Scattering model for two crossing metallic carbon nanotubes

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Single-walled carbon nanotubes (CNT) are highly conductive nanoparticles with a huge aspect ratio (up to 10^6). They interact effectively with electromagnetic radiation and have great potential as nanoantennas and nano-waveguides in the terahertz and far-infrared ranges. Moreover, CNTs are excellent inclusions for producing conductive composite materials with a low percolation threshold. The interaction of the electromagnetic field with individual nanotube or array of oriented CNTs has been under intensive investigation for more than two past decades. However, there is no paper describing the interaction of the electromagnetic field with two finite-length crossing SWCNTs. The scattering of the electromagnetic wave by crossing nanotubes is a fundamental task taking into accounts both electromagnetic interaction between CNTs and intertube electron tunneling at the crossing point. It is a first step to the development of the electromagnetic theory of a conductive network in the microwave and terahertz ranges.

Here we present the scattering theory for two crossing finite-length metallic single-walled CNTs. The boundary value problem has been formulated for those nanotubes exposed to the electromagnetic field. The CNTs are considered as finite-length cylinders with axial surface conductivity which follows the Drude formula. Due to the one-dimensional nature of the electron transport, the axial azimuthally-symmetrical current is excited in each CNTs. The conductance of the intertube contact has been found from the four-terminal Landauer formula of the quantum transport theory. The intertube current is taken into account by (i) a discontinuity of axial currents in CNTs, and (ii) by an introduction of extra charges on the CNT surface at the crossing points. The field of those charges must be the same as the field induced by the intertube current. In this way, we have reduced the scattering task to the system of Pocklington-type integral equations with respect to the surface current on CNT surfaces. Moreover, we have shown that the extra charges on the CNT surfaces can be replaced by the semi-infinite axial currents on the CNT surface. This replacement allows reducing the boundary-value problem to the system of Hallen-type integral equations with respect to the surface current in CNTs.

We calculated the polarizability tensor, current and charge distribution for the two crossing identical metallic carbon nanotubes (i) at both zero and non-zero intertube conductance, (ii) at different positions of the intertube contact, and (iii) different lengths of CNTs. At zero intertube conductance, the electromagnetic coupling between the tubes leads to the red or blue shift of the localized plasmon resonance in each CNT. The direction of the shift depends on the polarization of the incident wave. Electromagnetic coupling between CNTs is caused by radial components of the scattered fields. Since the radial component of the fields is much larger than the axial component of the incident field, it leads to the charge localization in the area of intertube contact. The effect of the electric field enhancement in the contact area results in an increase of the intertube tunneling current.

We also found that the coupling between two identical metallic CNTs leads to the appearance of a low-frequency peak in the polarizability spectra. The peak frequency f_0 decreases with a decrease of the intertube contact conductance. This peak divides the spectra into two regimes: at $f << f_0$ the intertube contact does not prevent current flow between the tubes, whereas at $f >> f_0$ the current between tubes is small and intertube coupling vanishes. The same peak appears in the polarisability spectra of the metallic CNT with a short low-conductive section [1]. It has been found that intertube coupling very slightly modifies a localized plasmon resonance in each of the crossing CNTs. This justifies the assumption of non-interacting nanoparticles for a description of the effective conductivity of CNT film in the terahertz range.

References

[1] M. V. Shuba, et al., "Integral equation technique for scatterers with mesoscopic insertions: Application to a carbon nanotube," *Phys. Rev. B*, **96**, November 2017, 205414, doi:10.1103/PhysRevB.96.205414.