New composite gyrotropic double-negative metamaterial

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ABSTRACT

This work is the continuation of our study started in Tralle et al. (J Appl Phys 115:233509, 2014). In it, we examined the possibility of fabricating the metamaterial in a relatively simple way. Our idea was to use the three-component mixture of ingredients, where one of them is responsible for the negative permeability $\mu(\omega)$ of hypothetical metamaterial, while the other two cause the negative value of effective permittivity $\varepsilon_{\text{eff}}(\omega)$. In our previous work (Tralle et al. in J Appl Phys 115:233509, 2014), we considered $\text{Hg}_{1-x}\text{Cd}_x\text{Te}$ semiconductor compound as one of the ingredients of the mixture, where the remaining components were the silver particles and ferromagnetic nanoparticles. As fabrication of the $\text{Hg}_{1-x}\text{Cd}_x\text{Te}$ is related to using mercury which is very poisoning, we tried to exclude this material. In this work, we proved by numerical simulations the possibility of substituting mercury cadmium telluride by $\text{Pb}_{1-x}\text{Sn}_x\text{Te}$. Additionally, taking into account that silver is relatively expensive material, we have also used Cu and Al particles as the cheaper substitute of it. We have shown by computer simulations that by the proper fitting of the parameters, e.g., the radius of nanoparticles, their magnetic moments, the relative concentration of ingredients, etc., it is possible to obtain the double-negative metamaterial that is with negative refraction index in a relatively broad range of temperatures and magnetic fields. The last seems to be very promising in terms of practical applications of metamaterials.

Introduction

Considerable interest has been shown during the last decade in composite materials of unusual physical and first of all optical properties. This wide range of artificial dielectrics and magnetodielectrics is not yet

clearly defined. These materials are commonly called *metamaterials*. Many of the researchers apply the term “metamaterials” to composites which contain inclusions of certain resonance properties and characteristic sizes of less than the wavelength, such as highly conducting needles, split rings, spirals. In 1967

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Veselago [2] considered theoretically the medium, which has simultaneously negative real parts of permittivity and permeability, $\text{Re}[\varepsilon]$ and $\text{Re}[\mu]$, respectively. Veselago himself called these materials ‘left-handed’; left-handedness here refers to the fact that, when the refractive index is negative, the electric field vector $\mathbf{E}$, the magnetic field vector $\mathbf{H}$, and the wave-vector $\mathbf{k}$ of a plane wave make a *left-handed* triad. Since the term left-handedness sometimes is confused with chirality, it is not universally accepted among the researches. In the nice paper [3] Agranovich briefly discussed how people came to the understanding of the phenomenon and clearly pointed out that negative refraction occurs at the interfaces as a natural consequence of the *negative group velocity* of waves propagating in one of the media. It is worth mentioning that there is no unanimity as for the term negative group velocity materials also. Some authors prefer the term negative phase velocity materials. This is because in case of such materials the phase velocity and group velocity are directed against each other and which direction is positive and which is negative is the matter of convention.

The results of Veselago on the other hand, confirmed that this type of medium has to have the negative refractive index, and thereby could exhibit a lot of extraordinary optical properties. The necessary requirement for the material to become negative refractive index material, as it was shown by Veselago and others is the negativity of both the real part of permittivity and real part of permeability, that is why we decided to use in this paper the term double-negative metamaterial. Despite the theoretically envisaged possibility for this type of materials to exist, there was no experimental evidence of metamaterials occurring in nature. In the end of 1990s, Smith et al. [4] and Pendry with co-workers [5] published the seminal papers, in which they have shown that these types of materials can be produced in totally artificial way in laboratory. It is worth mentioning that most of the proposed ever since designs of metamaterials were characterized by ever-increasing sophistication of fabrication methods. Contrary to these, in our previous work [1], we proposed a relatively simple way to produce metamaterial using the mixture of three ingredients, where the one was responsible for the negativity of $\text{Re}[\mu(\omega)]$ and the other two for the negativity of $\text{Re}[\varepsilon_{\text{eff}}(\omega)]$.

As one of the components of mixture, we considered in our previous work the $\text{Hg}_{1-x}\text{Cd}_x\text{Te}$

semiconductor compound. The fabrication of the $\text{Hg}_{1-x}\text{Cd}_x\text{Te}$ related to using mercury, which is very poisoning, that is why now we try to exclude this compound and substitute it by something else. Another goal of present work is to examine theoretically the possibility of producing the three-component material, which exhibits the properties of metamaterial in a broad range of parameters, such as external magnetic fields or ambient temperature by means of extensive computer simulation.

Since the silver is relatively expensive and aluminum and copper have very similar conducting properties as silver, we decided to verify whether the substitution of silver particles by Al and Cu particles leads to appear the domains of parameter space where our composite becomes the double-negative metamaterial, or not. This is another aim of the work.

The model

The model used in the paper is basically the same as in our previous work [1], where the theoretical and numerical examinations of three-component metamaterial have been done. As we have shown there, the mixture of appropriately chosen three components, where one of them is responsible for the magnetic properties of mixture, and the other two contribute to the negativity of real part of effective permittivity (in some range of frequency domain), may result in a negative index of refraction of such medium.

We assumed also that the magnetic nanoparticles responsible for the negativity of real part of magnetic permeability, are the grains of the spherical form. This is for sure the oversimplification, comparing to the irregular shapes of real nanoparticles, but in Ref. [1] our aim was to answer the inquiry, if such a mixture could in principle be such that it leads to the formation of the metamaterial. Of course, in more advanced studies, one should treat the grains as the ellipsoidal-shape or even much more complex, irregular shape. Such study will be reported elsewhere; here instead we concentrate on another problem. As it was mentioned in the *Introduction*, in Ref. [1] for one of the mixture components was chosen $\text{Hg}_{1-x}\text{Cd}_x\text{Te}$ semiconductor compound. The reasoning behind this choice was the following. The electrical properties of this material are crucially dependent on cadmium concentration x . If $x = 0$, that

is in case of HgTe, the material is semimetal with energy gap $E_g < 0$, while in case of $x = 1$ (CdTe) material becomes semiconductor with wide energy gap of about 1.5 eV at 300 K. Thus, changing the concentration of cadmium, one can change the energy gap, and hence the concentration of electrons. In terms of our model, it means that one can pass smoothly and continuously from Lorentz model for dielectric permittivity, where the electrons are almost tightly bounded to Drude model, where they are almost free to move. As a result, cadmium concentration becomes an important parameter of the model; by means of it—among others—one can control the frequency range where the real part of dielectric permittivity can be made negative and forced it to be overlapped with the frequency domain, where magnetic permeability is negative. In this way in Ref. [1] the above mentioned domains with respect to all model parameters, including external magnetic field, temperature, the sizes of magnetic nanoparticles etc., were established. The point however is, that the fabrication process of $\text{Hg}_{1-x}\text{Cd}_x\text{Te}$ involves mercury, which is very poisoning. That is why it is desirable to find the material whose electrical properties are similar to those of $\text{Hg}_{1-x}\text{Cd}_x\text{Te}$, but which does not contain Hg. Then, one should carry out the corresponding computer simulations in order to establish the domains of existence of the hypothetical metamaterial, which could be produced on such a basis. It turns out that the materials similar to $\text{Hg}_{1-x}\text{Cd}_x\text{Te}$, regarding its electrical properties do really exist; it can be, for instance, $\text{Pb}_{1-x}\text{Sn}_x\text{Te}$.

Following the line of reasoning of Ref. [1], since our material is gyrotropic one, we can write down the formulae for the magnetic susceptibilities as follows:

$$\chi_+ = \chi + G, \quad \chi_- = \chi - G$$

and

$$\chi = \frac{\chi_0 \omega_0^2}{\omega_0^2 - 2i\omega\Gamma - \Gamma^2 - \omega^2}, \quad G = \frac{\chi_0 \omega \omega_0}{\omega_0^2 - 2i\omega\Gamma - \Gamma^2 - \omega^2}.$$

These two susceptibilities correspond to two possible circular polarizations of electromagnetic waves which are the eigenmodes of the gyrotropic medium.

Then, the expressions for real and imaginary parts of these magnetic susceptibilities, $(\chi_+$ and $\chi_-)$ are of the form:

$$\text{Re}[\chi_+] = \frac{\chi_0 \omega_0 (\omega_0^2 - \Gamma^2 - \omega^2)(\omega_0 + \omega)}{(\omega_0^2 - \Gamma^2 - \omega^2)^2 + 4\omega^2 \Gamma^2} \quad (1)$$

$$\text{Im}[\chi_+] = \frac{2\chi_0 \omega_0 \omega \Gamma (\omega_0 + \omega)}{(\omega_0^2 - \Gamma^2 - \omega^2)^2 + 4\omega^2 \Gamma^2} \quad (2)$$

$$\text{Re}[\chi_-] = \frac{\chi_0 \omega_0 (\omega_0^2 - \Gamma^2 - \omega^2)(\omega_0 - \omega)}{(\omega_0^2 - \Gamma^2 - \omega^2)^2 + 4\omega^2 \Gamma^2}, \quad (3)$$

$$\text{Im}[\chi_-] = \frac{2\chi_0 \omega_0 \omega \Gamma (\omega_0 - \omega)}{(\omega_0^2 - \Gamma^2 - \omega^2)^2 + 4\omega^2 \Gamma^2} \quad (4)$$

where $\chi_0 = (N\mu_0^2)/3k_B T$, N is the concentration of magnetic nanoparticles, k_B is the Boltzmann constant, T —is the temperature, $\Gamma = \tau^{-1}$, where τ is the relaxation time, $\omega_0 = \gamma H_0$, where γ is the gyromagnetic ratio, H_0 is the external magnetic field and ω is the frequency of external EM-field. The idea here (see for details Ref. [1]) is the following. First, the ‘swarm’ of magnetic nanoparticles can be treated as paramagnetic in the frame of Langevin theory of paramagnetism, because in the absence of an external magnetic field their magnetic moments are distributed at random. Being placed in magnetic field, magnetic moments of individual grains, treated in terms of classical physics start to precess, that is why the frequency domain where $\text{Re}[\mu(\omega)] < 0$ appears in the vicinity of resonance ($\omega_0 \approx \omega$). Second, being in external magnetic field the whole ensemble behaves as gyrotropic material. Third, the magnetic moments of single-domain ferromagnetic nanoparticles are huge in comparison with atomic magnetic moments, that is why the ‘swarm’ of ferromagnetic nanoparticles forms ‘super-paramagnetic’. As a result, the frequency ω_0 can be made greater in order to look for such frequency domains, where the dielectric permittivity and magnetic permeability are simultaneously negative.

Taking into account the above equations one can obtain the expressions for the medium permeabilities, which are described by simple relations (here and later in the text we used SI units)

$$\mu_{\pm} = 1 + \chi_{\pm}.$$

To obtain the equation relating effective permittivity of the mixture with the permittivities of its components (denoted by $\varepsilon_1, \varepsilon_2, \varepsilon_3$), we use the Bruggeman approximation (one of the possible versions of *effective medium theory*). In this approximation, all

ingredients of the mixture are treated on the same footing in a symmetric way. We have

$$f_1 \frac{\varepsilon_1 - \varepsilon_{\text{eff}}}{\varepsilon_1 + 2\varepsilon_{\text{eff}}} + f_2 \frac{\varepsilon_2 - \varepsilon_{\text{eff}}}{\varepsilon_2 + 2\varepsilon_{\text{eff}}} + f_3 \frac{\varepsilon_3 - \varepsilon_{\text{eff}}}{\varepsilon_3 + 2\varepsilon_{\text{eff}}} = 0, \quad (5)$$

where f_i ($i = 1, 2, 3$) are the volume filling fractions of the i th component of the mixture, obeying the following obvious relation:

$$f_1 + f_2 + f_3 = 1. \quad (6)$$

It is clear that the values of effective permittivity of mixture are the solutions of Eq. (5).

Numerical results

The expressions for permittivities for silver particles ($\varepsilon_1(\omega)$) and magnetic nanoparticles ($\varepsilon_2(\omega)$) were derived in Ref. [1]. One should note here, that due to the fact that Ag is a very good conductor, we have used the Drude theory, whereas to obtain the relation for ($\varepsilon_3(\omega)$) we assumed the intermediate value of its real part and added the imaginary part of it in the following way: $\varepsilon_3(\omega) = 12.5 + 4i$ (see, e.g., Refs. [6, 7]). For the aluminum and copper particles, we have used also the Drude theory with parameters presented in Table 1.

The third component of our mixture, i.e., $\text{Pb}_{1-x}\text{Sn}_x\text{Te}$, is characterized by different conductivity properties (which vary from the semiconductor to semimetal phase) depending on tin's percentage content. As it was stated above, from the point of view of electron transport properties, $\text{Pb}_{1-x}\text{Sn}_x\text{Te}$ is similar to $\text{Hg}_{1-x}\text{Cd}_x\text{Te}$, that is, the concentration of free charge carriers (electrons) in it depends strongly on the tin's concentration. So, in order to calculate the $\text{Pb}_{1-x}\text{Sn}_x\text{Te}$ -permittivity, we should take into account the contribution which stems from the presence of free charge carriers. Using Drude model (we can do this, because we can express permittivity in terms of conductivity) we obtain:

Table 1 The values of parameters used in computations to obtain the dielectric function. ε_∞ is the high-frequency limit for permittivity; Γ is the damping constant, and ω_p is the plasma frequency

	ε_∞	$\Gamma[\text{Hz}] (\times 10^{15})$	$\omega_p[\text{Hz}](\times 10^{15})$
Al	~ 1.0	0.92	22.9
Cu	~ 1.0	0.14	13.4

Figure 1 The regions colored in red, orange and yellow (see text) in $T - x$ plane and for the different values of model parameters for the mixture of $\text{Pb}_{1-x}\text{Sn}_x\text{Te}$, ferromagnetic nanoparticles and Ag particles. B , r and m correspond to the domains in which at least one set of the filling factors f_1, f_2, f_3 exists, such that the resulting mixture possesses $\text{Re } n < 0$.

$$\varepsilon_2(\omega) = \varepsilon_\infty(x) - \frac{1}{\varepsilon_0} \frac{\sigma_0 \Gamma_2}{\omega^2 + \Gamma_2^2} + \frac{i\sigma_0 \Gamma_2^2}{\varepsilon_0 \omega(\omega^2 + \Gamma_2^2)}, \quad (7)$$

The concentration of electrons is calculated, using the following relationship [8]

$$n_e(x, T) = (8.92 - 34.46x + (2.25 \times 10^{-3})T + (4.12 \times 10^{-2})xT + 97x^2 \times 10^{14}) \times E_g^{0.75} T^{1.5} \exp[-E_g/(2k_B T)], \quad (8)$$

where E_g (in meV) is the energy gap:

$$E_g(x, T) = 171.5 - 535x + \sqrt{(12.8)^2 + 0.19(T + 20)^2}.$$

To get the mobility of electrons in $\text{Pb}_{1-x}\text{Sn}_x\text{Te}$, we used the experimental data obtained in Ref. [9]. In this work, the authors present the carriers mobility versus temperature for different values of tin content. For our purposes, we interpolated the experimental data for boundary values of tin content in $\text{Pb}_{1-x}\text{Sn}_x\text{Te}$ considered there. The corresponding relations for $x = 0.014$ and $x = 0.124$ are presented below:

$$\mu_{0.014}(T) = 345.729 + \frac{1.2659 \times 10^8}{T^2}$$

$$\mu_{0.124}(T) = -118.819 + \frac{226105}{T}.$$

It is worthy to mention that in a lengthy literature devoted to semiconductors, it is commonly accepted to denote the mobility of material by means of Greek character μ ; on the other hand, in Electrodynamics μ is used to denote the magnetic permeability of the material, that is why in order to not confuse them, we denote mobility by means of $\mu_{\dots}$ or μ_{mob} , while the magnetic permeability as μ .

The effective mobility of electrons (in $\text{cm}^2(\text{V s})^{-1}$) for given temperature was obtained by assuming the linear dependence of electron's mobility on Sn content (in the range between the boundary values) as follows:

Figure 2 Real and imaginary parts of the refractive index of the composite for selected cases presented on the ternary diagram. On each axis of the triangle, the relative contribution of individual components of the composite are indicated, which are expressed as the values of the filling factors f_1, f_2, f_3 . Model parameters: **a** $B = 0.2T, r = 8\text{nm}, m = 10^4 \mu_B, T = 300\text{K}, x = 0.08$; **b** $B = 0.2T, r = 8\text{nm}, m = 10^4 \mu_B, T = 300\text{K}, x = 0.08$; **c** $B = 0.4T, r = 8\text{nm}, m = 10^4 \mu_B, T = 300\text{K}, x = 0.08$; **d** $B = 0.4T, r = 8\text{nm}, m = 10^3 \mu_B, T = 290\text{K}, x = 0.08$.

$$\frac{\mu_\alpha(T) - \mu(x, T)}{\alpha - x} = \frac{\mu_\alpha(T) - \mu_\beta(T)}{\alpha - \beta},$$

where $\alpha = 0.014$ and $\beta = 0.124$. As a result we have

$$\mu_{\text{mob}}(x, T) = \frac{\mu_{0.014}(T) - [\mu_{0.014}(T) - \mu_{0.124}(T)]}{0.124 - 0.014} \quad (9)$$

To obtain the mixture's permeability, we use the relation (see Ref. [1])

$$\mu = f_1\mu_1 + f_2\mu_2 + f_3(\chi + 1) \approx f_{12} + (1 - f_{12})(\chi_+ + 1), \quad (10)$$

where $f_{12} = f_1 + f_2$, and the corresponding permeabilities μ_1, μ_2 of two non-magnetic components are approximately equal to 1.

Our goal is to figure out if metamaterial exists in a broad range of temperatures. Of course, the characteristics of composite are dependent not only on the temperature, but the effective values of permittivity and permeability of the composite are depending on eight parameters: temperature, external magnetic field, radius of nanoparticles, their magnetic moments, tin content in $\text{Pb}_{1-x}\text{Sn}_x\text{Te}$ and relative concentrations f_1, f_2, f_3 of the components in a mixture. Additionally, we must determine the appropriate frequency range for which the composite has the property of being metamaterial. So our objective is to find those combinations of the model parameters, for which the real parts of the permittivity and permeability of the composite are simultaneously negative. We have eight unknown parameters to determine and hence our parameter searching space is eight dimensional. The simplest and imposing solution is just to take and substitute the values of subsequent parameters and to see if they are good, but such a procedure is tedious and lengthy and requires the evaluation of complicated expressions (7)–(10). One of the alternatives is the use of some

kind of optimization method, but due to high non-linearity of the model equations, it is not a good solution, since it does not guarantee to find the global solution, and even it does not always succeed. The difficulty of the simulation which is related to the multidimensionality of the model can be resolved by taking a procedure which effectively and fast leads to the answer if the composite under consideration has a property of being a metamaterial for a particular set of parameters. This is why our choice is based on a systematic search as described below. In details, our approach is the following. Since the frequency for which our composite becomes a metamaterial could be in the region covering a range of several orders of magnitude, the key issue at the beginning is to effectively determine its value. We start with the localization of the frequency range for which the real part of the permeability for our composite could be negative. We search for it in the region of the anomalous behavior of permeability, where the real part of the permeability has its minimum. We want to find the smallest possible value of $\text{Re}[\mu]$. To attain this objective, we calculate the first derivative of $\text{Re}[\chi_+]$, equalize it to zero, and solve the obtained equation for ω . From two roots, we select the greater one, ω_R , for which the real part of χ_+ reaches its minimum. Furthermore, from the properties of $\text{Im}[\chi_+(\omega_R)]$, it follows that $\text{Im}[\chi_+(\omega_R)] > 0$. At that point, we make sure that for the frequency ω_R the real part of μ of the composite is to be negative; otherwise, the composite could not be metamaterial, and we stop further calculations avoiding evaluating expressions (7)–(10). The calculated value of ω_R is determined by properties of third component of composite, i.e., ferromagnetic nanoparticles, whose behavior in magnetic field is controlled by four parameters of the model, namely the strength of the external magnetic field itself, radii of particles, their magnetic moments, and the temperature. Having set those four model parameters, we try to choose the remaining ones to get the negative real part of ϵ_{eff} of the composite at the same time requiring the imaginary part of ϵ_{eff} to be nonnegative. To achieve this goal, we can still use three degree of freedom, i.e., we can change x , the concentration of tin in $\text{Pb}_{1-x}\text{Sn}_x\text{Te}$, and f_1, f_2, f_3 , relative fractions of components of the composite [in fact only two of them are independent due to relation (6)]. If at this point, all the required relations are satisfied we consider the determined frequency as such for which the

composite has a property of being a metamaterial. Computationally, this is the most demanding part of the entire calculation as it requires testing further combinations of parameter values and evaluating relevant complex formulas (7)–(10). Such searching procedure is much more effective, and faster leads to the goal than to blindly test all possible combinations of values from all parameters set.

Figures 1, 2 and 3 show the results of our simulations for the mixture of $\text{Pb}_{1-x}\text{Sn}_x\text{Te}$, ferromagnetic nanoparticles and Ag particles. Figure 1 presents in $T-x$ plane, for different parameter values of B , r , and ferromagnetic nanoparticle's magnetic moment m , the domains where at least one set of the filling factors f_1 , f_2 , and f_3 exists, such that the resulting mixture has the real part of the refractive index less than zero. The different colors have the following meaning: denote by D_1 the region colored in yellow, the domain colored in orange as D_2 , and the region colored in red as D_3 . Then, D_1 corresponds to $m = 10^2 \mu_B$, $D_1 \cup D_2$ corresponds to $m = 10^3 \mu_B$ and $D_1 \cup D_2 \cup D_3$ corresponds to $m = 10^4 \mu_B$. We observe that the greater value of nanoparticle magnetic moment is, the greater is the domain of metamaterial existence. In Fig. 2 we present the real and imaginary parts of refraction index of the hypothetical metamaterial as some kind of 'phase diagrams,' where the values of them are shown in the form of the triangular color maps and where the edges of triangles correspond to the changing of the f_1, f_2, f_3 , the relative

fractions of components of the composite. In Fig. 3 we present the color map of angular frequency ω_R for different values of model parameters B and r .

Figures 4 and 5 present the results of our simulations for the mixture of $\text{Pb}_{1-x}\text{Sn}_x\text{Te}$ with ferromagnetic nanoparticles and with Al and Cu particles, respectively. The simulations were carried out for temperatures and magnetic field strengths in the range of $T \in (150\text{--}300 \text{ K})$, and $B \in (0.2\text{--}0.8 \text{ T})$, respectively. The corresponding ferromagnetic nanoparticles' radii were set to 6, 7, and 8 nm. In the whole range of considered parameters the mixtures exhibit the metamaterial properties, both with Al and Cu particles. However, since from the point of view of the possible applications of metamaterials, the low magnetic fields and low temperatures are more desirable; our concern in this work was to find the existence domains for low magnetic fields and the temperatures close to room temperatures. Below only the results for the magnetic fields in the range of $B \in (0.2\text{--}0.4 \text{ T})$ are shown.

Of course as it usually happens, if produced, such a metamaterial will show its disadvantages or limitations in use, too. First of all, a negative refraction can be achieved only if the material is in an external, although moderate magnetic field. In our calculations, B was restricted to 0.8 T. On the other hand, in some circumstances, it could be an advantage, since switching magnetic field on and off, one can trigger on/off the *left-handedness* or rather, the state of matter when the material becomes metamaterial. The metamaterial which was examined by us previously [1] and which contained $\text{Hg}_{1-x}\text{Cd}_x\text{Te}$, in most of the cases studied by us exhibited relatively great imaginary parts of ϵ_{eff} and μ , which means that it would be characterized by significant losses. Sometimes, one can encounter with the statement that the losses render photonic negative refraction index media useless [10]. Recently, however, some authors argued [11, 12] that the losses in metamaterials can be used for developing new and interesting devices, too.

Conclusions

In this work, following the method elaborated by us previously [1], we examined the possibility to get the composite metamaterial by making mixture of three ingredients, where one is responsible for the negativity of $\text{Re}[\mu(\omega)]$ and the other two for the negativity

Figure 3 Color map of angular frequency ω_R for different values of model parameters B and r .

Figure 4 Diagram for the composite containing Al as one of the components. The regions colored in red, orange and yellow (see text) in $T-x$ plane and for the different values of model parameters for the mixture of $\text{Pb}_{1-x}\text{Sn}_x\text{Te}$, ferromagnetic

of $\text{Re}[\varepsilon_{\text{eff}}(\omega)]$. We have shown that it is possible to substitute such material as $\text{Hg}_{1-x}\text{Cd}_x\text{Te}$, whose fabrication is dangerous in regard of using mercury at its fabrication, by $\text{Pb}_{1-x}\text{Sn}_x\text{Te}$ which is much less poisoning for the environment. In the work, we carried out computer simulations in the frame of the proposed model in order to establish the domains of existence of such material, searching through a vast

nanoparticles and Al particles. B , r and m correspond to the domains in which at least one set of the filling factors f_1, f_2, f_3 exists, such that the resulting mixture possesses $\text{Re } n < 0$.

parameter space. We have seven parameters to be controlled in course of simulations, and these are the temperature, external magnetic field, radius of nanoparticles, their magnetic moments, fraction of tin in $\text{Pb}_{1-x}\text{Sn}_x\text{Te}$ —compound, and the relative concentrations f_1, f_2 and f_3 of the components in a mixture. As a result, the domains where the material

Figure 5 Diagram for the composite containing Cu as one of the components. The regions colored in red, orange and yellow (see text) in $T-x$ plane and for the different values of model parameters for the mixture of $\text{Pb}_{1-x}\text{Sn}_x\text{Te}$, ferromagnetic

becomes negative refractive index material, were established relatively to all parameters characterizing the mixture. Additionally, we have shown that the mixture of three compounds considered by us exhibits the metamaterial properties (for the parameter values described above) if we substitute Ag by Al or Cu particles.

nanoparticles and Cu particles. B , r and m correspond to the domains in which at least one set of the filling factors f_1, f_2, f_3 exists, such that the resulting mixture possesses $\text{Re } n < 0$.

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