The kinetic inductance of single-walled carbon nanotube metal type

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Abstract. The results of theoretical studies of the kinetic inductance $L_k$ of metallic single-walled carbon nanotube type, taking into account the electron-electron interaction in the approximation of a right circular cylinder are presented. The system under consideration is a cylindrically symmetric potential well with a finite height of the wall. As part of the response of the theory of two-dimensional electron gas in the external electromagnetic disturbance obtained in the form of kinetic inductance depending on the nanotube diameter, frequency and intensity of the radiation. Established that $L_k$ value increases with increasing frequency, and decreases with increasing radiation intensity.

1. Introduction
In 1991, in the course of studying the deposit forming on the cathode at dispersion of graphite in a voltaic arch, the attention of the Japanese researcher Sumio Iidzima was drawn by the unusual structure consisting of the smallest fibers [1]. In the course of detailed studying by methods of an eletkron microscopy it was established that the diameters of these fibers varies from one to several tens of nanometers, and length reaches several microns [2]. Fibers are formed by one or several layers of graphen curtailed into a tube. Due to the structural features and characteristic diameters, these structures were called carbon nanotubes. It is noteworthy that in most cases, nanotubes with closed ends are synthesized, representing half the fullerene molecule. Today technologies of receiving open nanotubes from material on the basis of the closed tubes are developed [3–5]. As it is possible to guess, there is a set of ways of turning of a decanter in a tube at which orientation of the hexagons making a grid, rather long axis of a tube differs. Depending on turning type, carbon nanotubes can have semiconductor or metallicity. At reference synthesis it is formed approximately single-wall carbon nanotubes (SCNT) of metal type and semiconductor nanotubes. Unique combination of such properties as ballistic conduction with the current density reaching $10^9 \text{A/cm}^2$, larger mechanical strength and high heat conductivity, give prerequisites for a wide range of applications of SCNT as element base of the modern nanoelectronics. In this regard intensive researches of electronic characteristics [6-11], dielectric [12,13] and magnetic [14, 15] characteristics of nanotubes are conducted. However unsolved is a question of an apparent type of dependence of the inductance arising when passing through a nanotube of a harmonic signal from geometrical characteristics of the studied object and parameters of an incident radiation. Results of the real research can be used at projection of nanoaerial arrangements for detecting of radiation, including, widely studied today, terahertz range.
2. Interaction with radiation

It is widely known that the geometry of a single-wall nanotube has cylindrical symmetry. Electronic properties of this sort of structures more are defined not by a concrete type of a crystal lattice, and a geometrical structure. In this work of SCNT the symmetric potential well with the terminating height of walls in the field of which there are conduction electrons interacting among themselves is considered as cylindrical. Taking into account explained, we will consider interaction of an external electromagnetic field with a nanotube within model of a response of the electronic gas which is in the symmetric potential external cylindrical.

The electromagnetic wave, normally incident on SCNT, causes the driving of electrons of this tube described within the chosen model, the second Newton's laws:

\[ m \frac{dV}{dt} = eE, \]

where \( m, e \) and \( V \) — the weight, a charge and speed of an electron respectively, \( E \) — electric field strength of an electromagnetic wave. Using the known ratio of \( j = enV \), connecting a current density with the speed and density of charge carriers, we will rewrite a Newton's laws:

\[ \left( \frac{m}{e^2 n} \right) \frac{dj}{dt} = E \quad \ldots \quad (1) \]

The part of expression (1) bracketed has dimension of specific inductance. Thus, at the description of interaction of an electromagnetic wave with electronic gas of a nanotube, the last can be considered within model of the passive dipole possessing specific the fissile \( R \) and jet \( X \) resistance, and the complete impedance registers in a look

\[ Z = R + iX, \]

where \( i \) — imaginary unit. The condensance is bound to inductance the known ratio:

\[ X = \omega L, \quad \ldots \quad (2) \]

where \( \omega \) — the frequency of an incident wave, and \( L \) — specific inductance of the considered structure. Thus, the impedance is equal

\[ Z = R + i\omega L. \]

Inductance of electronic gas of a nanotube of metal type is caused not by the magnetic flux penetrating a tube surface, and inert properties of electrons. In view of the fact that electrons possess a terminating rest-mass and terminating value of mobility, the gas response formed by them has no instantaneous character. Therefore, when passing a variable signal, electronic gas of a nanotube responds to external indignation with a delay. This phenomenon was called kinetic inductance [16–18]. As a sign of uniqueness of the nature of inductance of electronic gas of nanotubes we will designate further specific inductance of \( L_k \). It is remarkable that in classical metal conductors of the macroscopic sizes, strictly speaking, the effect of kinetic inductance takes place too. But because of its smallness in comparison with the inductance caused by change of a magnetic flux through an exemplar it is not taken into account.

\[ L_k = \frac{m}{e^2 n}. \]

According to results of work [13], the electronic density of OUNT of metal type depends on the frequency of an incident electromagnetic wave as follows:

\[ n(r, \omega) = U \left( \frac{A - 1}{A}, 1, \frac{ra}{2} \right), \]

where \( U \) — a higher transcendental Kummer’s function [15],

\[ A = 24 \sqrt{4.78 - E_m r} \left\{ \cos \left( \frac{\omega}{c} (ct - r) \right) + \cos(\omega t) \right\} + 1. \]

Electron density contains dependence on a space variable of \( r \) as its radial distribution is non-uniform. As it was noted in [13], when overcoming threshold value of intensity of an electromagnetic radiation, there is an imaginary part of electronic density which is responsible for presence at electronic gas of a carbon nanotube of the inductive properties.
Thus, the apparent type of dependence of kinetic inductance of OUNT of metal type on diameter of an object and frequency of an electromagnetic wave is received

\[ L_k = \frac{m e^2}{\epsilon_0} \cdot U \left( A - \frac{1}{A}, 1, \frac{r A}{2} \right) \] ...

(3)

The formula (3) allows to determine the size of kinetic inductance for a concrete configuration carbon with the given frequency and counting rate. The carried-out analysis shows that the size \( L_k \) practically does not depend from \( \omega \). With body height of irradiance of \( I \), there is a decrease of specific kinetic inductance of OUNT. Results of calculation of this size on a formula (3) are given in tables 1–3.

Table 1. Dependence of specific kinetic inductance on intensity of a wave for a nanotube of diameter of 2 nanometers with a frequency of visible light.

| \( I, \text{GW/m}^2 \) | 0.5 | 5 | 10 | 50 | 100 |
|----------------------|-----|---|----|----|-----|
| \( L_k, \text{nH/nm} \) | 20  | 11 | 10.5 | 10.2 | 10 |

From table 1 it is visible that with body height of diameter of a nanotube value of specific kinetic inductance increases. It is bound to decrease of electronic density that is according to results [13, 15]. Important is an analysis of dependence of a jet part of an impedance of the SCNT electronic gas of metal type on frequency and irradiance. As the impedance gives an immediate quantitative assessment of the inductive properties shown by a carbon nanotube at interaction with an electromagnetic wave.

Table 2. Dependence of a jet component of an impedance on intensity of a wave for a nanotube with a diameter of 2 nanometers in the terahertz range.

| \( I, \text{GW/m}^2 \) | 0.5 | 5 | 10 | 50 | 100 |
|----------------------|-----|---|----|----|-----|
| \( X, \text{Ohm} \)   | 963.65 | 509.36 | 497 | 480 | 475.93 |

Follows from tables 1 and 2 that with body height of intensity, an incident radiation, there is a decrease of the sizes \( L_k \) and a jet part of an impedance \( X \). By results of a research it is established what with body height of frequency of radiation, increases \( X \), at the same time dependence \( X(\omega) \) is not linear as could seem from a formula (3).

3.Conclusion.

The theoretical research of interaction of electromagnetic waves of terahertz and optical ranges with carbon nanotubes of metal type, within an approximation of a response of the two-dimensional electronic gas which is in cylindrical symmetric potential well is conducted. It is established that electronic gas shows the inductive properties which depend on diameter of a nanotube, frequency and counting rate. Expressions for calculation of size of kinetic inductance of \( L_k \) and a jet part of an impedance \( X \) are received.

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