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Electromagnetic interaction between a carbon nanotube and Plasmonic nano particle

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Abstract

The electromagnetic interaction between a carbon nanotube and a plasmonic nanoparticle is presented in this paper. In this communication the carbon nanotube is modeled using an integral equation involving a quantum mechanical surface conductance and the electrically small nanoparticle is characterized by its dipole moment. The model can be easily adopted to other systems consisting of electrically small objects coupled to larger objects requiring a full-wave treatment. The mathematical solution is provided for the current induced on a nanotube in the presence of a plasmonic nanoparticle.

Keywords: Carbon nanotubes, electromagnetic theory, nanosphere, nanotechnology, plasmons

Introductions

A carbon nantube is a fundamental structure in nanoelectronics, with applications in diverse fields. In particular, semiconducting nanotubes can be used as transistors [1] and related devices, and metallic tubes are envisioned as transmission lines [2-3]. It is important to understand the interaction between an electromagnetic wave and a carbon nanotube, and electromagnetic interaction effects among nanotubes and with other nanostructures.

A second nanostructure of fundamental importance is a plasmonic nanoparticle, such as a nonscopic noble metal spheroid at optical frequencies.

Plasmonic nanoparticles have formed an area of intense study in recent years for a number of reasons, such as their use in forming sub wavelength optical devices [4] and in biological/medical applications [5]. The importance of particle plasmons is due to their intense near-field, which can enhance electromagnetic effects by several orders of magnitude [6].

Mathematical Formulation

The formulation is developed for a carbon nanotube coupled to an electrically-small polarizable object characterized by its electric and magnetic polarizabilities, as depicted in Fig. 1.

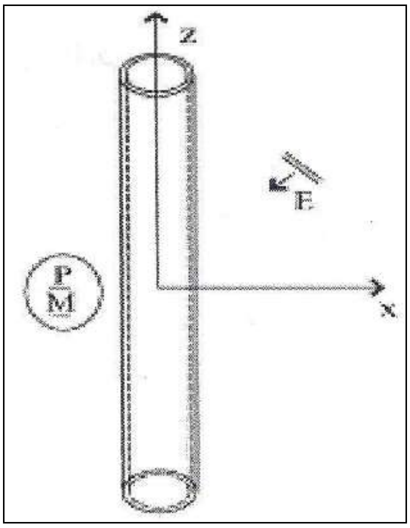

Fig 1: Electric and magnetic polarizabilities

The carbon nanotube is modeled as a finite length hollowcylinder with an infinitely-thinwall, characterized by a surface conductance σ_{cn}. But in general, carbon nanotubes are characterized by the dual index (m, n), $0 < \eta \neq m$, for chiral nanotubes. Obviously, carbon nanotubes can be their metallic or semiconducting, depending on their geometry. Thus, the resulting cross-sectional radius of a carbon nanotubes is given by

$$a = \frac{\sqrt{3}}{2\pi} b\sqrt{m^2 + mn + n^2} \qquad \text{---(1)}$$

Where b=0.142 nm is the interatomic distance in grapheme. From, Maxwell's equations

$$\nabla \times E(r) = -j\omega\mu H(r) - J_m(r) \qquad \text{----(2)}$$
$$\nabla \times H(r) = -j\omega\varepsilon E(r) - J_\varepsilon(r) \qquad \text{----(3)}$$

Where μ and ε are material parameters of the space occupied by the nanotube-sphere system, and Je,m are electric and magnetic current densities, respectively. Thus the solutions can be written as in the following forms [7].

$$E(r) = -j\omega\mu \int \underline{G}^{e,e}(r,r).J_e(r)d\Omega + \int \underline{G}^{e,m}(r,r).J_m(r)d\Omega \qquad \text{----(4)}$$
$$H(r) = -j\omega\varepsilon \int \underline{G}^{m,m}(r,r).J_m(r)d\Omega + \int \underline{G}^{m,e}(r,r).J_e(r)d\Omega \qquad \text{----(5)}$$

Where

$$\underline{G}^{e,e}(r,r) = P.V.\left\{\frac{1}{\omega^2\mu}\underline{F}^{e,e}(r,r)\right\} - \frac{L\delta(r-r)}{k^2} = \underline{G}^{m,m}(r,r) \qquad \text{----(6)}$$
$$\underline{G}^{e,m}(r,r) = \frac{1}{j\omega\mu}\underline{F}^{e,m}(r,r) = \underline{G}^{m,e}(r,r) \qquad \text{----(7)}$$

$k^2=\omega^2\mu\varepsilon$, P.V. indicates that the associated term is to be integrated in the principal value sense [8], L is the depolarizing dyadic, and Ω is the support of the current.
It is assumed that the lossy dielectric object is electrically small, such that its maximum linear dimension is much less than the free-space wavelength. In this case the object can be represented by its electric and magnetic dipole moment [9], p and m, respectively. The associated currents are

$$J_e = j\omega p\delta(r - r_{dm}) \qquad \text{----(8)}$$
$$J_m = j\omega\mu m\delta(r - r_{dm}) \qquad \text{----(9)}$$

Where r_{dm} is the location of the dipole moment.

$$r_{dm} = \hat{X}x_{dm} + \hat{Y}y'_{dm} + \hat{Z}z_{dm} \qquad \text{---(10)}$$

i.e., the polarizable object is centered at (χ_{dm}, y_{dm}, z_{dm}). The fields due to the dipole moments are then

$$E^{p,m}(r) = \underline{F}^{e,e}(r,r_{dm}).p + \underline{F}^{e,m}(r,r_{dm}).m \qquad \text{---(11)}$$
$$H^{p,m}(r) = \varepsilon\underline{F}^{e,e}(r,r_{dm}).m - \frac{1}{\mu}\underline{F}^{e,m}(r,r_{dm}).p \qquad \text{---(12)}$$

Results and Discussion

The following results lead to some predictions for the interaction between a carbon nanotube and a plasmonic nanosphere. For an isolated carbon nanotube at optical frequencies that integral equation model used here to comparison between optical Rayeligh scattering measurements and simulation results for armchair nanotube. The model concerns representing the electrically small polarizable object by its dipole moment. The dipole moment representation should be valid through the near ultraviolet regime. The upper size limit is dictated by the need for the sphere to be electrically very small, and the lower limit is due to the fact that spheres having sizes below.

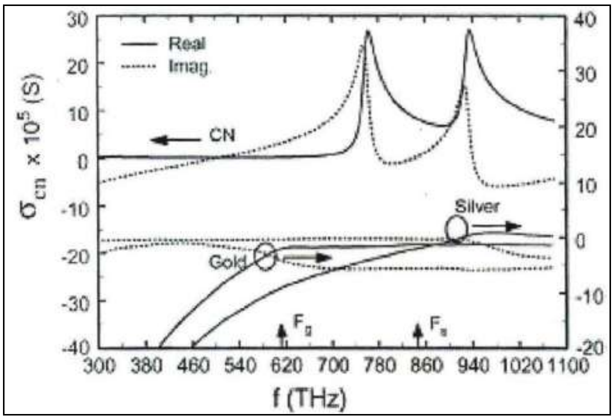

Fig 2: Frequency-dependent material parameters

Fig. 2. Shows the frequency-dependent material parameters for the objects. The complex conductance for a carbon nanotube is shows as upper two curves, corresponding to the left vertical axis, exhibiting optical interband transitions at certain frequencies.

Conclusion

A model has been presented for electromagnetic interactions between a carbon nanotube and an electrically-small materialsphere. The carbon nanotube is modeled as an infinitely-thin tube characterized by a full-wave intergral equation using a quantum surface conductance, and the electrically-small sphere is modeled by its dipole moment. It is predicted that the presence of a plasmonic nanosphere significantly affects the current on a nearby carbon nanotube, and can be used to induce relatively large currents on the tube in the vicinity of the sphere.

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