2023 IEEE MTT-S GRADUATE FELLOWSHIP REPORT

Smith-Purcell Terahertz Radiation from Beam of Particles Moving Above Finite Grating of Graphene-Covered Dielectric Rods

Dariia O. Herasymova, *Student Member, IEEE*

***Abstract*—This report summarizes the research into terahertz (THz) and infrared range diffraction radiation of a modulated beam of electrons flowing near the grating of graphene-covered dielectric nanowires. In our analysis, we assume that the beam velocity is fixed and characterize the graphene cover with the Kubo formalism and resistive-type boundary conditions. Then, using the separation of variables in the local coordinates and the addition theorems for the cylindrical functions to account for the wire shape and location, we transform the diffraction radiation problem to a Fredholm second-kind matrix equation. This yields a meshless numerical code, which has mathematically guaranteed convergence and allows us to compute the scattering and absorption characteristics and the far and near field patterns with controlled accuracy. This work can be useful in the design of novel sources of terahertz waves and dielectric laser accelerators.**

***Index Terms*—nanowire grating, lattice mode, charged particles beam, diffraction radiation, graphene, plasmon mode.**

I. Introduction

Diffraction radiation (DR) is a term used to characterize the effect of the electromagnetic-wave radiation, of any frequency, which accompanies the electron beams flowing near metal and dielectric objects without crossing their boundaries. Such a radiation is generated by the secondary currents induced by the beam field on the scatterers. Early example of DR is the Smith-Purcell effect, or visible-light radiation from the electron beam moving across a grating ruled on a metal plate. Later it was extensively studied theoretically in [1,2] and other publications. Experimental research led to development of extremely stable microwave and sub-THz sources – orotrons and clinotrons [3].

More recently, DR effects, including the Smith-Purcell radiation, started attracting attention of researchers in the THz and optical ranges of frequencies [4,5], where ruled gratings are impractical. This explains our choice of the grating configuration in the current project.

The characterization of DR is usually performed assuming that the disturbing action of the electromagnetic field on the beam can be neglected and its velocity and trajectory are fixed. This assumption implies that the powers associated with DR radiation and absorption losses are small in comparison to the power carried by the beam.

However, inverse situation, of the sizable losses, is also interesting because it can be used in the design of novel particle accelerators. Here, large attention is attracted today to the dielectric laser accelerators (DLA) [6-8]. DLAs are micrometer-scale structures made of silicon or other dielectric materials and illuminated by external laser light. They eliminate metal components and therefore overcome electrical breakdown limitations of conventional particle accelerators in the presence of high electric fields. Among various designs of DLAs, those based on circular nanorod gratings are simpler and cheaper than others and thus can be mass-produced using available nanofabrication methods [8]. Therefore, electromagnetic analysis of such gratings is important.

Dariia O. Herasymova is with Institute of Radio-Physics and Electronics of the National Academy of Sciences of Ukraine, Kharkiv, Ukraine (e-mail: dariia.heras@gmail.com).

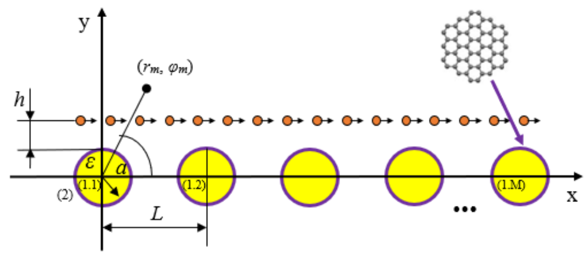

Fig. 1 Cross-sectional geometry of the Smith-Purcell DR problem associated with finite grating of graphene-covered circular dielectric wires.

Within the reported project, we have built efficient and trusted analytical-numerical solutions to several scattering problems associated with electron beams passing near gratings made of circular dielectric nanowires with graphene coatings.

The considered grating is created by finite number of infinite circular dielectric wires, covered with graphene – see Fig. 1. Above the grating and in parallel to its plane, a beam of charged particles flies without touching the grating. For simplicity, the beam is assumed to be flat, zero-thickness, infinite, and periodically modulated in time, while its velocity is fixed.

The formulation of the 2-D wave-scattering boundary-value problem associated with Fig. 1 involves the Helmholtz equation with corresponding wavenumber in each partial domain, the graphene-surface boundary conditions at the wire contours, the Sommerfeld radiation condition at infinity, and the condition of local power finiteness. These conditions guarantee the uniqueness of the boundary-value problem solution. On using the Fourier expansions, addition theorem, and boundary conditions, we cast the problem to the Fredholm second kind matrix equations for the expansion coefficients. This guarantees the convergence, with the larger truncation orders N, and the controlled accuracy As expected, such a code outperforms greatly the existing commercial codes.

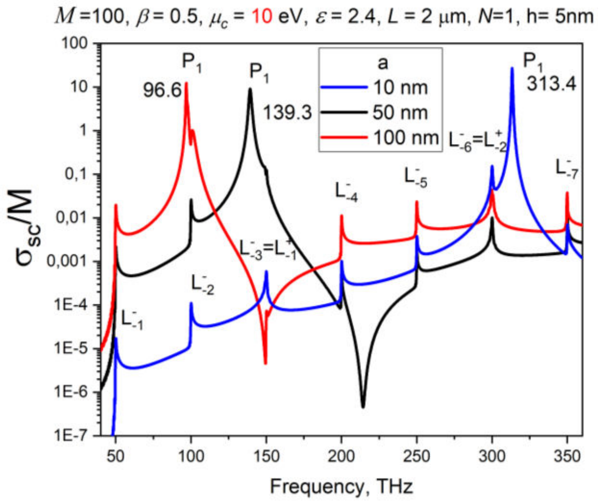

Fig. 2 TSCS spectra for the M = 100 graphene-wrapped dielectric nanorod gratings excited by the beam of electrons for three radii a = 10 nm, 50 nm and 100 nm and the chemical potential μ_c = 10 eV.

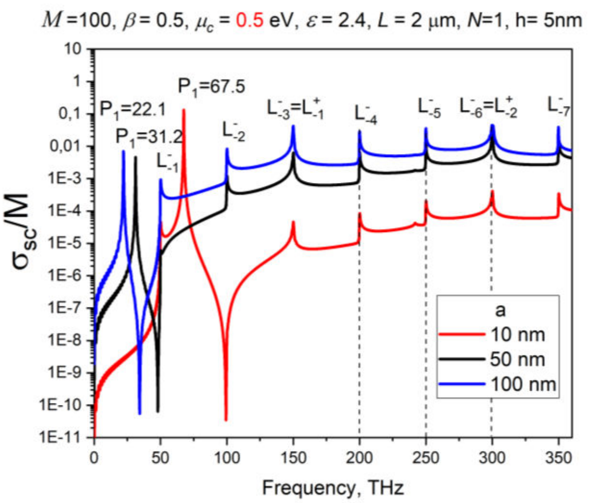

Fig. 3 The same as Fig.2 but for the chemical potential μ_c = 0.5 eV

II. Results

The broad range frequency spectra of the total scattering cross-sections (TSCS) for the electron beam with relative velocity $\beta = 0.5$ which passes at the distance h = 5 nm from the sparse grating of the wires of three radius values wrapped with graphene are depicted in Fig. 2. Here, the grating of 100 wires is sparse, as the period of L = 2 μm is much larger than the wire diameter. These spectra show two types of the natural mode resonances, on the plasmon modes denoted as P_m and on the lattice modes marked as L_m. The graphene characteristic parameters are denoted above the figures and the chemical potential is unrealistically large, μ_c = 10 eV, to emphasize the plasmon resonances, whose Q-factors grow as $\sqrt{\mu_c}$.

The tunability of the graphene-cover plasmon resonances can be observed through the change of the chemical potential to 0.5 eV, as shown in Fig. 3. The P_m frequencies display a four-fold redshift with respect to the curves in Fig. 2. This is because they scale as $\sqrt{\mu_c}$. As for the lattice-mode resonances, L_m, we have found that their frequencies keep their positions at the Rayleigh Anomalies of the corresponding infinite grating for the given value of β, however, their peak magnitude and sharpness significantly depend on the number of the wires, M.

Additionally, we have studied the influence of the wire radius on the both types of resonances. The plasmon resonances have higher frequencies and Q-factors for the smaller wire radii, because the both values scale as $1/\sqrt{a}$. The lattice-mode resonances keep their positions and their sharpness is almost intact.

III. Conclusions

Two types of the resonance effects in the DR for the finite gratings of graphene-covered circular dielectric nanowires have been demonstrated. The plasmon-mode resonances of each graphene cover and the lattice-mode resonances of finite gratings as a whole have been investigated. The obtained results are expected to be useful in the design of THz source slow-wave structures and DLA sectons built of graphene-coated low-permittivity dielectric wires.

IV. Impact Statement and Career Plan

I would like to express my sincere gratitude to MTT-S for the student fellowship. It gave me the valueless opportunity to conduct my graduate research and participate in international conferences in very challenging times of the barbaric Russian invasion of Ukraine. The only thing that did not work our properly, was my travel to the USA to attend the IEEE Microwave Symposium and Award Ceremony in San Diego. I applied for the visa and attended the embassy three months before the event, however, have never received any answer. Perhaps, I will have a chance to attend this symposium at a future opportunity. Now, I hope to pursue a career of postdoc researcher at my R&D center in Ukraine and hope to contribute more to the field of nano-electronics and computational electromagnetics.

References

1. P. M. van den Berg, "Smith-Purcell radiation from a line charge moving parallel to a reflection grating," J. Opt. Soc. Am., vol. 63, no 6, pp. 689-698, 1973.
2. A. I. Nosich, "Diffraction radiation which accompanies the motion of charged particles near an open resonator," Radiophys. Quant. Electron., vol. 24, pp. 696-701, 1981.
3. J. S. Rieh, “THz sources and related topics,” in “Introduction to Terahertz Electronics,” Springer, 2021.
4. N. Talebi, "Interaction of electron beams with optical nanostructures and metamaterials: from coherent photon sources towards shaping the wave function," J. Opt., vol. 19, art. no 103001, 2017.
5. T. Fu, D. Wang, Z. Yang, Z. Deng, and W. Liu, “Steering Smith-Purcell radiation angle in a fixed frequency by the Fano-resonant metasurface,” Opt. Expr., vol. 29, no 17, pp. 26983-26994, 2021.
6. R. J. England et.al.: “Dielectric laser accelerators,” Rev. Mod. Phys., vol. 86, no 4, pp. 1337-1389, 2014.
7. Y. Wei, M. Ibison, G. Xia, J. D. A. Smith, and C. P. Welsch, "Dual-grating dielectric accelerators driven by a pulse-front-tilted laser," Appl. Opt., vol. 56, pp. 8201-8206, 2017.
8. K. J. Leedle et.al., “Phase-dependent laser acceleration of electrons with symmetrically driven silicon dual pillar gratings,” Opt. Lett., vol. 43, pp. 2181-2184, 2018.