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Effects of the interplay of dissipation and chirality in magnetoelectric materials

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Certainly a very proper place to discuss the extremely rich variety of possible macroscopic behavior patterns of chiral materials is Belorussia with its great tradition on wave–material interaction studies, and, in particular, the University of Gomel where an active school with focus on magnetoelectric materials, lasers, and other nonlinear phenomena was founded several decades ago. The effect of Academician B.V. Bokut' (and here not forgetting the works of Academician F.I. Fedorov) continues to be felt through his writings and in the scientific output of his younger colleagues and students. Today, to an even greater degree, the results of the Belorussian school are available to the "Western" scientific community (see, for example [1]).

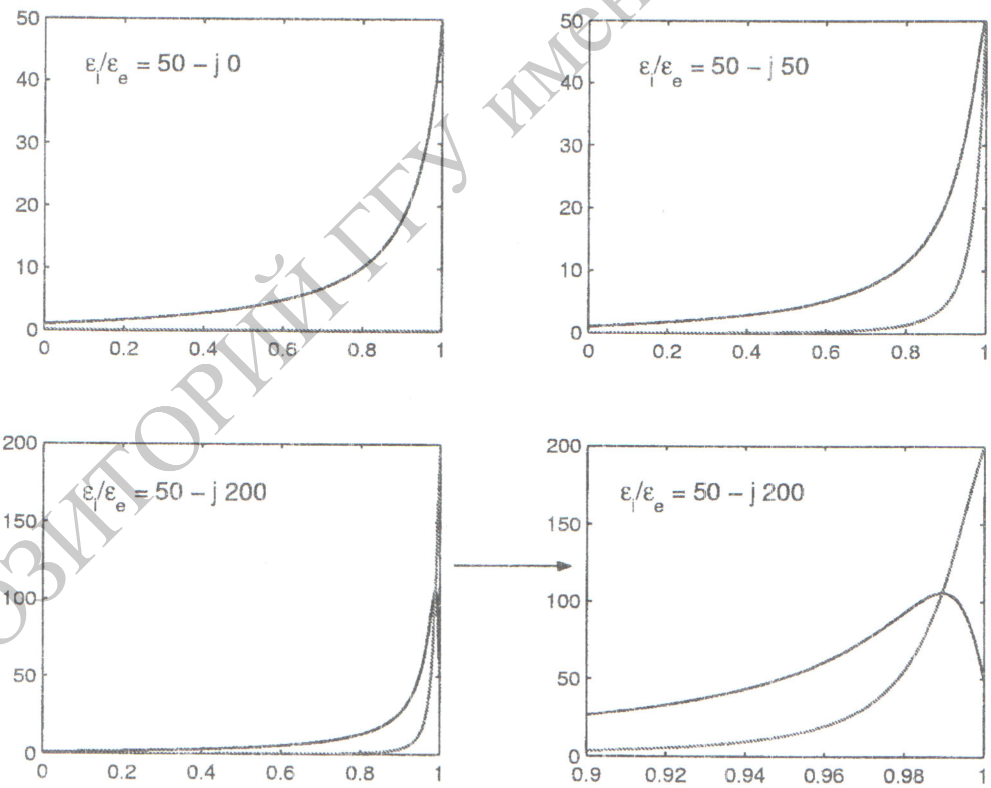

Figure 1. The percolation effect seen in Maxwell Garnett prediction for the effective permittivity of a mixture with the dielectric contrast ϵ_i/ϵ_e. The real part of the inclusion permittivity is kept the same ($\epsilon_i'/\epsilon_e = 50$), but the imaginary part is varied in the different figures. Dark line: the real part; light line: the imaginary part of $\epsilon_{\rm eff}$.

In this presentation I will focus on certain strange and counterintuitive ways in which the magnetoelectric materials can behave on their macroscopic level. It is of course acceptable that complex materials behave in a complex manner but certainly always there are the laws of physics that set unbreakable boundary conditions to the possible patterns of characteristics these materials may display. There exists literature on the modelling of the effective material parameters of chiral and other magnetoelectric composites [4, 5] and some of the "emergent" macroscopic phenomena are discussed in those references. Here, in this presentation, I would like to remind ourselves on these special effects and strange phenomena, and also intend to go somewhat further to phenomena that perhaps have not been given any attention before, even within the bi-anistropic community.

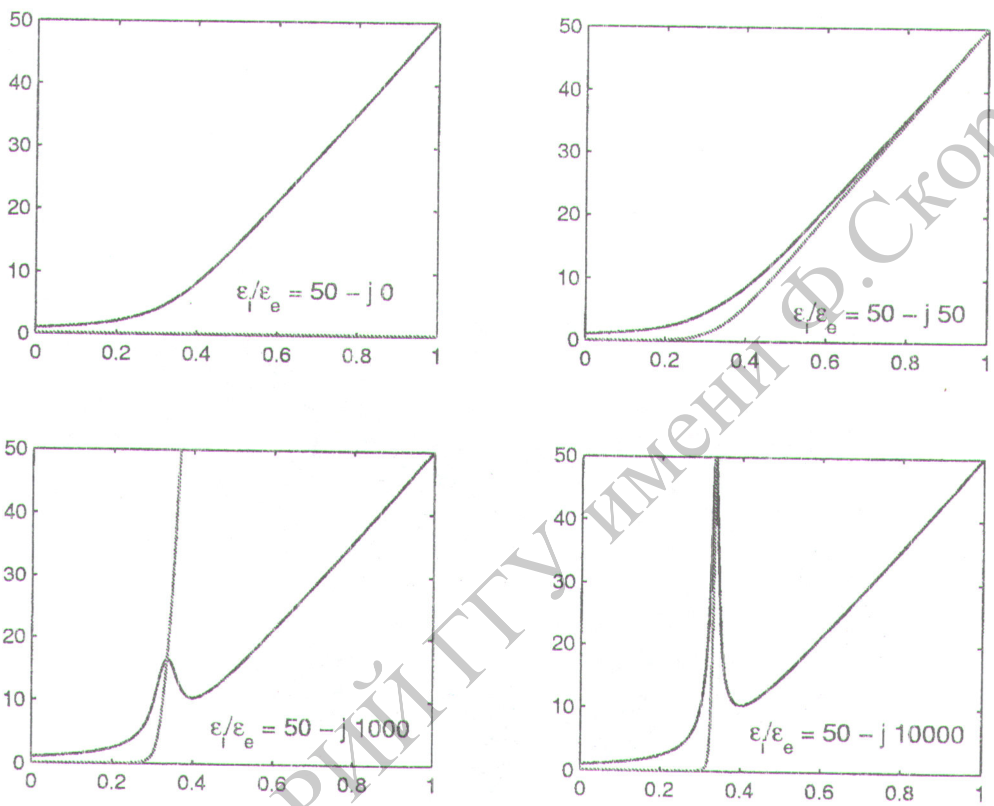

Figure 2. The same as in Figure 1; for the Bruggeman prediction.

One of the promising phenomena in this respect is *percolation*, not only in magnetoelectric material modelling but also in soil moisture studies, oil penetration in rocks, the spread of epidemics, forest fires, and wafer-scale integration in the manufacture of microchips [7]. Percolation is a nonlinear phenomenon; a very abrupt change in the behavior of certain parameters of a percolating material takes place there. In the modelling of random materials, percolation becomes important, when the material is composed of two components that have a strong contrast in one (or several) of their constitutive material parameters, for example permittivity.

And the percolation characteristics can be enhanced greatly by including losses to the mixture. Consider, for example, a mixture where spherical lossy dielectric scatterers are embedded in vacuum with volume fraction f. The effective permittivity of such a mixture is illustrated in Figure 1 where it is calculated according to the famous Maxwell Garnett formula [8], and also in Figure 2 where the model is the nearly-as-famous Bruggeman [9]. The percolatory abrupt change appears in the imaginary part of the effective permittivity, which happens at the volume fraction of $f = 0.33$ for the Bruggeman case, and which comes to $f = 1$ for Maxwell Garnett. But at least as interesting is the behavior of the real part. For certain conditions, the real part of the effective permittivity can become larger than that

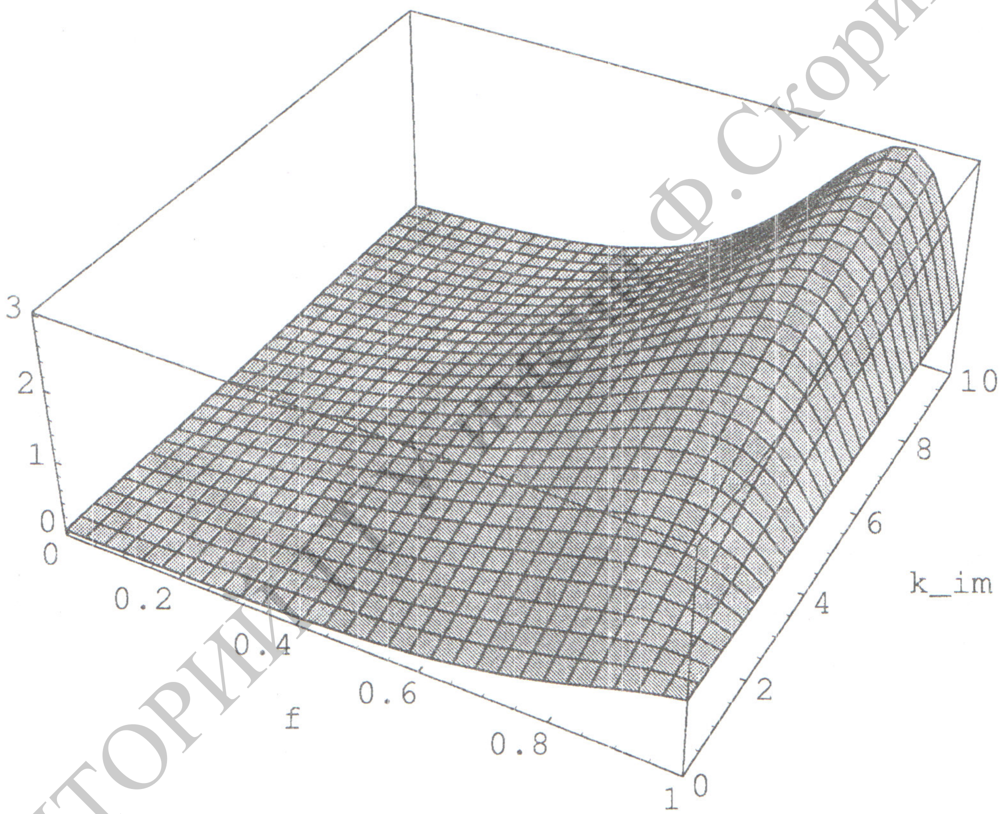

Figure 3. The real part of the effective chirality parametr κ_{eff} as a function of the volume fraction of the lossy chiral inclusions f and the imaginary part of the chirality parameter of the chiral inclusion phase. The other inclusion parameters are $\epsilon_i = 2 - \mathrm{j}10$, $\mu_i = 1 - \mathrm{j}$, and $\kappa_i = 1 - \mathrm{j}\kappa_i''$.

of either of the components (in the figures, the background (relative) permittivity is 1, and that of the inclusions 50). Furthermore, the increase is by no means marginal; it can be severalfold.

A maximum in ϵ'_{eff} can be observed if the imaginary part of the relative permittivity of the inclusion phase is large enough; for example, in the Maxwell Garnett case, it has to obey $\epsilon''_i > \sqrt{\epsilon'^2_i + \epsilon'_i - 2}$. Then a volume fraction of

$$f_{\max} = \frac{(\epsilon'^2_i + \epsilon'_i - 2)^2 + \epsilon''^2_i[2\epsilon'_i(\epsilon'_i + 1) + 5] + \epsilon''^4_i - 3\epsilon''_i\sqrt{[(\epsilon'_i - 1)^2 + \epsilon''^2_i][(\epsilon'_i + 2)^2 + \epsilon''^2_i]}}{[(\epsilon'_i - 1)^2 + \epsilon''^2_i][\epsilon'^2_i + \epsilon'_i + \epsilon''^2_i - 2]} \quad (1)$$

gives the maximum for the real part of the effective permittivity of the mixture, given these values of the inclusion permittivity.

These examples were for "ordinary" dielectric materials, although superlossy. But what happens if we try to look for analogous phenomena in the magnetoelectric domain? One interesting effect that has not been paid attention before is what emerges when such highly-lossy materials are also allowed to be chiral. Let us look at the effective chirality parameter κ_{eff} of a mixture where the background is again vacuum and the inclusions spherical. Let the material parameters of the inclusions be $\epsilon_i = 2 - \text{j}10$, $\mu_i = 1 - \text{j}$, and $\kappa_i = 1 - \text{j}\kappa''_i$ with varying imaginary part of the inclusion chirality. (Note that here imaginary parts are forced on the permittivity and permeability for physical, rather than percolatory, reasons: the imaginary part of the chirality parameter for any material is bounded from above by the imaginary parts of the permittivity and permeability [4].) The real part of the effective chirality parameter—calculated according to the Maxwell Garnett mixing model—is illustrated in Figure 3 as a function of the volume fraction f of the inclusions. An effect is clear that the real part of the chirality parameter can attain higher values in a mixture as compared to the inclusions. Such an effect suggests a possibility to increase the rotatory power of chiral material by mixing it into a nonchiral host.

References

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also [6] for a discussion of some unintuitive properties in the macroscopic behavior of composite media.

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