Tuning the optical response of Nano dipole antenna by using plasmonic materials as a load in the gap

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Abstract

Possibility of tuning the optical response of a Nano dipole antenna by using various plasmonic based materials is demonstrated. By incorporating various load geometry in Nano dipole antenna’s gap, different optical characteristics of Nano dipole antennas, e.g. extinction cross section (ECS), input impedance, scattering cross section (SCS), has been numerically investigated. It is shown that by properly design, based on desired goal, tunable and broadband absorption cross section can be achieved. In addition, a graphene based load is also incorporated, and multiple peaks for ESC at THz band was showed.

1. Introduction

Recently, due to impressive development in nano-scale fabrication technology, Nano dipole antennas which have so much in common with ordinary microwave antennas, have attracted increasing attention. Till now huge number of publications based on different kind of antennas and their characteristic have been proposed [1]. Ability of tuning the scattering and radiation spectra of this kind of antennas, is one of the major challenges in designing process. On way to control radiation spectra, is using a proper load between Nano dipole arms as a capacitor or in inductor [2–4]. Several types of nano-antenna designs have been proposed and investigated thus far, such as monopoles, dipoles, Yagi—Udas, and bowties [2, 3]. It was demonstrated antenna input impedance, can be modified as desired by appropriately filling the gap defined between the antenna arms with different materials. Several studies have confirmed that the shape of a nanoantenna primarily dictates its radiation characteristics [5, 6].

In this paper, by using plasmonic effect of metals at THz regime, various load designs in order to have a tunable optical response for nano dipole antennas presented. Through this paper, different loads, i.e., sphere and cylinder cores made by either gold or silver and combination of ordinary metals and new material knows as graphene, have been used. All of the simulation results documented in this paper were computed using the finite element-based numerical solver, COMSOL.

2. Design and simulation

Figure 1, shows the cross section of general Nano dipole antenna. The structure consists of two cylindrically shaped arms comprised of silver, which is separated by a ‘g’ long gap. In order to have resonance in THz regime, the gap height (g = 25 nm) was used. Besides, the length (L) and radius (ra) of each arm is 30 and 15 nm, respectively. On each end of the dipole, the arms are tapered with hemispherical caps with a radius of 15 nm.

In our simulations through this paper, silver [7] and gold [8] was modeled as a Drude dielectric with a permittivity by using [7] and [8] respectively.
Where

\[ \varepsilon_r^{Ag} = \varepsilon_\infty + \left( \frac{f_p^2}{f (j\nu - f)} \right) \]  

\[ \varepsilon_\infty = 5, \; \nu = 5.13 \text{ THz}, \; f_p = 2213 \text{ THz} \]  

And for gold we have;

\[ \varepsilon_r^{Au} = \varepsilon_\infty + \left( \frac{\omega_p^2}{\omega (j\nu - \omega)} \right) \]  

\[ \varepsilon_\infty = 10, \; \nu = 110 \text{ THz}, \; \omega_p = 1.3753 \times 10^{16} \text{ Hz} \]

2.1. Metallic cylindrical load for tuning the radiation characteristic

As a first step, a cylindrical load was used between the Nano dipole arms. The schematic is shown in figure 2.

Input impedance of antenna for different materials and load height and radius, was simulated and shown in figure 3. At this simulation the radius of cylinder was kept constant at 5 nm and height has changed. As one can see from figure 3, by varying the load’s height, one can change the input impedance of whole system and make it as close as possible to final goal.
In order to have a better comparison, the case when we different load radius has also simulated and showed in figure 4. It is clear that we have another parameter that can be used to alter the radiation characteristic. Furthermore, we have tested different materials, e.g. metal, and the ability of multiple peak was saw. So, a cylindrical load can be considered as a good candidate for the purpose of tunable Nano dipole antenna.

Figure 4. Input impedance of Nano dipole antenna, when a cylindrical load is used. (a) real, (b) imaginary part of input impedance versus frequency for different load height. (the load radius is 5 nm and its material assumed Ag).

2.2. Metallic spherical load for tuning the radiation characteristic
In the following, as a second step for tuning nano antenna, possibility of using sphere load was investigated. In figure 6, schematic of a Nano dipole antenna loaded with a multilayer sphere core is shown.

By simulating the proposed structure in figure 6, we have saw an interesting broad band scattering spectra, which is very good for the case of absorbers, detectors and modulators. The ECS and other scattering characteristics of a nanoantenna loaded with this proposed spherical load, is shown in figure 7(a).

In figure 7(b), the input impedance of proposed nanoantenna in figure 6 is shown. The ability of tuning spectra of nanoantenna is clearly observed from radiation characteristic plot. Therefore, if the aim is a broad band response from a general Nano dipole antenna, a proper designed spherical load can accomplished this mission. In addition, in figure 8 the 3D plot of component of electric field in z direction (Ex) is shown.

2.3. Combination of graphene and two spherical metallic core as a load for tuning the radiation characteristic
The third proposed load, incorporates the new discovered material, graphene, as a very powerful plasmonic material for designing a very tunable load.

Graphene is a two-dimensional material with honeycomb formation that has excellent properties such as optical transparency, flexibility and high electron mobility and conductivity. Its density of state and Fermi energy can be controlled via electrochemical potential with the aid of electrostatic gating, magnetic field or chemical doping. It is a material that has been the focus of much academic interest for its unique material properties. Moreover, graphene based devices are promising to exceed the performance of a variety of
conventional devices [9]. On the other hand, in the infrared and THz regimes, since graphene supports excitation of surface plasmons (SPs) and allows for strong sub-wavelength confinement of the electromagnetic fields, it can be used in designing metamaterial absorbers providing perfect absorption.

The proposed hybrid graphene-metallic load, consists of two metallic core (Au), which was shown its advantages, and an intersection layer of graphene which is placed right in the middle of two gold core at the center of gap. For simulating graphene, we have used conductivity model from kubo formula [10]. The cross section of proposed hybrid structure is shown in figure 9. The optical scattering cross section and input impedance of proposed structure is shown in figure 10. During the simulation of graphene in comsol, the value of 0.5 eV was used for chemical potential [10]. Due to existence of a graphene layer between these two gold spheres, plasmonic effects has been amplified and interband and intraband transition in graphene caused another scattering peak seprated from resonance frequency. Depends on how many graphene layers used between these two spheres, one can produce a very tunable radiation spectra in different frequency regime.

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In figure 10(b), the input impedance of Nano dipole antenna loaded with proposed load showed in figure 9 have plotted. In figure 11, 3D electric field (Ez) is shown. One thing that is interesting in figure 11, the amplitude of electric field in figure 11(a), is more than electric field in resonance condition (figure 11(b)), however the concentration of electric field around the perimeter of sphere is less than case b, so the abruption cross section in case b is much larger than case a.

3. Equivalent circuit

According to the results obtained in [4], the effective transit coefficient of the proposed nano-antenna system for the state of an object with eh transit coefficient within a host with e\text{h} transit coefficient is as follows:
Where \( N \) is the number of expansion terms, and \( A_n \) and \( U_n \) are the coefficients obtained by trial and error for each proposed form. In other words, the following auxiliary equation can be used, for example, to solve the above statement:
Figure 7. (a) Extinction, scattering and absorption cross section of Nano dipole antenna loaded with a layered spherical load. (b) The real and imaginary part of input impedance of Nano dipole antenna showed in figure 6.

Figure 8. Electric field (Ez) for the proposed Nano dipole antenna showed in figure 6. (all the geometry parameters are same as figure 6 and frequency of plotted figure $f = 630$ THz).
Figure 9. The proposed hybrid graphene-metallic load, consists of two metallic core (Au), and a graphene layer.

Figure 10. (a) Extinction, scattering and absorption cross section of Nano dipole antenna loded with a proposed hybrid graphene-metallic load. (b) The real and imaginary part of input impedance of Nano dipole antenna showed in figure 9.
Using these auxiliary equations (as shown in figure 12), the value of the unknown coefficients can be easily obtained.

Now, using the effective transit coefficient obtained, the equivalent circuit of the proposed shapes can be drawn in the form of series and parallel capacitors. For each equivalent state, such as figure 13, an equivalent circuit such as figure 14 can be drawn.
In which the values of the capacitators can be obtained as follows:

\[
C_0 \equiv \varepsilon_2 \varepsilon_0 (1 - w_1), \quad C_{11} \equiv \varepsilon_2 \varepsilon_0 \frac{w_1}{1 - h_1}, \quad C_{12} = \varepsilon_1 \varepsilon_0 \frac{w_1}{h_1}
\] (8)

Now, using the method described, the final equivalent circuit of all the proposed shapes can be obtained (figure 15). For instance, the equivalent circuit of the second proposed form, which involved the use of metal nanospheres, is as follows:

\[
C_0 \equiv \varepsilon_n \varepsilon_0 \left(1 - \sum_{i=1}^{\infty} w_i \right), \quad C_{11} \equiv \varepsilon_n \varepsilon_0 \frac{w_1}{1 - h_1}, \quad C_{12} = \varepsilon_f \varepsilon_0 \frac{w_1}{h_1}
\] (9)

4. Conclusion

The design presented in this paper consists of a multi-step adjustability process. In the first step, the placement of a dielectric body or homogeneous conductor in the space between the two arms of the bipolar nano-antenna arm was described. In the second step, in order to achieve optimal performance and show a greater degree of
freedom, we loaded the load into a bipolar dielectric sphere consisting of a three-layered object called the core, the first shell, and the second shell. One of the advantages of this shell-core object, which is electrically small, is its ability to become an adjustable nanomaterial element whose characteristics depend on the structure of the object and its volumetric ratio. Nuclear-shell loads have been shown to have a wide range of scattering and adsorption and are very suitable for manufacturing applications. Also, using graphene, it was shown that with a well-engineered design, a multi-peak spectrum could be created for the radiant properties of a bipolar nano antenna.

**Data availability statement**

The data that support the findings of this study are available upon reasonable request from the authors.

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