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Losses in metamaterials: Restrictions and benefits

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A R T I C L E I N F O

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A B S T R A C T

Results of studies in the influence of losses on the superresolution achieveability are presented. The studies involve modeling and realization of superresolution devices. It is found that rigorous electrodynamic models that are not based on homogenization of composites can be effectively used in modeling devices with metamaterials. The possibilities to compensate losses in near-optic metamaterials by means of "active" inclusions are discussed; they appear to be rather doubtful. Alternatively, new designs are suggested for applications where losses are desirable.

1. Introduction

More than 60 years have passed since the first publication of Mandelshtamm's investigations [1] where he indicated the possibility of negative refraction caused by antiparallel directions of group velocity and wavenumber of electromagnetic wave. And 50 years have passed since Sivuhin [2] published his work that showed the specific properties of a matter with negative ε and μ, and more than 40 years have passed since Prof. Veselago [3] summed up those results and introduced a remarkable device, i.e. a lens which is now called after him. In 2000 Prof. Pendry demonstrated [4] that the Veselago lens possessed still another property, that is the images of two sources separated by a distance much less than a wavelength could be transferred undistorted, and thus the diffraction limit could be overcome. A great number of articles devoted to this subject have been published lately. In 2003–2004 a few publications appeared practically simultaneously [5–9]. They were devoted to the analysis of the influence of material losses to the superresolution efficiency. All of them contain almost identical conclusions, namely, that the losses lead to substantial deterioration of resolution quality. However, the reduction of lens thickness changes the situation dramatically. But in that case the image appears too close to the object, i.e. in the near field. It should be noted that the losses should by all means be present in materials with negative refraction. Prof. M. Stockman [10] has proved that negative refraction can be reached only if substantial losses are present. Note, the losses could be compensated by means of active media. In this case the Kramers–Kronig's relation used for conclusions about the inevitability of losses in negative refraction media [10] becomes inapplicable because the system is non-conservative. In 2008 a publication [11] appeared which described a 2D structure suitable to create a circuit-based metamaterial. Though, in that case the circuit contained additional amplifying elements. As the authors claimed, an active circuit showing negative group delay (NGD) and gain simultaneously was for the first time designed and implemented at microwave frequencies.

Therefore it would be interesting to consider to what extent the image could be improved if an active medium is used. Here we shall dwell on the following:

1. what could be done to improve superresolution if we use a matter with minimum possible losses?
2. what could be obtained if we use an active medium for the same purposes?
3. finally, we shall show that the losses in metamaterials can in some cases lead to creation of rather useful devices.

2. Losses and the problem of superresolution

We tried to assess the distorting effect of losses in a metamaterial through simulating separate registration of two closely spaced sources with the help of a flat Veselago–Pendry lens; we shall not yet consider other systems for reaching superresolution (like hyperlens or near-field microscopy).

Let us see what limits could be achieved by reducing losses. In [12] superconductive metamaterial with wire and SRR inclusions made of niobium was investigated for that purpose. Effective losses at the niobium temperature of several degrees (Kelvin's scale) were about 6 times less than at a normal state. In particular,

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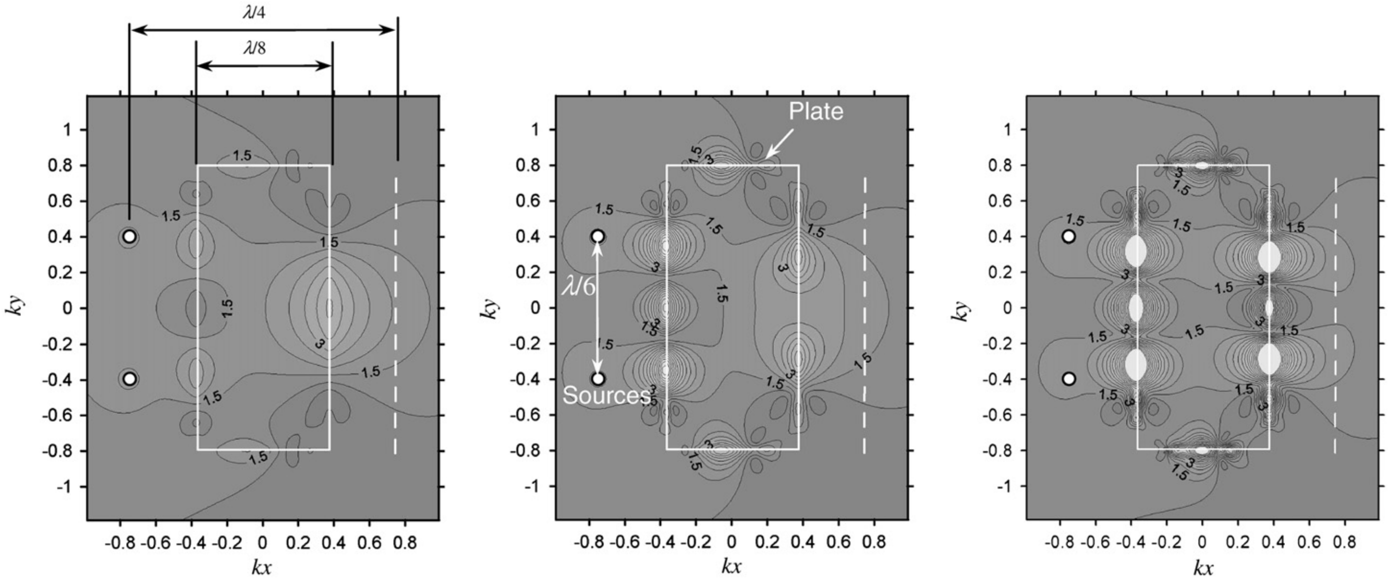
an imaginary part of permittivity ε'' changed from $\varepsilon''=1.6\times10^{-2}$ (ordinary metal) to $\varepsilon''=2.6\times10^{-3}$ at a superconducting state for 10.75 GHz frequency.

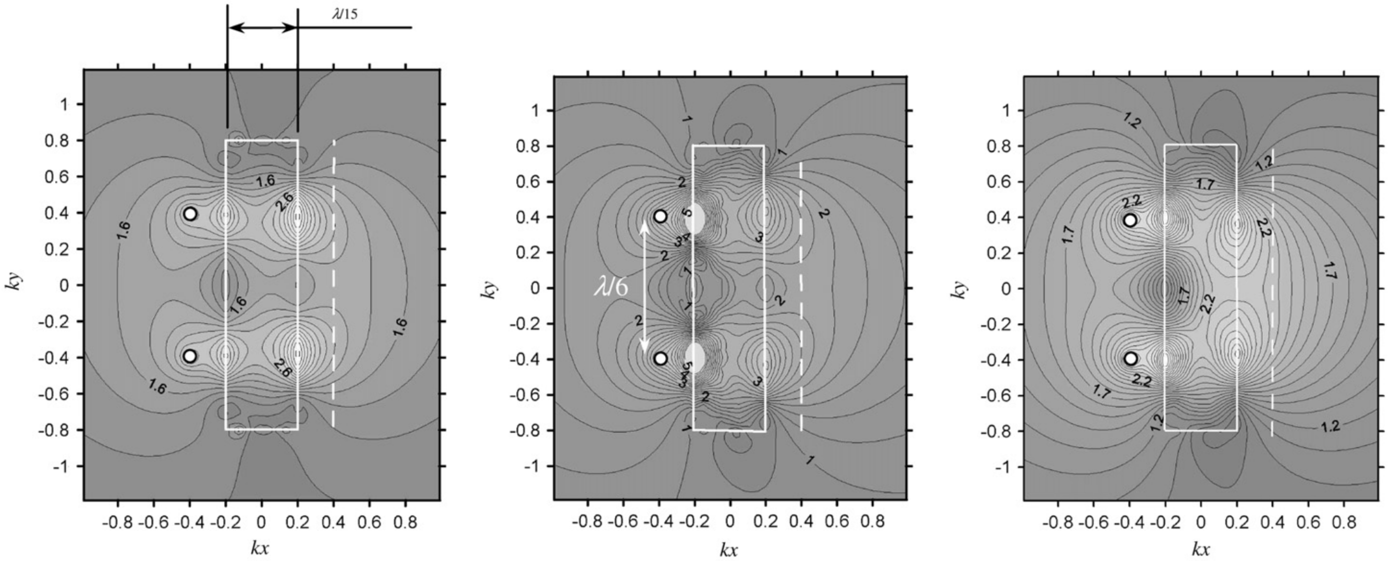
Let the lens thickness be small (about $\lambda/15$), the sources are separated by $\lambda/6$. Calculations indicate, that in this case at $\varepsilon=\mu=-1=i0.05$ the superresolution is observed. If we increase the lens thickness twice, the superresolution disappears. To obtain the superresolution at the given lens thickness the losses should be considerably reduced (see Fig. 1). We shall make them in our simulation 3 times less than in the experiment with superconductive niobium. And even at this quite small value and at the plate thickness of $\lambda/8$ the images of two sources are hardly distinguished.

Now we shall see what could be attained with the help of an active medium. Let us look at the Fig. 2. The plate thickness is $\lambda/15$. Let us use a mixture of two materials, one being active $\varepsilon=\mu=-1+i0.15$, the other is passive, $\varepsilon=\mu=-1-i0.2$, and consider various composites with inclusions of different sizes and structures. Let us consider three options, the lattice constant (the doubled size of inclusions) is equal to $\lambda/150$, $\lambda/30$ and $\lambda/15$. It should be noted here that we do not know how to create an active matter with $\varepsilon=-1$, while the use of active matter with reasonable positive ε' practically destroys the superresolution. We see (Fig. 2) that the use of rather specific active inclusions could be efficient only if the size of inclusions is at least few times less than the resolution interval. From the physical point of view it is clear that if we prepare a mixture of materials with the same real parts and with the imaginary parts of different signs, than the media will be homogenized provided the inclusions size is very small, thus an efficient near-lossless media could be obtained.



$\varepsilon=\mu=-1-i0.05$ $\varepsilon=\mu=-1-i0.005$ $\varepsilon=\mu=-1-i0.001$

Fig. 1. Field of a pair of filament sources nearby a metamaterial plate with different level of losses.



$\Delta=\lambda/150$ $\Delta=\lambda/30$ $\Delta=\lambda/15$

Fig. 2. Field of a pair of filament sources nearby a metamaterial plate with active inclusions of different size $\Delta/2$.

However, to have this result we should be able to manufacture active inclusions with negative permittivity that are hundred times less than a wavelength.

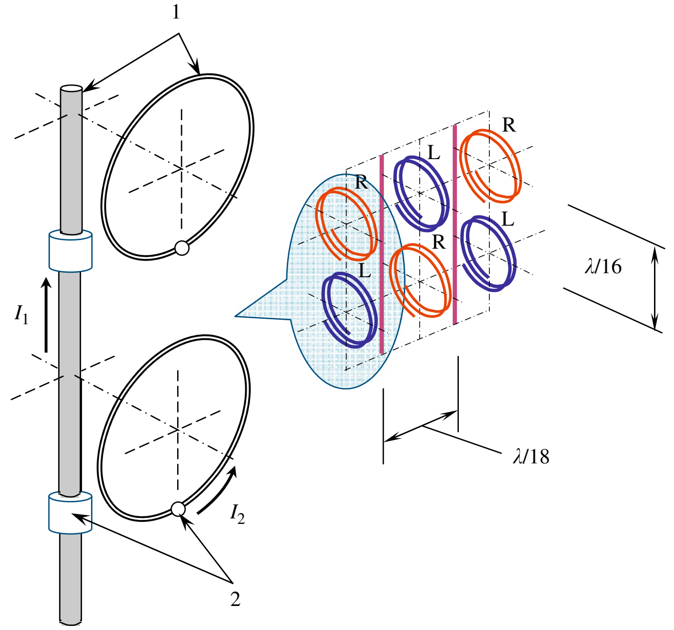


Fig. 3. Model of a metamaterial (the composite whose fragment is shown in the inset) with active insertions: (a) a lossy conductor and (b) active capacitive loads.

All said above deals with hypothetic materials that can be described by effective properties. As was shown previously [13], the mentioned approximation becomes incorrect for thin lenses. Therefore, further investigations of active medium related effects would be carried out with the help of integral equations. Let us consider a real flat lens with wire and spiral inclusions. To calculate currents in inclusions we used Pocklington's equation. Let us consider for numerical simulations a rather simple model (Fig. 3). That system could be actually manufactured in practice. Namely, we insert into the ring and wire splits active inclusions as shown in the figure. It is noteworthy that the energy is introduced locally while the losses are distributed along rings and wires uniformly. And we do not see any other realistic way of having active compensation in microwave regime.

We may start from observing what occurs in realistic thin lens at different values of conductivity. The three options are shown in Fig. 4, the conductivity of the "almost perfect conductor" was chosen to be close to that of copper at a superconducting state. The goal was to obtain the same resolution (field distribution) as with the superconductor while using active inclusions to compensate losses in ordinary copper.

Fig. 4 shows the distribution of electric fields for different values of inclusion's conductivity. For the case of copper conductor we varied the active part of reactance to get an optimal resolution. We have failed to get the resolution that is observed in almost ideal conductor (Fig. 4a), though some increase of image quality could be observed (compare Figs. 4b and c).

Previous considerations showed that even the application of superconducting niobium would not lead to a superresolution image transfer further than few fractions of a wavelength. So we would like to make the following conclusion: neither conductivity

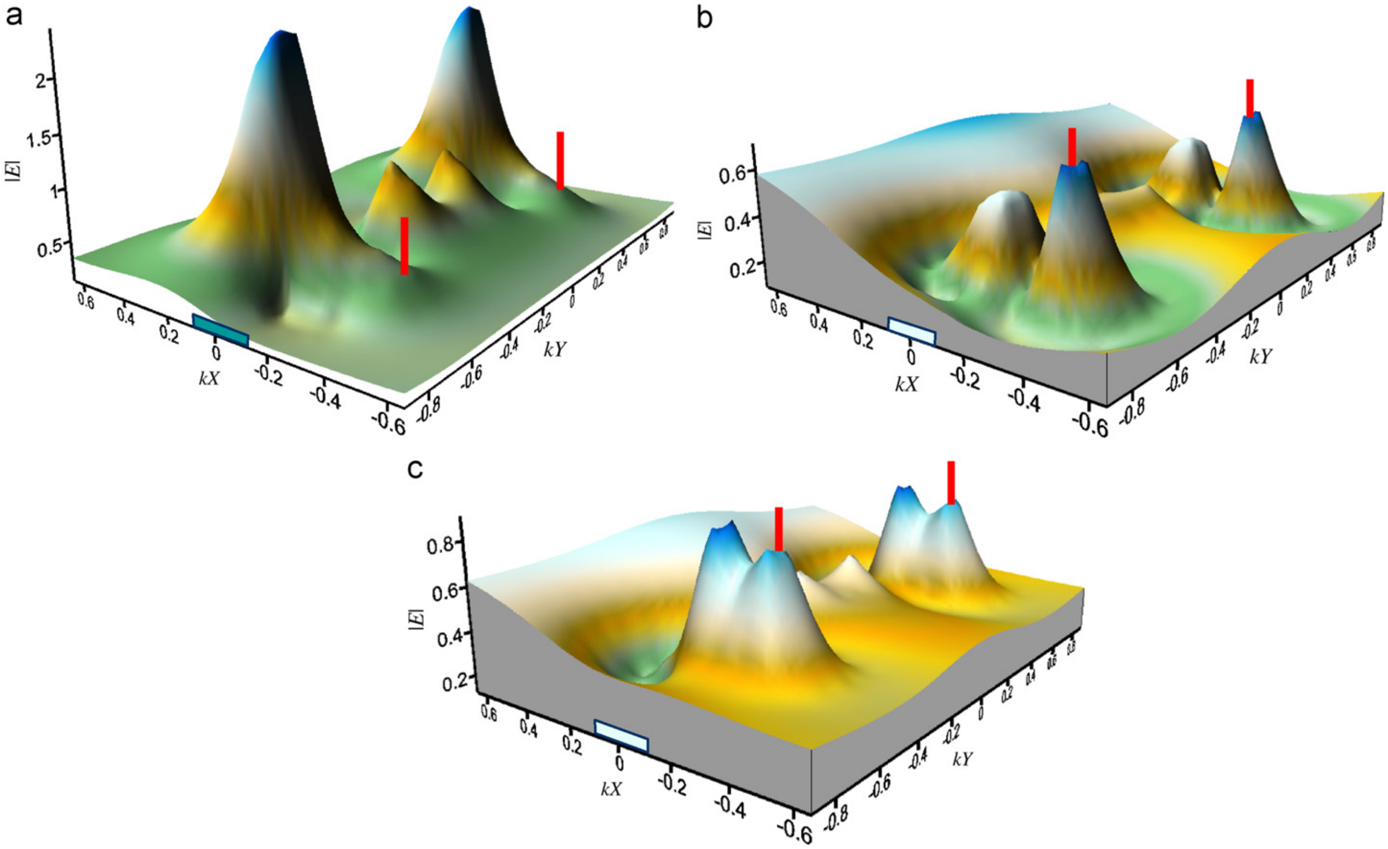


Fig. 4. Field of filament sources near a metamaterial plate with wire elements made of an almost perfect conductor (a), copper (b), and copper with active inclusions (c).

reduction, nor active media application could provide the possibility to use the Veselago's lens for creating superresolution at distances more than a few fraction of a wavelength from an object.

3. Absorbers and open resonators based on metamaterials

The losses inherent to metamaterials can successfully be employed in certain applications. In studies [14,15], it is noted that, being used as absorbers of electromagnetic waves, metamaterials may be superior to conventional materials. A reason for such an advantage is the possibility of artificial realization of (optimal) radiophysical properties that are not exhibited by conventional materials: for example, a substantial level of absorption of the electromagnetic-wave energy (reasonably large values of imaginary parts of μ and ε) can be obtained in a coating that is well-matched with the exterior space. Simultaneously, such a coating can have a small weight and thickness and exhibit good operational characteristics. Inclusions which were found to be suitable for those coatings are suggested and analyzed in [16]. Since the unique properties of metamaterials are manifested in a narrow frequency band, there is a natural restriction on the bandness properties of such coatings. But in many cases (e.g., when problems of electromagnetic compatibility are solved), it is more important to provide for a wide angular range of a coating's operation. This is just the case in which metamaterials can be very helpful.

The problem of radiation of a point (or filament) source over a conducting plane with a radio-wave absorbing coating can be considered as a model problem. The key point is to find the plane's coating such that this structure should absorb the maximum portion of the energy radiated by a lumped source, to determine this portion, and to find a method for realizing the necessary coating. It is evident that, in the absence of a coating, the total energy of the source is radiated into the exterior half-space. In the other extreme case, i.e., in the presence of an ideal nonreflecting coating (as well as in the absence of a coated plane), an omnidirectional source radiates equal powers into the upper and lower half-spaces. Thus, a half of the source's energy is radiated into the exterior space.

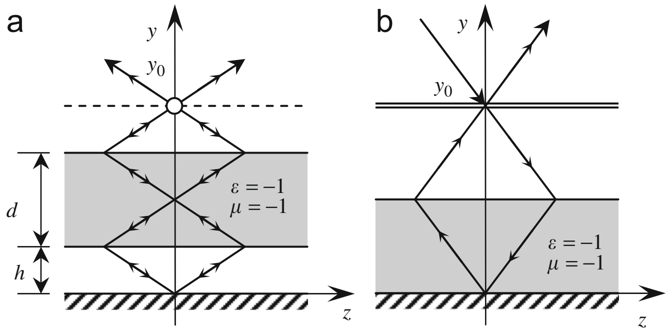


Fig. 5. Ray diagram illustrating suppression of the radiation of a point source in the exterior space (a) and the diagram illustrating the operation of an absorber with a metamaterial and semitransparent film (b).

As has been shown in [17], with the use of a metamaterial, it is possible to construct a passive system that ensures the complete compensation of a source's energy in the upper half-space and, accordingly, ensures the transfer of the source's total energy into the lower half-space.

Let a filament source with a single, x, electric-current component be located at point y_0 over the conducting plane $y=0$. Consider a focusing plane plate (a Veselago lens) that has the thickness $d=y_0/2$ and is fabricated from a metamaterial with $\varepsilon=-1$ and $\mu=-1$. We place this plate between the source and the conducting plane at height h such that $0<h<y_0/2$. Then, the focal point and its mirror image are superposed directly on the conducting plane (see, e.g., the ray diagram in Fig. 5a). Let us calculate the phase incursion taking into account that the wave phase velocity in the plate is negative and the phase of the wave reflected from a metal is reversed. Then, we obtain that, in the region $y>y_0$, the primary and secondary fields compensate each other. In the ideal case when the loss in the system is negligibly low, the total field in the upper half-space approaches zero. The rigorous solution of the corresponding boundary value problem leads to the same conclusion [17]. Moreover, the computations have shown that, in the case of a real lossy metamaterial (e.g., when $\varepsilon=\mu=-1-i0.1$ and the layer's thickness is $\lambda/12$), most (about 99%) of the energy is transferred into the lower half-space and absorbed there (Fig. 6).

In addition to the field compensation in the upper half-space, zones with a high field concentration are formed near the plate's faces. The presence of these zones is due to accumulation of the reactive energy. The maxima are especially large in the case when the plate is located directly on the metal at $h=0$. Therefore, new-type open resonators without usual restrictions on the geometric thickness of a system can be created on the basis of such structures. Note that, previously, another idea of a thin resonator based on a metamaterial (a closed resonator with a metamaterial placed in between conducting planes [18]) was proposed. Another structure of an open resonator based on a photon crystal or a metamaterial with a negative refractive index is also known [19].

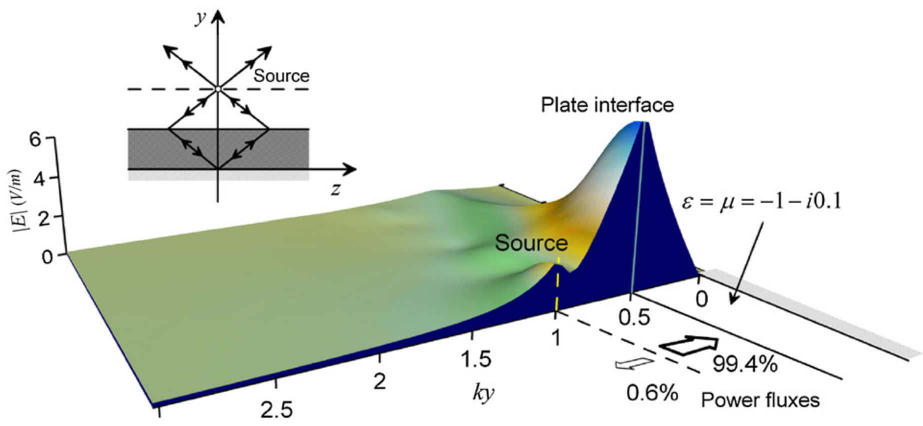


Fig. 6. Field power transfer in the presence of a realistic absorptive metamaterial plate.

We also suggest that new absorbers of the plane-wave energy can be created on the basis of metamaterials. Their special properties can be provided through the appropriate compensation of the phase incursion of the wave propagating in a metamaterial. A possible structure of an absorber of a perpendicularly polarized wave is shown in Fig. 5b. Consider two waves: the wave that is reflected from the film and the wave that is transmitted into the region $y < y_0$ and, when reflected from the conducting substrate, undergoes the π change of the phase. When the correct characteristics of a semitransparent film (the reflection and transmission coefficients of the film) are chosen, these two waves are mutually suppressed. When $y < y_0$, the total electric path of a ray is zero for any incidence angle of the wave. Hence, in contrast to classical radio-wave absorbing materials [20], in particular, the Salisbury screen, the radio-wave absorbing coating described above can operate within a wide angular range. As in the case of the system of complementary metamaterials previously proposed [21], there are no physical restrictions on the thickness of an absorber having the structure described above. The experimental results [22] have confirmed the expected good angular properties of such metamaterial-based composite absorbers.

4. Conclusions

Thus, it is seen that neither conductivity reduction, nor active media application could provide the possibility to use the Veselago's lens for creating superresolution at distances more than a few fraction of a wavelength from an object. However, the use of metamaterials offers new possibilities for the development of absorbers and resonators, including open resonators.

References

[1] L.I. Mandelshtam, Lectures given on February 26 1940 and on May 5 1944// Complete issue of works, vol. 5. Moscow: Izdatelstvo trudov AN SSSR, 1950.
[2] D.V. Sivuhin, About the energy of electromagnetic field in dispersing media, Optica i Spectroskopiya 3 (1957) 308 (in Russian).
[3] V.G. Veselago, Sov. Phys. Usp. 10 (1968) 509.
[4] J.B. Pendry, Phys. Rev. Lett. 85 (2000) 3966.
[5] N. Fang, X. Zhang, Appl. Phys. Lett. 82 (2003) 161.
[6] D.R. Smith, D. Schurig, M. Rosenbluth, et al., Appl. Phys. Lett. 82 (2003) 1506.
[7] X.S. Rao, C.K. Ong, Phys. Rev. E 68 (2003) 067601.
[8] A.N. Lagarkov, V.N. Kissel, in: L. Hock, O.C. Kim, S. Matitsine, G.Y. Beng, (Eds.), Proceedings of the International Conference on Materials for Advanced Applications, Symposium F: Electromagnetic Materials, World Scientific, Singapore, 2003, p. 145.
[9] A.N. Lagarkov, V.N. Kisel, Dokl. Phys. 49 (2004) 5.
[10] M. Stockman, Phys. Rev. Lett. 98 (2007) 177404.
[11] B. Ravelo, A. Perennec, M. Le Roy, Y. Boucher, IEEE Microwave Wireless Comp. Lett. 17 (2007) 861.
[12] M. Ricci, N. Orloff, S. Anlage, Appl. Phys. Lett. 87 (2005) 034102.
[13] V.N. Kissel, A.N. Lagarkov, Phys. Rev. B. 72 (2005) 085111.
[14] A.N. Lagar'kov, V.N. Kisel', Dokl. Phys. 46 (2001) 163.
[15] V.N. Kisel', A.N. Lagar'kov, Elektromagn. Volny Elektron. Sist. 7 (2002) 62.
[16] A.N. Lagarkov, V.N. Semenenko, V.A. Chistyaev, et al., Electromagnetics 17 (1997) 213.
[17] V.N. Kisel, A.N. Lagarkov, Phys. Rev. E 76 (2007) 065601.
[18] N. Engheta, IEEE Antennas Wireless Propag. Lett. 1 (2002) 10.
[19] S. He, Y. Jin, Z. Ruan, J. Kuang, New J. Phys. 7 (2005) 210.
[20] K.J. Vinoy, R.M. Jha, Radar Absorbing Materials: From Theory to Design and Characterization, Kluwer Academic, Boston, 1996.
[21] A. Alu, F. Bilotti, N. Engheta, L. Vegni, in: Roberto D. Graglia (Ed.), Proceedings of the Joint Ninth International Conference on Electromagnetics in Advanced Applications (ICEAA 2005) and the Eleventh European Electromagnetic Structures Conference (EESC 2005). Torino, Italy, 2005, p. 229.
[22] A.N. Lagarkov, V.N. Kisel, V.N. Semenenko, Prog. Electromagn. Res. Lett. 1 (2008) 35.