Propagation and Generation of Electromagnetic Waves in Carbon Nanotubes and Graphene

K. Batrakov, P. Kuzhir, M. Shuba, S. Maksimenko[*]
Institute for Nuclear Problems, Belarusian State University, Bobruiskaya Str. 11, 220030, Minsk, Belarus

Current trends in nanoelectromagnetics are analyzed with the focus on applications in the terahertz frequency range. The analysis is exemplified by the discussion of the THz response peculiarities of carbon nanostructures and composite materials with nanocarbon fillers. Some electromagnetic applications of nancarbons are discussed, such as nanoantennas, amplifiers and generators of terahertz radiation, THz range functional materials for radar absorbing and reflective coatings.

We demonstrate theoretically the dominant role of finite length effect in the non-Drude conductivity of CNT films due to the strong slowing down of surface plasmon-polariton [1,2]. The THz peak frequency depends on the length and diameter of CNTs and their doping [3]. Localized plasmon resonance in MWCNTs and in graphene is also theoretically described in [4-5]. A method has been developed allowing evaluation of the CNT conductivity in a wide range of frequencies and at different values of chemical potential, see Fig. 1.

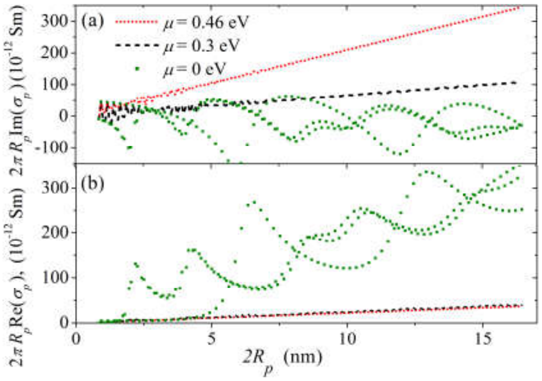

Fig. 1 The real (a) and imaginary (b) parts of the zigzag SWCNTs conductance versus diameter at different chemical potentials $\mu = 0$ (1), 0.3 eV (2) and 0.46 eV (3). The frequency is 100 THz and temperature is 300 K. Each SWCNT has a diameter $2R_p$, conductivity σ_p and chiral indices $(10+p,0)$, p=1,2,…200.

The propagation of an electron beam over a graphene/dielectric sandwich structure [6] is considered assuming the distance between the graphene layers in sandwich is large enough to prevent interlayer tunneling. Generation frequency tuning is proposed by varying the graphene doping, the number of graphene sheets, the distance between sheets, etc. [7]. The advantage being achieved by graphene doubling is the appearance of the acoustic mode among plasmon oscillations inherent in the system. The frequency of this mode is proportional to the difference of frequencies of plasmonic oscillations in layers. As a result, the phase velocity of this wave appears to be much less than that achievable in monolayer and can be tuned by altering of interlayer distance.

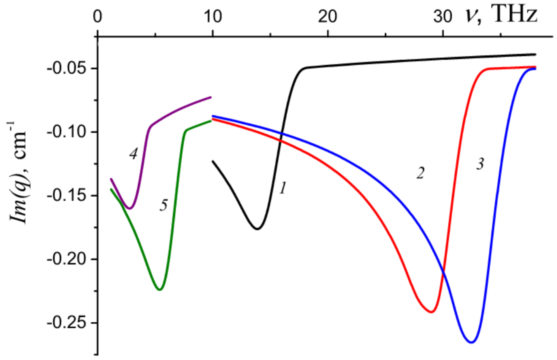

Fig. 2 Frequency dependence of the instability increment for 4 (1), 8(2) and 9 (3) graphene layers with chemical potential of a single layer $\mu = 0.2$ eV. Electron beam energy $E = 10$ keV, $\Gamma = 10$ THz. The same dependencies are given for a single graphene layer at the electron beam energy $E = 4$ keV, and chemical potential $\mu = 0.1$ eV (4) and 0.2 eV(5).

For graphene structure with number of layers more than two, effective conductivity is equal to sum of layers conductivities. Such an additivity has been observed experimentally in studying of electromagnetic wave transmission through graphene/PMMA sandwich [8]. Maximal absolute values of the instability increments presented in Fig. 2 show us that the strong amplification regime can already be realized at the interaction length of the order of several centimeters.

This publication is based on work supported by a grant from the U.S. Air Force under Agreement FA9550-15-D-0003 and EU FP7 project FP7-612285 CANTOR.

[1] G. Y. Slepyan, et al., PRB 81, 205423, 2010.
[2] M. V. Shuba et al., PRB 85, 165435, 2012.
[3] A.M. Nemilentsau et al., PRB 82, 235424, 2010.
[4] M.V. Shuba et al., PRB 79, 155403, 2009.
[5] K. G. Batrakov et al., J. Nanophotonics 6, 061719, 2012.
[6] K. G. Batrakov et al., Sci. Rep. 4, 7191, 2014.
[7] K. G. Batrakov et al., PRB 95, 205408, 2017
[8] K. G. Batrakov et al., APL, 108, 123101, 2016

---

[*] Email: sergey.maksimenko@gmail.com