Reviewer's report on the PhD thesis of Mgr. Hynek Němec "Time-Resolved Terahertz Spectroscopy Applied to the Investigation of Magnetic Materials and Photonic Structures"

The PhD thesis of Mr. Hynek Němec is related to "hot topics" in the fields of terahertz spectroscopy, photonic bandgap materials, and left-handed metamaterials that not only contribute to basic knowledge in physics but also have a number of existing and prospective applications in materials research, optical communications, sensing, security, *etc.* The written report to be reviewed consists of 142 pages of an English text. It is divided into two main parts devoted successively to the techniques of a terahertz spectroscopy, and to selected problems of metamaterials and photonic crystal structures. These parts consist of three and four chapters, respectively. Except acknowledgments, summary, and conclusion, the thesis contains a really impressive list of 308 references cited in the text. Let us mention right now that just *ten* of these publications are co-authored by Mr. Němec, and in *seven* of them he is the first author. It is also worth mentioning that all these papers were published or accepted for publication in reputed international archive journals.

Let us first briefly review the content of the thesis. In chapter 1, the methods of generation and detection of terahertz radiation are briefly described, with the accent on methods utilizing femtosecond optical pulses. Chapter 2 is devoted to the description of methods of time-domain terahertz transmission and reflection spectroscopy and to its present and perspective applications. The third chapter brings first original results based on a rather simple but very powerful idea of independent determination of electric and magnetic properties of investigated materials from its (complex) propagation constant (or effective index) and impedance. Several concepts and applications of this approach are presented there. Chapters 4 and 5 of the second part of the thesis are devoted to a rather brief but comprehensive description of fundamental properties of photonic bandgap structures and left-handed metamaterials. Two basic methods used for their theoretical analysis and numerical modelling are represented there: the plane-wave expansion method, and the transfer matrix method. The latter one was chosen as a tool for the detailed numerical study of selected photonic structures, and a corresponding numerical code was developed by the author of this thesis. In the following chapter 6, the transmittance and reflectance properties of a slab waveguide grating are theoretically investigated and compared with published experimental results. For deeper understanding, the dispersion characteristics of eigenmodes of the slab grating were calculated, too. Chapter 7 is devoted to theoretical as well as experimental study of a "defect modes" in a 1D photonic bandgap structure consisting of two Bragg gratings separated by a "defect" layer. A very interesting structure of a thermally or electrically tuneable terahertz band-pass filter has been theoretically analyzed in detail, fabricated, and experimentally characterized, with excellent agreement. In a brief conclusion, the main contributions brought about by the work described in the thesis are summarized.

The text is written in a very proper way – it is concise but well understandable, with clear explanations, and, as far as I can judge as a non-native speaker, in a very good English, practically without misprints and typing errors. A uniform appearance and high typographic quality is ensured by the application of LaTeX editing system. It was really difficult to find anything to object; one can perhaps mention missing labels of vertical axes of graphs in Fig. 7.12 on page 108 (their meaning is clear enough from the labelling of curves, however).

A striking feature of the thesis is its very strong background brought about by both French and Czech reputed laboratories where Mr. Němec has the opportunity to learn the field and to pursue his experimental and theoretical work. The scope of the introductory and overview chapters (1, 2, 4 and 5) is rather extraordinarily broad, covering not only the very field of terahertz spectroscopy but overlapping also to solid-state physics, materials research, microwave engineering, nonlinear optics, guided-wave photonics, and electrodynamics of photonic bandgap structures and left-handed metamaterials. It is belief of the reviewer that the author had the unique possibility of in-depth discussions of such a broad scope of problems with his tutors and colleagues from both laboratories, and was undoubtedly able to fully utilize this potential on his behalf. Although I can well understand the enthusiasm of a young author for fundamental recent breakthroughs in physics and technology in these novel fields, I would nevertheless prefer to choose a bit more „earth-bound" and apposite title of Part II of the thesis: negative refraction due to both left-handedness of metamaterials and diffraction in periodic structures is undoubtedly adequately described (or at least mentioned) there, but it does not represent the dominant contribution of this chapter; it is, in my opinion, the tuneable band-pass filter based on a microcavity embedded in a 1D photonic bandgap structure.

The author has proven an excellent ability to combine an in-depth understanding of physical problems with efficient theoretical and numerical modelling and sense for experimental work. Among others he developed his own specialized computer codes based on (known) advanced contemporary modelling methods for the analysis of rather complex structures like slab waveguide grating and photonic bandgap structures, and was able to efficiently utilize them for successful interpretation of rather complex experimental results.

The first part of the thesis results in an original, rather simple but powerful and efficient method of independent extraction of both electric and magnetic parameters of materials from their transmittance and/or reflectance TDTS measurements. Several approaches have been developed, tested, and their accuracy mutually compared. Although direct experimental evidence of a weak magnetic resonance in the measured sample of $TmFeO_3$ crystal could not be reported due to too low signal to noise ratio, there is no doubt that magnetic properties strong enough for envisaged applications (*e.g.*, for the construction of left-handed metamaterials) can easily be measured by the proposed method. It is worth mentioning that the transfer matrix modelling of the two-dimensional array of rectangular columns confirmed the existence of pronounced effective magnetic properties also for rectangular cross-section of columns.

From my point of view, the most interesting results are described in Part II of the thesis. As I have already mentioned, a rather complex 2D structure of a slab grating waveguide was thoroughly analyzed and results successfully compared to measured transmittance. The „masterpiece" of the thesis is, however, in my opinion, the modelling, design, fabrication, and experimental verification of a temperature-controlled tuneable band-pass terahertz filter. It is an excellent example of a „canonical" photonic bandgap structure that allows for a rather simple laboratory fabrication, can be accurately modelled by a 1D transfer matrix method (with a good physical interpretation in terms of a generalized Fabry-Perot cavity concept), and is simultaneously experimentally accessible by the TDTS methods available to the author, and may have important potential applications – a very rare combination of advantages in the photonic crystal research, indeed!

It is perhaps no wonder that such a comprehensive thesis gives rise to a number of questions or comments. They are mentioned below, and some of them might perhaps be briefly discussed during the defense.

1. I would appreciate to know more about the author's own role at the experiments described in the thesis.
2. In all experimental arrangements in Figs. 2.2 to 2.4, the measured sample is placed at the "focal point" of the THz radiation while in the theoretical analysis, a plane-wave approximation to the incident wave is used. In Fig. 2.4, the gating beam is also incident on the measured sample. To what extent could these effects influence the interpretation of measured results?

3. A minor formal comment: the transition from time-dependent Maxwell equations (5.1) to their spectral counterpart (5.2) is not fully consistent; while Eqs. (5.2) take into account material dispersion, Eqs. (5.1) do not.
4. Is the developed TMM software capable of modelling TM modes of a slab waveguide grating in Fig. 6.1, too? If yes, are there "proper Fourier factorization rules" (according to, *e.g.*, Lalanne and Morris, JOSA A **13**, 779, 1996) applied in the software?
5. What programming environment was chosen for the development of the TMM core?
6. I would very much appreciate a more thorough explanation of the nature of "resonant modes" revealed in the slab waveguide grating in Fig. 6.1. As the zeros of the determinant $\det(\mathbf{M}^{-1}.\, \mathbf{P} \pm \mathbf{I})$ are determined purely numerically on a finite-precision computer with a finite number of terms taken into account, the term "*nearly, but not exactly singular matrix*" should be better specified. The description on p. 87 states that they "*cannot exist without excitation by a plane wave from the exterior of the waveguide. These modes are analogous to constructive FP interferences observed when a homogeneous planar waveguide (=slab) is irradiated by a wave from the exterior. In the periodically modulated waveguide, even a very weak incident wave can couple a significant amount of energy into resonant modes leading to a considerable enhancement of the field inside the waveguide. This means that an incident radiation with appropriate values of β can efficiently excite resonant modes.*" However, these features are very typical characteristics of standard leaky modes on dielectric waveguides, especially on periodically modulated ones, and, at least as far as I know, such "resonant modes" do not appear in the rigorous theory of dielectric waveguides.
7. Is it possible to roughly but realistically estimate the necessary tuning *voltage* and the resulting electrical capacitance of tuning electrodes of the tuneable bandpass filter based on a $SrTiO_3$ "defect" mode?

There is no doubt that the author exhibited in his thesis a sound working knowledge of methods of scientific work. He has proven an excellent ability of individual research work, and has notably contributed to the knowledge in physics and applications of terahertz electromagnetic fields. The originality and novelty of his scientific contributions has been confirmed by the acceptance of several his papers for publication in reputed international journals. I am thus fully convinced that the PhD thesis of Mr. Hynek Němec fully satisfies all the demands of both the Czech and French rules posed on PhD theses. It is my great pleasure that I can unanimously recommend the thesis for defense towards awarding the PhD degree to Mr. Hynek Němec.

Prague, February 27, 2006

Prof. Ing. Jiří Čtyroký, DrSc.