REFERENCE

of **Volodymyr M. Fitio** as official opponent of the dissertation of Fedir O. Yevtushenko entitled, **"Resonant scattering and absorption of electromagnetic waves by infinite gratings of graphene strips on dielectric substrates,"** submitted for the defense of the degree of Doctor of Philosophy in specialty 104 - Physics and Astronomy (10 - Natural Sciences).

Timeliness of the dissertation topic. By now, various periodic structures operating in the visible and infrared regions of the spectrum have been already studied. On their basis, various devices have been developed that have practical applications: diffraction gratings for spectral devices, various filters, grating polarizers, wavefront dividers, physical quantity sensors, etc. The study of such grating-based structures has revealed interesting features, such as the resonance on the localized surface plasmons in periodically arranged nanowires on a dielectric substrate. In the grating structures with a metal substrate, excitation of a surface plasmon-polariton wave occurs under certain conditions, and when resonance occurs, it is possible to obtain a reflection coefficient that is close to zero, and the resonance gets spoiled if the grating or the environment parameters change. The resonance is rather narrow-band if the substrate is silver or gold one. In dielectric gratings, the guided-wave resonance can occur, and the reflection coefficient can be equal to unity.

Recently, intensive studies of the structures based on the periodic arrangement of graphene strips on a dielectric substrate with/without the gain have begun. Due to the physical features of monolayer graphene, such structures have interesting properties in the infrared and terahertz ranges. This is due to the fact that graphene has high electron mobility, which can be rearranged electrostatically (due to the chemical potential of graphene), and displays plasmonic effects. In order to effectively study the periodic structures based on graphene, it is necessary to "adapt, or rather modify" reliable theoretical methods that have proven themselves well in the study of periodic structures without graphene, as well as to develop an appropriate code for numerical modeling. Numerical study allows to quickly analyze a variety of periodic structures, even those that existing technologies cannot manufacture at the present time. Through numerical experiments, we can optimize a structure to achieve the required parameters, and then manufacture it precisely. From this point of view, the study of the gratings based on graphene strips on dielectric or gain substrates and the development of appropriate new numerical analysis methods are important and contribute to the creation of new devices in the terahertz range of electromagnetic waves.

Therefore, the scientific results of theoretical research and computer modeling related to this topic, presented in the dissertation of F. O. Yevtushenko, are relevant and timely, and have both fundamental and applied significance.

The research within this thesis has been performed at the Laboratory of Micro and Nano Optics of the Quasioptics Department of IRE NASU, in the framework of the following projects:

1. Research project of NASU "Development and application of methods of optics and quasioptics for generation and transforming the electromagnetic waves of 29 terahertz, infrared and visible ranges", code "Oreol-1". #0117U004036, (2019-2022)

2. Research project of NASU "The research of interaction processes of electromagnetic radiation in terahertz, infrared and visible ranges with various natural or artificial materials, mediums and structures", code "Oreol-2", #0122U001710 (2022-2026)

3. Competitive research project of NASU, "Radiophysical phenomena in nanoelectronic systems based on graphene, unconventional superconductors and magnetized semiconductors", code "Nanograph", #0122U200724 (2022)

4. Research project of the National Research Foundation of Ukraine (NRFU) "Electromagnetic modeling of micro and nano lasers with resonant graphene elements, at the threshold of stationary emission", code "Sonata", #2020-02-0150 (2020-2022)

5. Joint research project with Universite de Rennes 1, "Dnipro" Programme of the Ministry of Education and Science, Ukraine and the Ministry of European and Foreign Affairs, France, code "Vilen" #0119U102172 (2019), #0120U104419, (2020)

6. Tender research project with Taras Shevchenko National University of Kyiv, code "Universum", #0120U104925 (2020), #0121U113145 (2021)

It has been also partially supported by the IEEE Antennas and Propagation Society Doctoral Research award for the project «Resonant scattering and absorption of terahertz waves by infinite gratings of graphene strips on dielectric substrate: analytical regularization based analysis» (2021).

Scientific novelty. The novelty of the obtained results is convincingly shown in the thesis. Among the most significant and interesting are the following:

- The existence of high-Q resonances on the guided-wave modes of gratings has been established, in both polarizations, that are associated with the Rayleigh anomalies, however, do not exist on the gratings made of perfectly conducting or graphene strips of "zero thickness" placed in the free space. In the H-polarization, the resonances appear on the plasmon modes, which are not present in the E-polarization.
- In the scattering of the H-polarized plane wave, the effect of electromagnetically induced transparency has been revealed at certain grating and substrate parameters, obtained due to the tuning of the plasmon modes with the aid of the chemical potential of graphene.

- It has been shown that if a graphene strip grating is placed on the gain substrate, the laser generation is possible. Numerical methods have been used to determine the emission frequencies and threshold values of the substrate gain. It is shown that the lowest generation thresholds are possible for the lattice modes of each polarization with odd symmetry, and the best tunability is shown by the plasmon modes in the case of the H-polarization.

Validity and reliability of scientific conclusions. The research results presented in the dissertation, were carried out at least from 2019 to 2023. This conclusion can be made based on the publication of the first papers in 2019. That time was enough to gain the necessary experience in scientific research, obtain a detailed introduction to achievements in this area, analyze them (120 references are cited), and plan and perform the corresponding research.

The problem of diffraction from **the gratings of graphene strips on dielectric substrates** was posed in the rigorous mathematical formulation, the final equations of which were derived using the mathematically grounded transformations of the Maxwell equations, taking into account the exact boundary conditions. As a result of correct mathematical operations, the Fredholm matrix equations of the second kind were obtained. These equations are infinite, however their truncation to the number N possesses convergence to the exact solution with larger N values. The solution of the Fredholm matrix equation is numerically stable for the given grating parameters.

The mode emission frequencies and threshold values of gain for the **nanolasers based on graphene strip gratings on a substrate with gain** were found in the absence of the incident field, as the roots of the corresponding determinant equations. The results of numerical experiments related to nanolasers are in agreement with the basic principles of quantum electronics and laser technology, in particular, with the general conclusions of the theory of distributed feedback lasers.

It should also be noted that the developed in the dissertation methods of wave diffraction were tested on sample problems available in references. The results of such numerical analysis showed a good agreement, at least with graphical accuracy.

The results of research were discussed with a number of leading scientists working in this area and presented at the scientific seminar of the O. Y. Usikov Institute of Radiophysics and Electronics of the National Academy of Sciences of Ukraine (headed by Prof. P. M. Melezhyk), and also at numerous international conferences, such as

– IEEE Ukrainian Conferences on Electrical and Computer Engineering (UKRCON), Lviv, 2019, 2021;

– IEEE International Conference on Microwaves, Communications, Antennas, and Electronic Systems (COMCAS), Tel Aviv, 2019, 2021;
– IEEE International Conference Ukrainian Microwave Week (UKRMW), Kharkiv, 2020, 2 papers;
– IEEE International Conference on Information and Telecommunication Technologies and Radio Electronics, Proceedings, (UkrMiCo) Kyiv, 2021;
– European Microwave Conferences (EuMC), Milan, 2022, Berlin, 2023;
– IEEE International Conference on Electronics and Nanotechnology (ELNANO), Kyiv, 2022;
– International Conference on Applied Electromagnetics and Communications (ICECOM), Dubrovnik, 2023.

The practical value of the dissertation is as follows: the developed numerical method is a reliable scientific instrument for studying and analyzing the scattering and absorption characteristics of electromagnetic waves, the near and far fields, as well as the frequencies and self-excitation thresholds of laser modes of graphene strip gratings to active substrates. The developed numerical methods can be efficiently applied in design of various devices in the terahertz range. The regularities found in this dissertation can be useful in the development of micro- and nanolasers of the terahertz and infrared ranges, which can be tuned with the aid of controlled change in the chemical potential. The discovered effect of electromagnetically induced transparency, which arises due to the tunability of the plasmon modes with the aid of the chemical potential of graphene, can be used to create new types of terahertz range filters, modulators and absorbers. In particular, the modulators can have a switching frequency above 100 GHz due to the fact that the relaxation time of electrons in graphene can be less than 1 ns.

The completeness of presentation of the main results. Research results have been published in 16 refereed articles indexed in Scopus, including 5 papers in international journals [A1-A5] and 11 papers in the proceedings of international conferences [A6-A16].

Evaluation of the language, style and design of the thesis. The dissertation consists of an abstract, introduction, four chapters, conclusions and recommendations, a list of references, and one appendix. It is presented on 163 pages of printed text, contains 62 figures and 3 tables. The bibliography includes 120 references.

In general, the dissertation is written in standard English at a satisfactory stylistic level. The applied scientific terminology is commonly used, the style of presentation of the results of scientific research, derivations, conclusions, and recommendations ensures an adequate perception of what is written. The results of meticulous studies are presented concisely and concretely.

The content of the abstract is identical to the main contents of the dissertation and written using modern scientific terminology. The design of the dissertation meets the requirements of the Ministry of Education and Science of Ukraine, which are requested from works submitted for the award of the scientific degree of Doctor of Philosophy in accordance with the "Temporary Procedure for Awarding the Degree of Doctor of Philosophy", approved by the Decree of the Cabinet of Ministers of Ukraine dated March 6, 2019 No. 167 and amended according to the Decree of the Cabinet of Ministers of Ukraine No. 608 dated 09.06. 2021.

In general, the dissertation makes a good impression on the reader with its relevance, novelty, practical significance, and shows that the author has mastered a wide range of theoretical and applied knowledge, is able to develop computer codes of rather high complexity, and, most importantly, is able to formulate new important tasks and solve them successfully.

Critical comments on the thesis. Despite the high quality of the dissertation, one can find certain shortcomings of various nature.

1. The thesis states that the chemical potential of graphene can be changed within wide limits by an electrostatic field, however, it is not explained how to apply the voltage to the graphene strip grating.
2. In the thesis, the author used a non-standard notation for the refractive index, $v = \alpha - i\gamma$. In optics, it is customary to denote the refractive index with the letter n, which is complex for absorbing or amplifying materials. The letter v usually denotes the frequency (the number of oscillations per unit of time). In quantum electronics and laser technology, the letter γ indicates the gain index, so that the wave amplitude when propagating in the gain medium increases as $\exp(\gamma z)$.
3. Fig. 3.4 is of low resolution, therefore, it is difficult to understand the calculation conditions.
4. In Fig. 2.4-a and Fig. 2.3-d a significant drop in the calculation error is visible at approximately $N = 50$, by several orders of magnitude. This effect is not explained.
5. In the text of the thesis, there are typos due to inattention, for example: in equation (1.4) it should be $T_{mm}(\theta)$?, p.41; in the explanations after equation (1.5) it is difficult to understand the expression $P_s - u$ that can be possibly $P_s(-u)$. Equations (1.4), (1.7), and (1.8) are not clear; in equation (2.25) there are $A^H_{m,n}$ i B^H_m, and in formula (2.26) - $A_{m,n}$ i B_m; what will happen when in equation (2.27) if $m - n + 1 = 0$ is unclear; Fig. 3.5-a shows the designation of the peak as L_{20}, while the designation of the same peak in Fig. 3.5-d is $L_{106.738}$; Fig. 4.5 shows the map of the magnetic field for one period while the caption to the figure tells "... on three periods for...", the same error is in Fig. 4.6; it looks like there is a typo in equation (4.14).

6. It is not explained why $\kappa = p/\lambda = 14.1$ and $\kappa = p/\lambda = 100.1$, but not 14 and 100, respectively, were chosen (p. 62). Did this choice complicate or simplify the calculations?

However, these shortcomings do not lead to even a slight misunderstanding of the content of the dissertation, do not reduce its scientific novelty and practical value, and, therefore, have no influence on the final conclusion about the thesis. Most of the shortcomings were caused by the oversights of the author.

General conclusion. The opinions expressed above make it possible to state that the dissertation work of Fedir O. Yevtushenko is an independent and complete scientific study. The work convincingly shows the scientific novelty and reliability of the obtained results and their practical value. In terms of the relevance of the problems considered, the volume of research, scientific level and practical value, the thesis fully meets the requirements for dissertations for obtaining the scientific degree of Doctor of Philosophy, and its topic and content correspond to the passport of specialty 104 - physics and astronomy (10 - natural sciences).

The dissertation meets the requirements of the Ministry of Education and Science of Ukraine, which are submitted to the works submitted for obtaining the scientific degree of Doctor of Philosophy, in particular clauses 9, 10, 11, 12 of the "Temporary procedure for awarding the degree of Doctor of Philosophy", approved by the Decree of the Cabinet of Ministers of Ukraine dated March 6, 2019 No. 167 with changes according to the Decree of the Cabinet of Ministers No. 608 dated 09.06. 2021, and its author F. O. Yevtushenko deserves to be awarded the degree of Doctor of Philosophy in specialty 104 - physics and astronomy (10 - natural sciences).

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I certify the signature of Professor V. M. Fitio,
University Academic Secretary

Roman BRYLYNSKYI

МІНІСТЕРСТВО ОСВІТИ І НАУКИ УКРАЇНИ
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