rectangular cross section of 72.14x34.04 mm.

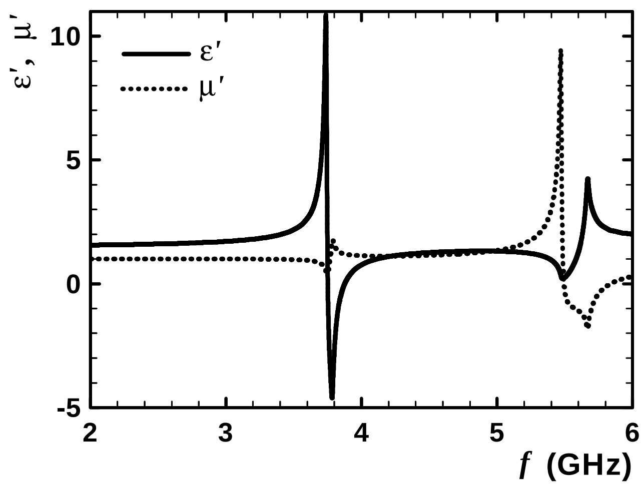


Fig. 13. Calculated [20] real parts of the effective permittivity and permeability of the double H-shaped resonator located in the TEM waveguide in position 2.

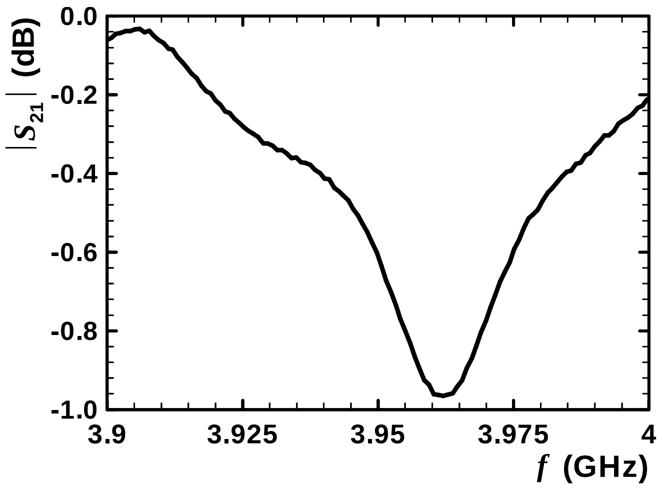
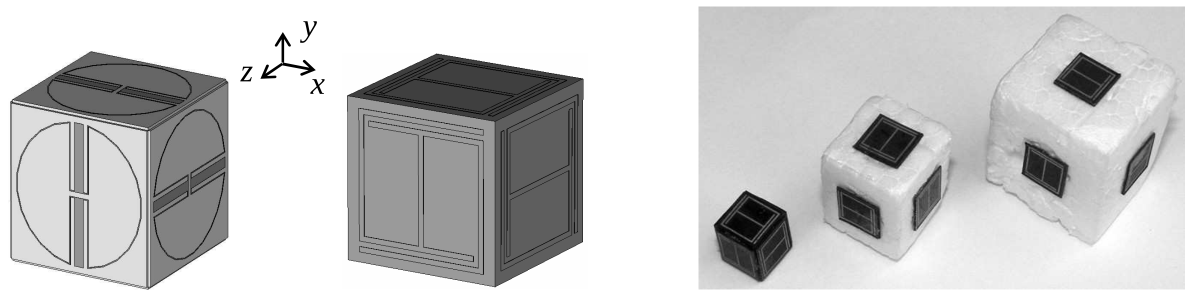


Fig. 14. Measured transmissions of the double H-shaped resonator located at the center of the R32 waveguide.

6. CUBIC CELLS WITH AN ISOTROPIC RESPONSE

A 3D isotropic unit cell providing negative permittivity or permeability can be designed by placing the planar resonant elements on the faces of a cube, observing the appropriate crystallographic groups of symmetry [20,21]. The cells composed of a tetrahedral symmetrical system are shown in Fig. 15. The cube with particular planar resonant elements is a complex system with many internal couplings. Moreover, the presence of the waveguide walls, the existence of the TE_{10} mode longitudinal magnetic field component and the non-homogeneity of the field influence the electromagnetic response of the cube. These effects result in a response of the cube that is different from the response of a single planar resonator. Cubes composed of various versions of split-ring resonators have been already proposed and studied in [20,21]. Cubes composed of electric resonant elements are shown in Fig. 15. The transmission characteristics of these cells with electric dipoles, both calculated and measured, have been presented in [22] for their different positions in the waveguide of the rectangular cross-section and the TEM waveguide. For the main resonance at which these metamaterials are aimed to work, the response of the cell does not depend on its orientation. This proves that these unit cells behave with an isotropic response.



(a) **(b)** **(c)**

Fig. 15. Cubic-like cells, not drawn to scale, composed of electric dipoles (a), and double H-shaped resonators (b). Fabricated cubes with double H-shaped resonators (c).

Fig. 15b is a sketch of the CST Microwave model of the cube cell composed of double H-shaped resonators. The three fabricated versions of this cube, with dimensions 6x6x6, 12x12x12, and 15x15x15 mm, are shown in Fig. 15c. They are composed of planar double H-shaped resonators, see Fig. 10f, stuck on to polystyrene cubes of given dimensions. The isotropy of these cells was tested by measuring the transmission through the R32 waveguide with the cube located in its center in different positions, see Fig. 16 for the cube with dimensions 15x15x15 mm. Position 1 refers to the cube located as shown in Fig. 6c, assuming that *z* is the waveguide axis and the waveguide side walls are parallel to the *yz* plane. The cube is rotated by 45 deg around the *x* axis in position 2, while in position 3 the cube is additionally rotated by 45 deg around the *y* axis. The cell response depends only slightly on its chosen position. We can therefore conclude that this cube-like unit cell behaves isotropically, and is a suitable building block for an isotropic epsilon-negative metamaterial.

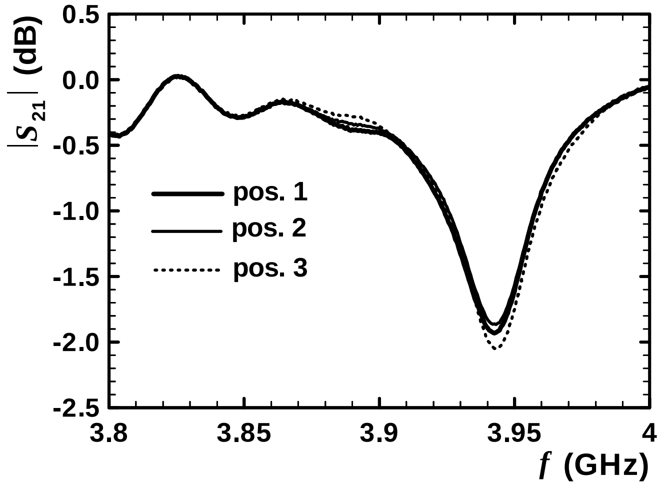
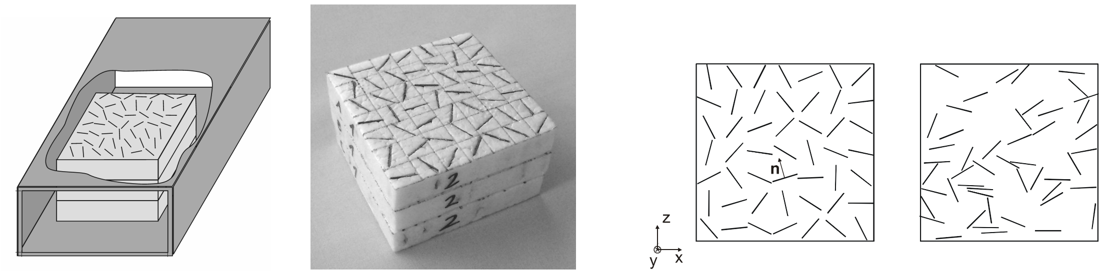


Fig. 16. Measured transmissions of the R32 waveguide with a cube of dimensions 15x15x15 mm assembled from six double H-shaped resonators for its different positions.

7. 2D RANDOM DISTRIBUTION OF ELEMENTS IN SPACE

The 2D random system consists of the host material - polystyrene - in the shape of a parallelepiped with the base 50x50 mm cut into three slices that are equal in height 10 mm, Fig. 17a. In each slice, an equal number of planar resonant elements of any kind from Fig. 10a,e,f are inserted with random orientation. Two different random arrangements were used and tested, as depicted in Figs. 17b,c, representing the top view of a slice [24]. The surface normals of the elements, and thus also the magnetic moments, lie only in the *xz* plane, forming the desired 2D system. The centers of the particular resonators are either positioned periodically in the nodes of a squared net, Fig. 17b, or their position varies randomly, Fig. 17c. Randomness is obtained by choosing random angles between the normals of the resonators and the *x* axis. The distribution of these angles and also the distribution of the resonator positions on each slice were generated independently. Consequently, by changing the mutual orientations of the slices in the parallelepiped by 90-degree rotations, there are 64 different parallelepipeds with randomly distributed resonators inside, assuming that the vertical order of the slices is kept. Interchanging the vertical order of the slices, with their three rotations, we obtain a total of 384 combinations of resonator locations. However, we utilized only the first 64 combinations in the experiment.



(a) **(b)** **(c)**

Fig. 17. Waveguide loaded with a parallelepiped composed of three slices with randomly distributed planar resonators (a), periodic positions of resonators with randomly chosen angles (b), doubly random distribution (c).

An experiment performed with the use of a mu-negative metamaterial consisting of broadside-coupled split ring resonators was reported in [24]. The parallelepiped with doubly randomly distributed resonant elements, see Fig. 17c, proved not to be suitable for fabrication of isotropic metamaterials [24], while the distribution from Fig. 17b provides a material with acceptable isotropy.

Here we report the results of two epsilon-negative metamaterials composed of single dipoles, Fig. 10e, and double H-shaped resonators, Fig. 10f. Sixty-four measured transmissions of 147 resonators inserted in the polystyrene slices consecutively rotated by 90 deg provided very good isotropy of the cubic sample. This follows from the small disperse shown in Fig. 18 for the electric dipoles and in Fig. 10 for the double H-shaped resonators. Both measurements were performed in the R32 waveguide and show a small dispersion. The measured metamaterial specimens can therefore be considered as isotropic, assuming that the electromagnetic wave propagates in the *xz* plane and the electric field is parallel to the *y* axis, Fig. 17b.

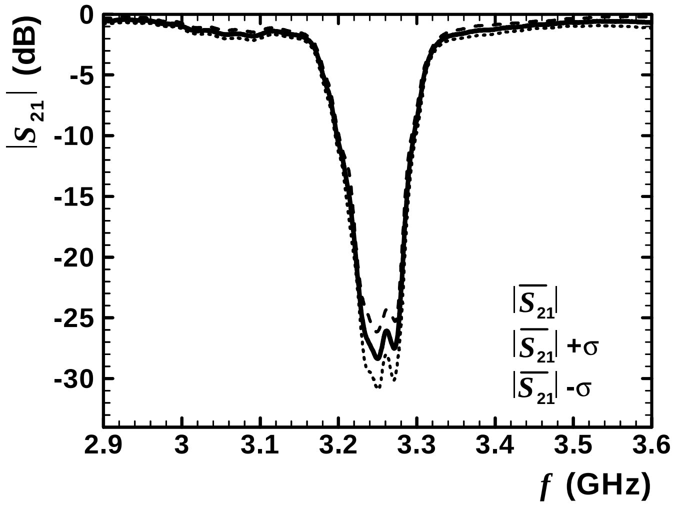


Fig. 18. Arithmetic mean value of the transmission through the sample with 147 planar reduced size electric dipoles, and the disperse when the resonators are in the nodes of the squared net, Fig. 17b.

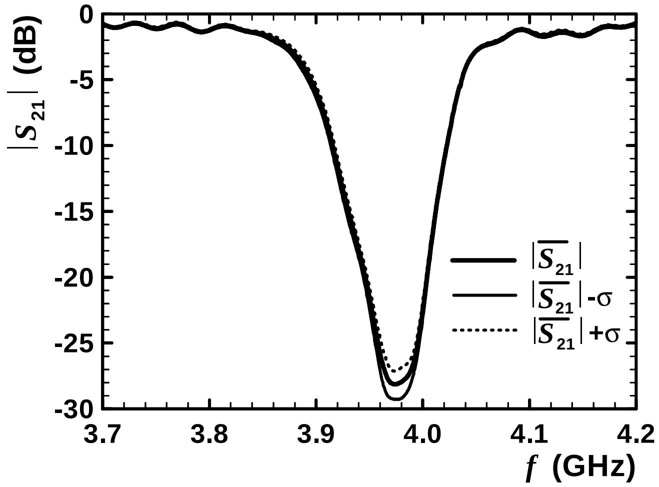
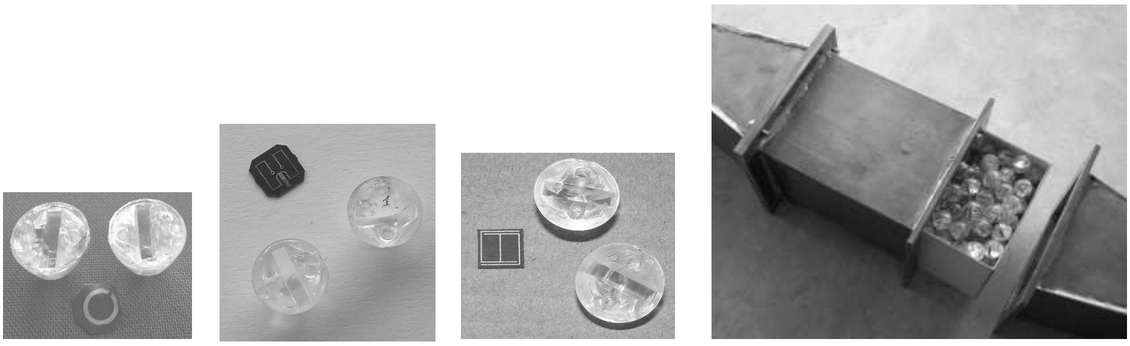


Fig. 19. The same plot as in Fig. 18, but for double H-shaped resonators.

8. ISOTROPIC SINGLE-NEGATIVE METAMATERIALS

Real volumetric isotropic metamaterials cannot be based on the 2D distributions presented in the previous paragraph. The planar resonant elements have to be distributed with a real 3D random location and orientation in the host medium. As it turned out, 3D random location of the planar resonant elements was a great technological problem. Finally, the actual 3D metamaterial with randomly distributed and oriented resonant elements was achieved by boxing the planar resonant elements into plastic spherical shells, Fig. 20a. The shells with an outer diameter of 11 mm consist of two yoked hemispheres with inside slots for inserting the resonant element. About 256 shells are placed in the cube with the edge 72 mm in length, Fig. 20b. These specimens of the single-negative metamaterial were measured in the squared R32 waveguide, Fig. 20b.



(a) (b)

Fig. 20. Planar resonant elements boxed in plastic spherical shells (a), the partly disassembled measuring setup (b).

The transmission characteristics of the prepared single-negative metamaterials were measured repeatedly, changing the positions of the shells each time. Finally, the dispersion of these characteristics was calculated and plotted. Fig. 21 shows the behavior of the mu-negative metamaterial composed of broadside-coupled split ring resonators. The response of the reduced size electric dipoles is plotted in Fig. 22, and Fig. 23 shows the results of measurements of the epsilon-negative metamaterial consisting of boxed double H-shaped resonators.

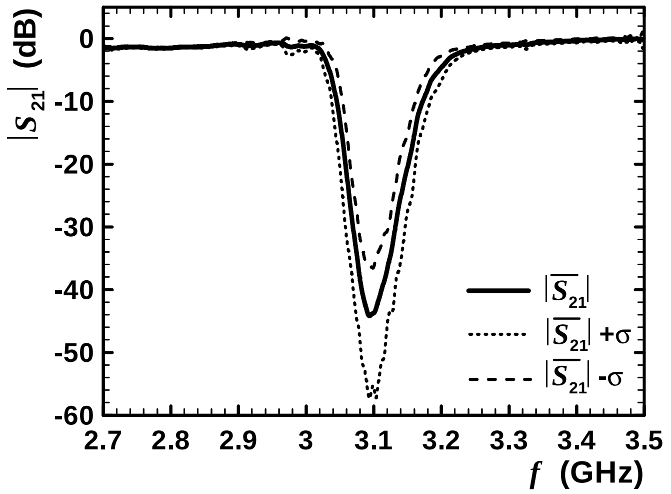


Fig. 21. The arithmetic mean value and its disperse for 25 measurements of transmission through the 3D mu-negative metamaterial in the raised R32 waveguide with 256 boxed broadside-coupled split ring resonators randomly located in the volume of a cube with sides 72 mm in length [24].

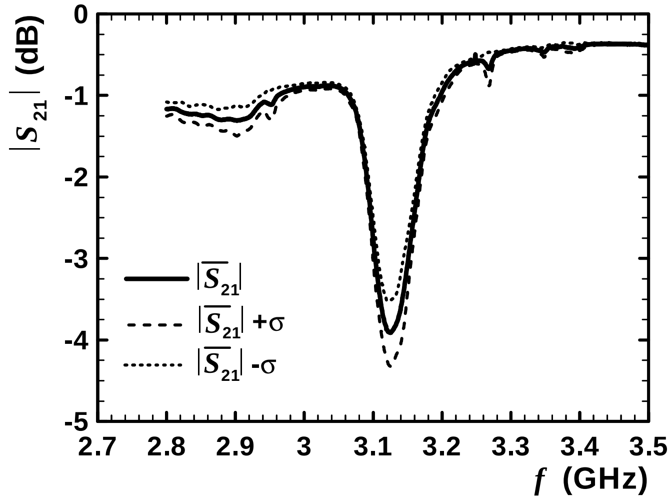


Fig. 22. The same dependence as in Fig. 21, but for the epsilon-negative metamaterial consisting of 256 boxed reduced-size electric dipoles.

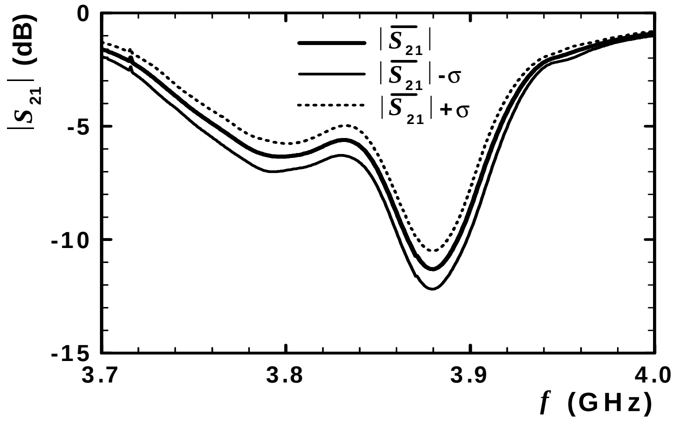


Fig. 23. The same dependence as in Fig. 21, but for the epsilon-negative metamaterial consisting of 256 boxed double H-shaped resonators.

The characteristics plotted in Figs. 21 – 23 show dispersion that is slightly higher than in the case of 2D metamaterials, see Figs. 18, 19. Nevertheless, single-negative metamaterials composed of boxed planar resonant elements can be viewed as real 3D isotropic metamaterials.

9. CONCLUSION

The review defines the two forms of metamaterials. The first is known as a volumetric metamaterial, and it is an artificial medium of given effective material parameters usually not known in nature. The second form of the metamaterial is called planar, and it is represented by a 1D or 2D planar transmission line. The basic theory describing the parameters and the behavior of these two kinds of metamaterials has been presented here. The volumetric metamaterial is characterized by determining the vector of polarization and the vector of magnetization defining the effective permittivity and permeability. The planar metamaterial is treated as a transmission line with its equivalent circuit.

The author has been investigating metamaterials for more than five years. The results of these investigations have been presented. They include a left-handed coplanar line as an example of a 1D planar left-handed transmission line. A 1D volumetric metamaterial is a 1D structure based on a parallel plate waveguide with a left-handed behavior. It is shown that a 3D wire medium exhibits an isotropic behavior with negative permittivity.

This review presents two ways of designing a bulk isotropic metamaterial with a single negative response. Simple and consequently cheap planar resonant elements are proposed as the building blocks of these metamaterials. Broadside-coupled split ring resonators are used. When irradiated by an electromagnetic wave these resonators show negative effective permeability. Two different resonant elements sensitive to an electric field are used to show negative effective permittivity, assuming they are irradiated by an electromagnetic wave. These are: an electric dipole loaded by a loop inductor, and a double H-shaped resonator. The behavior of these two resonant elements is similar. In comparison with the electric dipole using a two-loop inductor, the double H-shaped resonator has the advantage of a simpler structure with no vias. Consequently, it can be produced more cheaply and more reliably.

An isotropic response with both negative permittivity and negative permeability was proved in the case of a unit cell in the form of a cube with six identical planar resonant elements located with tetrahedral symmetry on its faces.

To test a simple way of manufacturing an isotropic single negative metamaterial, we placed the planar resonators in a 2D system with their periodic positions but with random orientations. This system measured in the R32 waveguide showed good isotropy.

The concept of manufacturing real isotropic 3D metamaterials with randomly distributed resonant elements has been proved practicable in the case of a magnetic single negative medium and also an electric single negative medium. The resonant elements are boxed into plastic spherical shells, preserving their random positions in space together with random orientation. The frequency band of composites with randomly located unit cells is wider than the band of a single resonant element. This medium can fill a volume of any shape, and can therefore be used in a wide range of applications.

The designed planar resonant elements showing effective negative permittivity or permeability under irradiation by electromagnetic wave can be simply scaled down or up to be applied in a different frequency band. Their combination provides the material with a negative refractive index. To do this, the cubic cells can be combined like panes in a chessboard. The boxed resonant elements of the two kinds can be simply mixed together. The fabricated isotropic single negative metamaterials are ready to be used in many applications.

Metamaterials constitute a new field of science and engineering that goes back only about eight or nine years. There are still many open questions to be solved and challenges to be met. It is very challenging to shift the application of metamaterials into the optical range of frequencies, where metals can no longer be treated as good conductors. A possible way is to apply parallel nano-wires [54] and modified split-ring resonators [55].

Metamaterials can be used as ideal lenses, antenna radomes, layers increasing the sensitivity of electrically small antennas, frequency selective surfaces, cases reducing a target effective radar cross-section, phase compensating layers, etc. Another interesting way to modify the material parameters is by terminating the particles that constitute volumetric metamaterials by various loads, including active and nonlinear elements.

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CURRICULUM VITAE

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Born: April 1st, 1953, Hranice na Mor.

Education:
1977 - Ing. (MSc..), CTU, Faculty of Electrical Engineering
1982 - CSc. (PhD) in Electronics, Institute of Radioengineering and Electronics, Czechoslovak Academy of Sciences in Prague
1991 - Doc. (Associate Professor) in Electrical Engineering, CTU, Faculty of Electrical Engineering
1996 - DrSc. in Radioelectronics, CTU, Faculty of Electrical Engineering

Professional Career:
1977 - 1984 Institute of Radioengineering and Electronics, Czechoslovak Academy of Sciences in Prague
1984 - ____: CTU, Faculty of Electrical Engineering

Courses, education, PhD students:
- electromagnetic field theory (lectures and seminars in English)
- waves and transmission lines (lectures and seminars in English)
- numerical solution of electromagnetic fields (for undergraduate and PhD students) (participated in creation of a new course)
- selected problems from mathematics (created as a new course)
- analysis methods for passive elements of microwave and millimeterwave techniques (for PhD students) (created as a new course)
- numerical methods in the design of microwave elements (at University of Magdeburg) (created as a new course)
- supervisor of student projects and diploma theses
- author and co-author of 5 textbooks (2 in English)
- supervisor of (currently) 4 PhD students (3 at CTU, 1 at University of Magdeburg)
- graduated PhD students: 2, 2 (supervisor specialist)

Research activities:

- modelling of waves on planar transmission lines used in microwave and millimeter-wave techniques, leaky waves
- propagation of electromagnetic waves in periodic structures
- metamaterials
- leaky wave and planar antennas
- planar microwave filters
- field theory, numerical solutions
- nanotechnology
- UWB fields and propagation

Projects - external:

- **recipient of:** MŠMT (1998), (1999), FRVŠ (2003), GAČR (2006-2008), INGO-MŠMT (2006-2009), EU - Tempus (1992), EU - "Community's Action for Cooperation in Sciences" (1993)
- **present project:** GAČR (2009-2012), 102/09/0314 "Investigation of metamaterials and microwave structures with the help of noise spectroscopy and magnetic resonance"
- **collaborator:** MŠMT (2000), GAČR (2000-2002), GAČR (2003-2005), MŠMT (since 2004)

International cooperation and stays:

- University of Ulm, Germany, Prof. Wolfgang Menzel, 1991-1998
- Otto von Guericke University Magdeburg, Germany, Prof. Abbas Omar since 2002

Memberships and activities:

- member of the Technical and Programme Committee of the European Microwave Conference 1995 - 1997
- Secretary of the 26th European Microwave Conference 1996
- member of the Technical and Programme Committee of 2004 URSI International Symposium on Electromagnetic Theory
- member of the Technical and Programme Committee of the IEEE Microwave Theory and Techniques International Microwave Symposium since 2008
- member of the Radioengineering Society
- member of the Czech Electrotechnical Society
- member of the Committee of the Czech Electrotechnical Society since 2001

- Chairman of the Czech Electrotechnical Society 2005-2008
- Vice-Chairman of the Czech Electrotechnical Society since 2008
- member of the Committee of the Microwave Techniques Professional Group of the Czech Electrotechnical Society since 1998
- Chairman of the Committee of the Microwave Techniques Professional Group of the Czech Electrotechnical Society since 2007
- Senior member of IEEE, member of MTT Society of IEEE
- member of the Committee of the Czechoslovak Section of IEEE 2003-2008
- Vice-Coordinator for Region 8 of the IEEE MTT Society
- member of the Membership Services Committee of the IEEE MTT Society AdCom
- member of the Technical Committee MTT-15 Microwave Field Theory of the MTT-S IEEE since 2007
- reviewer of IEEE Trans. on Microwave Theory and Techn., IEE Proc., Electronics Letters, European Microwave Conference, Radio Science, PIER – Progress in Electromagnetic Research.

Author/co-author (full life):

• Czech monograph	1
• paper in an international journal with non-zero impact fact.	10
• paper in an international reviewed journal	8
• paper at an international conference (in. Proc.)	63
• invited lecture at an international conference	7
• paper in a Czech scientific journal	26
• paper at a Czech scientific conference (in. Proc.)	63
• invited lecture at a Czech scientific conference	1
• works cited (ISI)	38

Papers in international scientific journals (full life):

- Kučera L., Macháč J., Mišek J.: Effect of feedback carrier excitation on LED external quantum efficiency, *IEE Proc.*, 129-I, 1982, pp. 28.
- Macháč J.: A static model of DH laser, *Proc. IEE-I, Solid-State and Electron Devices*, vol. 130, Pt. I, No. 2, 1983, pp. 61.
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- Buchar P., Macháč J., Zehentner J.: Microwave reflectivity from gold sputtered nanolayer, *IEEE Transactions on Nanotechnology*, Vol. 6, No. 6, November 2007, pp. 645-651, IF 1,909.
- Balalem A., Macháč J., Omar A.: Microstrip-CPW bandpass filter for antenna application, *Microwave and Optical Technology Letters*, Vol. 50, No. 1, January 2008, pp. 51-55, IF 0.568.

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EDUCATION AND SCIENTIFIC WORK, RESEARCH GROUP IN ELECTROMAGNETICS AND METAMATERIALS, FUTURE PROSPECTS

Let us finally review the general history of forms of research and design in electromagnetics and microwave techniques. Until the 1960s, relatively simple tasks were solved. Analytic methods and some perturbation methods were used with the help of some labor saving graphical tools, e.g., the Smith Chart. With increasing complexity of the problems that were worked on, and increasingly complex technology, numerical solution methods started to be necessary. Researchers and designers usually had to create a single-purpose code based on an appropriate numerical or approximate method for each individual problem. At that time, in the early 1990s, I reflected this situation by introducing a course in “Analytical Methods for Passive Elements of Microwave and Millimeterwave Techniques”. This course introduced PhD students to ways of doing this kind of work. Since that time, the progress made by software companies in very successfully introducing wide-purpose sophisticated professional software for solving various electromagnetic problems in microwave techniques has substantially changed the work of designers. At the same time, fine numerical methods were also being introduced. I was a member of a group of teachers who introduced a course in “Numerical Solution of Electromagnetic Fields”, which reflected this situation. Each user of software needs detailed knowledge of the numerical method that the code he is using is based on. More recently, only researchers working on very specialized tasks have written their own electromagnetic field codes. The use of wide-purpose professional software is in many cases the only way to solve very complex systems and circuits used in present-day technology. The application of this software, however, has led to a new phenomenon that has infected, above all, young engineers. They sit in front of a computer and work by the “cut and try” method, which is suitable only for routine circuit design. They just repeat and repeat the analysis with the use of the software. The physical understanding and the sense for the technology are almost lost. This can be improved by returning back to the use of analytical methods, i.e., mathematics. For this reason, I introduced the course in “Selected Problems from Mathematics“. The aim of this course is to stimulate students’ understanding of the problems, and their interests in the really basic design of technical problems. This is my vision of education in my field, which has in fact been put into practice. I see the future in teaching these two courses on a facultative basis and offering them to the best students, of course according to their stage of study. These courses aim to motivate students in the field of electromagnetics and high frequency technology in the use of modern ways and methods of work, but at the same time help them to gain a deep physical and mathematical understanding of the problems.

This lecture deals with the progress that I have made in the field of metamaterials, together with my group of coworkers named in the Acknowledgements. It demonstrates the most important part of the activities of my research group in the field of electromagnetics and metamaterials. The full scope of my interests is apparent from my list of publications. Chapters 2 to 8 show some of our original results, presented in scientific journals and conferences. My PhD students and also my undergraduate students have contributed to this process through their research or by working on their projects.

With my research group, I intend to continue in all fields documented in our latest publications, namely in the framework of the project "Investigation of metamaterials and microwave structures with the help of noise spectroscopy and magnetic resonance", funded by the Czech Grant Agency. Among the very broad scope of my plans for the future, I emphasize the following:

- Investigation and modeling magnetoinductive lenses composed of split ring resonators capable of operating with resolution below wavelength. The aim is to improve the sensitivity of measurement in magnetic resonant systems (in cooperation with Prof. Marquez, University of Sevilla).
- The design and realization of homogeneous and isotropic metamaterials on the basis of the random distribution of resonant particles. A very important task is to reduce losses in these particles. We will take into due account the size reduction of elementary resonant particles, by means of which an improvement in metamaterial homogeneity will be attained.
- Investigation, design and realization the "active" particles applicable in active metamaterials. Controlling of the properties of the circuits (tuning and loss compensation) will be realized using subsidiary wave irradiation.

I will continue my tight cooperation with Prof. Omar and students from his department, University of Magdeburg. I also plan to establish the cooperation with Prof. Marquez's Group at University in Sevilla.