Review Report on Ph.D. Thesis "Metamaterials for the terahertz spectral range"

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Reviewer: Lukas Jelinek

General report:
Submitted thesis is clearly written and presents an ability of a student to perform independent research. Language and stylistics are properly chosen. The thesis is also graphically well made with quite carefully and consistently typeset equations. The results of Sec. 5 are novel and represent a valuable addition to the research in the field.

Although I do have substantial reservations with respect to the content of the thesis, in my opinion, the student should be allowed to defend the thesis and, if successful, to acquire a title Doctor of Philosophy.

Below I am detailing some of my concerns and also rising several questions which I would like to discuss during the defense.

Substantial Comments:
S01) I do not clearly see what is the main goal of the thesis. The author should explicitly state what are the novel results achieved. At page 127 it is still an overview of more or less known results. A Ph.D. thesis is not a textbook. A Ph.D. thesis should, in my opinion, present an ability of a student to perform research in the topic of the thesis. In this respect, the thesis should mostly contain novel material, leaving aside a review work which belongs to textbooks. In my opinion, roughly 3/4 of the entire thesis can be found elsewhere and the author should use citations in those cases otherwise a reader can get an impression that these results are novel.

As an example of the content (entire sections) that can be found in textbooks and can thus be removed from the thesis, I mention:

Sec. 2.1., 2.2., 2.3., 5.1. (Introductory)
Sec. 3.1. (This method is a part of standard computational packages.)
Sec. 5.2. (There are journal and textbook sources describing the wire medium in great details.)

S02) I didn't find the solution to the second goal of the thesis. Where can I find the presentation of the extracted spatially dispersive material parameters?

S03) I found it quite difficult to replicate some of the results. As an example, I haven't found the exact dimensions of structures in Fig. 5.16, especially the dimensions of capacitive pads.

S04) Sec. 1.1. (Introduction) lacks references to relevant review literature such as books and review papers.

Technical Comments:
T01) Although the vector **K** is normalized in graphics, the frequency is not. The reading of figures is thus rather difficult. It would be much easier if dimensionless numbers such as *ka* are used instead of frequency. This would for example allow for simple comparison between different structures which naturally resonate at different absolute frequencies.

T02) Division of two vectors in (2.17) is an invalid algebraic operation. Also, the assumption of complex time domain field is unphysical. The permittivity should be defined differently.

T03) Mathematical notation is not always followed - names and constants should be in upright font. As a good example I highlight (2.26).

T04) The green dashed and full black curves in Fig. 2.10 are not identical although they should be. Why?

T05) What is the meaning of group velocity in a lossy medium used in Sec. 2.24? Either ω or k must be complex.

T06) I do not understand the claim: "*Both time- and frequency-domain simulations used in this thesis use complex numbers to represent all field components*", which can be found at p. 80. Can you explain?

T07) From which source the permittivity data in Fig. 3.2. comes from?

T08) The claims on FDFD in the very end of the section 3.1.2 seems contradictory to me. At one hand the author is claiming that the advantage of FDFD is a possibility to use materials with arbitrary permittivity and permeability. On the other hand, few lines below the author reports the instability of FDFD scheme when used with plasmonic materials.

T09) What was the reason for not using a commercial solver package such as CST? Most of the problems described in Sec. 3.2 would be solved automatically. Especially, the cutting of the field time course is solved in CST to great details.

T10) Signs in (3.20) and (3.21) are not independent. Choosing one, automatically gives the second. It however seems to me that the author potentially vary both of them. Can you comment on this?

T11) The problems accompanying Nicolson-Ross-Weir method used in Sec. 3.2.1. are well known and well described in the literature.

T12) In my opinion, the source driven 3D periodic system simulation used in Sec. 3.2.2. is very problematic from a numerical point of view when the source excites one of the eigen-modes of the structure. Why not to directly use eigen-mode solver to retrieve dispersion diagrams? In fact, eigen-mode solutions are presented in the thesis, for example in Sec. 5.1.

T13) It is not clear how dispersion diagrams evaluated by method of Sec. 3.2.2. are transformed into the effective medium parameters. Please comment on this.

T14) It is not clear to me how the two sieves shown in Fig. 4.4b separate spheres from ellipsoids. It seems to me that an ellipsoid with minor axis equal to the radius of the first sieve will remain in the middle irrespective of its major axis. Can you please elaborate the anisotropic sieving in more details at the defense?

T15) What is the meaning of index of refraction of a structure described in Sec. 5.1.? Do the wave refract on the boundary with this structure according to Snell's law with that index of refraction? The reader cannot know since the index of refraction is derived only for normal incidence, under which the wave does not refract. Please, elaborate this point at the defense, best with actually calculating the refraction for several angles of incidence. Does the refraction depends on polarization and angle of incidence according to a common Snell's law?

T16) The permittivity of a wire medium described in Sec. 5.2. is anisotropic. Although the author is probably aware of this, this fact is nowhere mentioned and a scalar ε is used, confusing the reader.

T17) An effective permeability is not extracted in Sec. 5.3. Can you do it for the purpose of the defense and comment on the results?

T18) Please comment on the physical meaning of the extracted permittivity in Fig. 5.8d, especially in the frequency range from 1 THz till 1.5 THz.

T19) The comparison of simulation and experiment in Fig. 5.11 went rather bad. Why?

T20) The claim: "*Asymmetric structures therefore have properties that cannot be matched by any (reciprocal) homogeneous medium*" from p. 136 is not valid in my opinion. The medium describing the system of such particles would only need to be bi-anisotropic. How could this system be possibly non-reciprocal?

T21) The claim: "*The permittivity spectrum $\varepsilon_{eff}(f)$ is, however, also affected by the magnetic dipole resonance (Fig. 5.14d).* " from p. 136 sound odd to me. How is the effective permittivity defined that this is possible? In other words, how a permittivity can depend on a distribution of magnetic dipoles?

T22) The claim: "*We believe that the influence of a magnetic resonance on $\varepsilon_{eff}(f)$, or conversely, of an electric resonance of $\varepsilon_{eff}(f)$, is a mere artefact of approximating a strongly nonlocal structure with a concept of local effective parameters*" from p. 137 is not fully justified in my opinion. Why it is not an artefact created by improper extraction of material parameters via NWR method? Does this behaviour persist also for highly sub-wavelength unit cells which certainly can be created by modifying the geometry of the structure?

T23) Is it possible to modify the dimensions of the resonator from Fig. 5.20a so that the left-handed band will appear for $ka < 0.5$? At the present moment the corresponding ka is simply too big to consider this periodic structure as an effective medium. Please elaborate this point at the defense.

Prague, 28.11.2016 Lukas Jelinek