ELECTROMAGNETIC RESPONSE OF A ONE-DIMENSIONAL CHAIN OF INTERCONNECTED CARBON NANOTUBES IN THE SUB-TERAHERTZ RANGE

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Electromagnetic response from a finite-length one-dimensional chain of interconnected identical single-walled carbon nanotubes has been theoretically studied in the sub-terahertz range. It has been shown that the polarizability spectrum of this chain has two peaks. High frequency peak originates from a finite length effect in each tube of the chain, whereas low frequency peak is a result of a collective interaction of the tubes with the electromagnetic radiation.

1. Introduction

Due to their high conductivity and aspect ratio, single walled carbon nanotubes (CNTs) are actively applied as inclusions for composite materials having a high conductivity and low percolation threshold [1]. CNT-based composites demonstrate strong shielding effect in the gigahertz range [1].

According to quantum mechanical consideration, the axial conductivity of the single-walled CNT satisfies Drude law in the terahertz and sub-terahertz ranges [2]. The polarizability of finite-length CNT can be found by solving Hallen's integral equation for current excited by the incident electromagnetic radiation [3]. The electromagnetic properties of the composite materials have been analyzed previously using the effective medium approach [4] for uncoupled CNTs, i.e. at concentration below the percolation threshold.

Above the percolation threshold, both electronic and electromagnetic coupling of the CNTs should be taken into account. As the first step to investigate the composite materials comprising coupled CNTs, we consider one-dimensional chain of metallic single-walled CNTs electrically connected by tunnel junctions, referred to as a nanotube chain (NC). We will consider straight NC, where CNTs are coupled by their tips as depicted in Fig. 1(a). The polarizablity of the NC will be compared with the polarizability of (i) the same chain comprising electrically uncoupled CNTs (Fig.1 (b)), and (ii) hypothetical individual tube with diminished conductivity (Fig. 1 (c)).

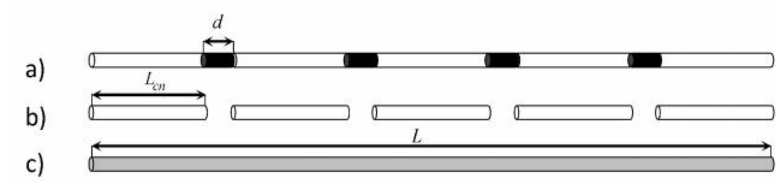

Fig. 1. Schematic illustration of the NC comprising of electrically coupled (a) and uncoupled (b) CNTs. Dark sections indicate tunnel junctions between adjacent CNTs; (c) hypothetical individual CNT with diminished conductivity.

2. Calculation method

Let us consider a NC comprising of N identical metallic CNTs with a length L_{cn} and a radius R. CNTs are connected by the identical tunnel junctions, and aligned parallel to the z axis of Cartesian coordinate system. Each nanotube can be modeled as a conductive cylinder and the only azimuthally symmetric electric current densities can be excited in the CNTs [3]. We assume that the tunnel current through each junction between adjacent CNTs has the same azimuthal distribution as the current on the nanotube surface. Under these assumptions we can model the NC as a single nanotube of total length $L = NL_{cn}$ and having z-dependent axial conductivity. The polarizability of this model nanotube can be found by solving the Hallen's integral equation for an axial current excited by the incident electromagnetic radiation [3]. The axial surface conductivity of the CNT σ_0 has Drude-like behavior with electron relaxation time τ as follows from quantum transport theory [2]. For the case of identical CNTs and the same velocity of the electrons near the Fermi energy in all the conductive channels, the conductance of the tunnel junction $G(\omega)$ can be derived from Landauer formula [5]:

$$G(\omega) \approx G(0) = \frac{e^2}{\pi\hbar} \cdot N_c \cdot \sum_{i=1}^{N_c} T_i \cdot \frac{1}{\sum_{i=1}^{N_c} R_i} \tag{1}$$

where e is the electron charge, $\hbar$ is reduced Planck constant, N_c is a number of the conductive channels in the CNT. T_i and $R_i = 1 - T_i$ are, respectively, the total transmission and refection coefficients for the electron with Fermi energy in channel i . We assume that the conductance of the junction is pure real and determined by Eq. (1) in the frequency range $10^8 - 10^{13}$ Hz. Then the effective conductivity of the junction with length d is $\sigma = G(0) \cdot d / 2\pi R$. We found that the polarizability of the NC weakly depends on the value of d and is determined mainly by $G(0)$. To simplify numerical calculations of Hallen's integral equation we will assume the value d to be much larger than realistic junction size.

3. Numerical results and discussion

Figure 2 demonstrates the frequency dependence of the polarizability a_{zz} for the NC comprising of electrically coupled and uncoupled CNTs shown in Fig. 1(a) and 1(b) respectively. The polarizability of the hypothetical individual CNT of length L and axial conductivity σ_d are shown as well. For calculations, we used the following parameters: L = 10 µm, L_{cn} = 1 µm, N = 10, R = 0.5 nm, τ = 50 fs, d = 20 nm, $T_1 = T_2$ =0.005, N_c = 2, $\sigma_d = \sigma_0/18.46$. The conductance of the hypothetical individual CNT equals to the conductance of NC.

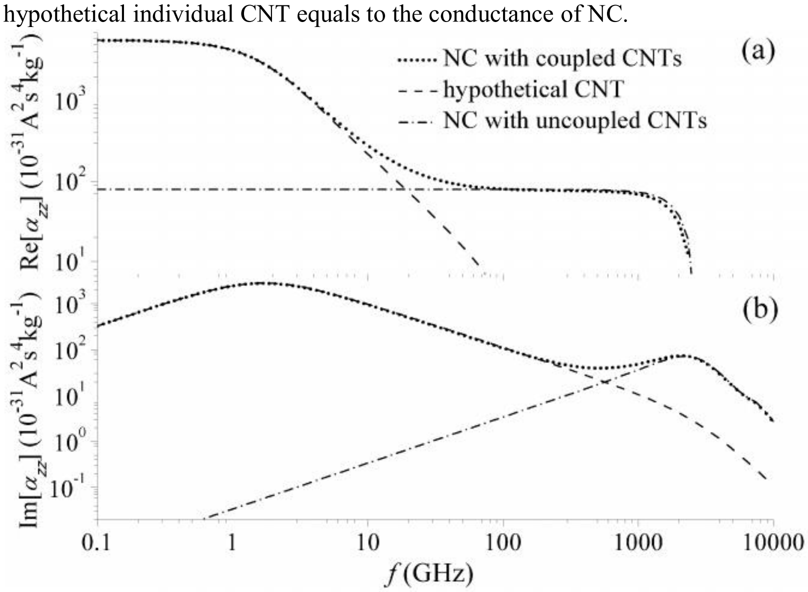

Fig. 2. The frequency dependence of the real (a) and imaginary (b) parts of the NC polarizability comprising of coupled (dotted line) and uncoupled (dot-dashed line) tubes. The polarisability of hypothetical CNT is shown by dashed line.

In Fig. 2, we can indicate three regimes of NC interaction with the electromagnetic wave:

- In the quasi-static regime (below 1 GHz), tunneling junction do not prevent charge propagation along the tubes. In this regime, the real part of the NC polarizability is the same as for the infinitely conductive nanotube of the same length L as the NC. The imaginary part of the NC polarizability is much higher for the case of electrically coupled than uncoupled CNTs. This means that tunnel junctions change the phase between the current and total field on the tube surface providing stronger energy dissipation. Thus the coupling leads to a weakening of finite-length effect in CNTs.

- In the range 0.5-10 THz, the junctions between adjacent CNTs in the chain suppress charge propagation along the NC. Therefore the polarizability of the NC of coupled CNTs coincides with that for uncoupled tubes. The length effect in the CNTs is strong resulting in the terahertz peak in the polarizability spectra of the CN (see Fig.2(b)).
- In the range 1-500 GHz, the tunnel junctions partly suppress propagation of the charges along the chain. Collective interaction of the coupled tubes with electromagnetic field leads to a low frequency peak at 2 GHz in the polarisability spectra of the NC.

Conclusions

The polarizability of finite-length NC has been calculated and analyzed in the sub-terahertz frequency range taking into account both electromagnetic and electronic coupling of the CNTs. Two peaks emerge in the polarizability spectra. Low frequency peak is a result of collective interaction of coupled CNTs with the electromagnetic field. High frequency peak is due to the finite length effect in each tubes of the chain.

Acknowledgments

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