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Emergence of Nanoantenna: A Review

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Abstract - The emergence of Nano-antenna holds a high potential for enhancing the interaction of light with nano-scale matter. We discuss the role of Nano-antenna in transforming a kind of radio frequency energy to electricity. The function of an antenna is based on the fact that the free charge carriers are constricted into certain well- defined regions of space. A Nano-antenna at optical frequency is popularly known as optical antenna. It is the goal of this review to summarise and explain the current understanding of Nano-antenna. Today the importance of an antenna is dominated by their ability to provide an interface between the localized information processing using electrical signals and the free space wireless transmission of information encoded in various parameters of electromagnetic waves. In addition to enhancing the sensitivity of nanoantenna, carbon nanotube materials have been proposed which can be fabricated as a split ring at the facet of a coated fiber. In order to tune an antenna at optical frequencies one requires to adjust both inductor 'L' and capacitor 'C' with efficient material such as carbon nanotube as being low impedance to bring the resonance into optical regime.

Fabrication of Nano-antenna runs through different model such as electron –beam lithography focussed, ion-beam milling Nano- imprint lithography (NIL). Nano-antenna has potential applications ranging from scanning near field optical microscopy, Spectroscopy and lithography, photon superemitters, sensors plasmonic resonator as a localized cavity for surface plasmon amplification. It is conceivable that Nano-antenna combined with appropriate rectifying elements. In near- future the researchers have to prefer new materials that will easily comply with manufacturing process and designing new devices.

Key words: Nano-antenna, optical frequency, resonance, plasmonics, lithography, radiation.

I. INTRODUCTION

A nano-antenna is a nanoscopic device to transmit radfio frequency energy from the transmitter to radiator. We can't forget Richard Feymann[1] who gave a talk at the annual meeting of American Physical Society, entitled there is plenty of room at the bottom[1]. In this talk Feynman anticipated most of the experimental fields and issues of concern, which more than 20 years later, would become key issues in the understanding of Phenonmenon on the nanometer scale. He also talked the possibility of building nanoscale electric circuits. For example to emit light from a whole set of antenna, radio beam are emitted from an organised antenna. In course of time, Feynmenn's suggestion has already become reality and research and nanoantenna that work at optical frequency has developed into a strong branch of nano Science-nano optics in practice.[2, 3]

It is the goal of this review to summarise and explain the current understanding of nanoantenna at optical frequency.

1.1Function of antenna:

The function of an antenna is based on the fact of free charge carriers are constricted into certain well defined regions of space. These charges may start to oscillate if an ac voltage is applied or an electromagnetic wave is reaching in such a region of space. An ac voltage applied to a piece of metal changes the spatial distribution of charges as a function of time, which in turn will eventually affect the electric field of the charge distribution at any distance from the source. Due to the finite speed of light, C any change in the electric field at a remote point at a distance R only after a time $t_0+(\frac{nR}{c})$, where n is refractive index of the medium [4, 6].

A well- known fundamental source of such E.M. disturbances is a harmonically oscillating dipole which may be pictured as two metallic spheres connected by a thin wire as it was realised in H. Hertz's pioneering experiment [14]. If such a system is prepared in an initial state where some negative charge is on one sphere and the corresponding positive charge on the other one, the system when left alone- will start to perform an exponentially damped harmonic oscillation at a frequency $\omega_0 = \frac{1}{\sqrt{LC}}$ Where 'L' and 'C' are inductance and capacitance of the system respectively. The system is exponentially damped i.e. the energy loss is proportional to the energy still stored within the system[7]. It consists of two reasons:

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1.A finite resistance is felt by the charge carriers in the metal wire .

2.loss of energy due to radiation of electromagnetic waves.

This is so called radiation loss occurs due to oscillation creating time dependent electric fields at remote distances accompanied by magnetic field which vary according to Maxwell's equations[8]. At large enough distance these fields transform into plan waves which are free space solutions of the wave equation. If the dipole oscillations were suddenly switched off, far away fields would continue to propagate as they carry energy that is stored in the field themselves and has been removed from the energy originally stored in the charge distributed.

In contrast, the so called near field zone correspond to the instantaneous electrostatic fields of the dipole, which do not contribute to radiation but return their energy to the source after each oscillation cycle or when the source is turned off.

1.2Optical antenna:

In order to tune an antenna in such a way that it is resonant at optical frequencies one needs to adjust both L and C to bring the resonance into optical regime. According to R.Feynmann to achieve a resonance in the optical wavelength regime one would have to design L and C very small [1]. This can be achieved by shrinking the dimensions of the antenna to the scale of the wavelength [15]. However it is very difficult to adjust at higher frequency because metals no longer behave as perfect conductors. The main difference between the interaction of the low frequency and very high frequency electro -magnetic waves with the conduction electrons in metal stems fro a finite effective mass of electrons. Such an effective mass causes the electrons to react with increasing phase lag to oscillating E.M. fields as the frequency increases. This behaviour is in perfect analogy to a mass on a spring excited by an oscillating external force. In the case of electrons in a metal, the restoring force is Coulomb interaction with the stationary metal ions. For low frequencies the electrons follow the excitation without any phase lag. For increasing frequency of excitation they exhibit increasing oscillation amplitude as well as in increasing phase lag. As soon as the phase lag approaches 90°, the amplitude of the charge oscillation goes through maximum and in only limited. In metallic nanoparticles, this resonance corresponds to localised Plasmon resonance for certain materials (such as gold, silver aluminium and copper) happens to appear close to visible spectral range. Plasmon resonances do not appear in perfect conductors (metals at low enough frequencies). In those materials no phase change exists between excitation and charge response. The presence of localized Plasmon resonance is therefore characteristic for optical frequencies and can be exploited to balance drawbacks of antenna systems in this frequency range. The metallic character of doped semiconductors at low frequencies makes it possible to excite surface plasmons resonant at mid IRT Hz and microwave frequency[16, 17], while even perfect metal if periodically structured can support excitations which behave very similar to surface Plasmon polaritons(SPPs), so called spoof plasmons [18].

1.3 Potential of nanoantenna at optical frequencies:

The wavelength of visible light in vacuum in the green spectral range, is about 500nm, corresponding to an energy of about 2.5 eV. Photons with such energy can interact with matter through transitions between electronic states of spatially confined electrons.

Quantum mechanical approach:

This is the simplest as the particle in box model. The length scale of electron confinement i.e.the lenth of the box, must be on the order of 1nm. It suits the lowest energy transitions to occur in the visible spectral range. Electrons are encountered in larger organic molecules and artificial quantum confined systems eg:Quantum dots.

Since the size of the molecule is so much smaller than the free space wavelength of light, the birth of a photon from a quantum emitter is a highly inefficient process [22]. The total power emitted by a time harmonic line current element in a homogenous space with a length Δl much shorter than the wavelength λ_0

$$P_0 = \frac{I^2}{3}\pi\eta\left(\frac{\Delta l}{\lambda_0}\right)^2 \quad \text{.............................(1)}$$

Where I is the current amplitude and $\eta = \sqrt{\frac{\mu_0}{\epsilon_0}} \sim 377\ \Omega$ the wave impedance of free space [2].

Classically such a current element can be considered a model for the oscillatory motion of electrons in a molecule.

Since optical antennas are able to (i) confine E.M. radiation to very small dimension and (ii) very efficiently release radiation from localised sources into the far field, they provide the possibility to tailor the interaction of light with nano-matter. Since the higher the frequency, the more will be the information encoded, the visible and I.R. the wavelength band is widely used in today's high- speed data communication networks. As an interesting side effect, when entering the optical regime, the frequency becomes large enough such that detection of single radiation quanta is readily achievable and that quantum jumps in single molecule and atoms can be induced and observed [25]. Therefore, in the optical regime quantum aspects of the interaction of radiation and matter can be exploited in the context of long distance communication [26]. The whole description of the paper is given as section-wise –theory and technique in section (II) applications in (III) conclusion in (IV) and acknowledgement in sec (V).

(II)Theory:

The electromagnetic field emitted by an antenna is completely determined knowing time- harmonic current density j(r) along the antenna wires is known from which

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the charge density $\rho(r)$ then follows according to the continuity relation ∇.j(r) = $-\frac{\partial\rho(r)}{\partial t}$ = i$\omega\rho(r)$

In Lorentz gauge $\nabla.A(r)$ = i$\omega\mu$ $\in_0\in$ ϕ(r)

The vector potential A(r) and scalar potential ϕ(r) satisfy set of four inhomogeneous scalar Helmholtz equations.

$[\nabla^2 + k^2]$A(r) = $-\mu_0\mu J(r)$..(2)

$[\nabla^2 + k^2]$A(r) = $-\frac{1}{\epsilon_0\epsilon}\rho$(r) ....(3)

Where k = $2\frac{\pi}{\lambda_0}$, λ_0 = free space wavelength

A(r) = $\mu_0\,\mu \int g(r')G_0(r,r')dv'$ .... (4)

$\phi(r)$ = $\frac{1}{\epsilon_0\epsilon}\int \rho(r')G_0(r,r')dv'$ .... (5)

B(r) = $\nabla \times A(r)$ ....(6)

E(r) = $-\nabla\phi(r) - \frac{\partial A(r)}{\partial t}$ .... (7)

The current distribution, I(z) = $I_{max}.\sin[k(\frac{1}{2}L - |z|]$ ....(8)

Here I_{max}. = I(0) $\left|\sin\frac{1}{2}kL\right|$

Input impedance Z_L = $\frac{V_0}{I_0}$ voltage / current

= $R_L + iX_L$

$R_L = R_r + R_{nr}$ ....(9)

Where

R_L = antenna impedance

R_r = radiation loss

R_{nr} = Ohmic losses

The radiation efficiency of an antenna is η = $\frac{R_r}{R_r+R_{nr}}$ ....(10)

On introducing carbon-nanotube material, the resistivity, ρ = $\frac{R\times A}{\xi}$ (11)

Here ξ is nanotube length

$R_r = \frac{\rho\xi}{A}$

Cross sectional area of the tube A

$= \pi r^2$

$= \pi\left[(\frac{2r}{2})^2\right]$

$= \pi(\frac{d_t}{2})^2$

Now $R_r = \frac{\rho\xi}{\pi(\frac{d_t}{2})^2}$

$= \frac{X}{{d_t}^2}$

From eqn. (10) $\eta = \frac{\frac{X}{{d_t}^2}}{\frac{X}{{d_t}^2}+R_{nr}}$

η = X/ X +$R_{nr}.{d_t}^2$ ....(12)

Where, X= $\frac{4\rho\xi}{\pi}$

II. RESULT AND DISCUSSION

It is evident from eqn.(12) that d_t being diameter of nanotube, posses least value in nano range. So the numerator exceeds for higher efficiency. If the material for inductor and capacitor be preferred of nanotube material, the efficiency of nanoantenna increases according to eqn.derived in (12). Therefore, in antenna design it is important to specify the carbon nanotube material over which a certain performance is achieved.

Mass and spring Model:

To achieve a resonance condition, mass and spring model is one of them. In this model the Plasmon resonance by a simple mass and spring model with a resonance frequency,

$\omega_r = \sqrt{\frac{D}{m}}$

Where, D and m are the elastic constants of the restoring force and the total effective mass of the electron system respectively. We sketch a plasmonic particle whose electron cloud has been displaced by Δx. The restoring positive and negative charges at the ends are treated as point like- charges that posses potential energy due to Coulomb interaction.

If 'n' be the charge carrier density and A the area of cross-section then

Q = neAΔx.. (13)

Where, e is the elementary charge, the Coulomb potential energy

W(Δx) = $\frac{1}{4\pi\epsilon_0}.\frac{q^2}{d}$ = $\frac{1}{4\pi\epsilon_0}(neA)^2.\Delta x^2$

The restoring force is now given by F(Δx) = $-\frac{\partial W(\Delta x)}{\partial\Delta x}$

F(Δx) = $-\frac{1}{2\pi\epsilon_*}(ne)^2.\frac{A^2}{d}.\,\Delta x$

In case of nano- tube material , cross sectional area A = πr^2

$= \pi\left[\frac{2r}{2}\right]^2$

$= \pi\left[\frac{d_t}{2}\right]^2$

$A^2 = \pi^2.\frac{d_t^2}{4}$

Hence, F. Δx = $-\frac{1}{2\pi\epsilon_*}(ne)^2.\frac{1}{d}.\,\pi^2.\frac{d_t^2}{4}\,\Delta x$

$= -D'.\,\Delta x$ .... (14)

Where, $D' = -\frac{1}{2\pi\epsilon_*}(ne)^2.\frac{1}{d}.\,\pi^2.\frac{d_t^2}{4}$

From this relation spring constant D' can be obtained. The equation (14) has linear relation between displacement and resulting force leads to harmonic oscillations of the system. The approximate resonance frequency, ω_{res} of the particle Plasmon of an elongated particle is given by

$\omega_{res} = \sqrt{\frac{D'}{m}}$ ....(15)

$= \sqrt{\frac{1}{2\pi\epsilon_0}.\frac{n^2}{d16m}e^2\pi^4{d_t}^4}$

$= \frac{ne\pi^2{d_t}^2}{4}\sqrt{\frac{1}{2\pi\epsilon_0}\frac{1}{dm}}$

$= \frac{ne^2\pi^2{d_t}^2m_e}{4\epsilon_0m_e.e}\sqrt{\frac{1}{2\pi\epsilon_0}\frac{1}{dm}}$

$= \frac{{\omega_p}^2}{4e}\pi^2{d_t}^2m_e\sqrt{\frac{1}{2\pi\epsilon_0}\frac{1}{dm_enAd}}$

Here ${\omega_p}^2 = \frac{ne^2}{\epsilon_0m_e}$ plasma frequency, and m_e is effective mass of electron.

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$$= \frac{\omega_p{}^2}{4ed}\pi^2 d_t{}^2 m_e \sqrt{\frac{1}{2\pi\epsilon_0}\frac{1}{d m_e n A d}}$$

$$= \frac{\omega_p{}^2}{4ed}\pi^2 d_t{}^2 m_e \sqrt{\frac{1}{2\pi\epsilon_0}\frac{1}{m_e n \pi^2 d_t{}^2/4}}$$

$$\boxed{\omega_{res} = \frac{\omega_p{}^2}{8ed}\pi d_t \sqrt{\frac{1}{2\pi\epsilon_0}\frac{m_e}{n}}} \qquad (16)$$

In this model it is seen that resonant frequency is directly proportional to the diameter of Nanotube. A resonance in the plasma oscillations occurs at the bulk plasma frequency ω_p, independent of geometry. Here it is remarkable that the mass-and-spring model also accounts for a shift in the resonance. If it is maintained to have diameter in nano-range of carbon nanotube material, a sharp resonance may occur.

III. Applications of Nano-antennas

The topic of Nanoantenna is a new trend and aggressively progressing field of research. It holds promise for a variety of possible applications. We review different fields in which nanoantnnas are already applied today and might play a significant role in near future. Some of the important applications are listed below which should be more efficient with carbon nanotube materials.

1.Scanning near-field optical microscopy, spectroscopy and lithography.
2.Nanoantenna-based single-photon superemitters.
3.Optical tweezing with nanoantenna
4.Antenna-based photovoltaics and ifrared detection.
5.Optical antenna sensors.
6.Ultrafast and nonlinear optics with nanoantenna
7.Perspectives for lasing in nanoantennas.
8.Nanoantennnas and plasmonic circuits
9.Nanoantennas and thermal fields.

IV. Conclusions

We hope that this tour on nanoantanna has been able to show how lively and flowering the area of research. our suggestion to fabricate a new antenna with carbon nanotube material maintaining at frequency ω_{res} calculated theoretically in equation (16) may lead to achieve a new destination and predict efficient nanoantenna in the fields of listed above.

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