Study On Optical Nano Antennas: State of the Art, Scope and Challenges

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Abstract

The present paper reveals that the concept of optical antennas in physical optics is still evolving. Like the antennas used in the radio frequency (RF) regime, the aspiration of optical antennas is to localize the free propagating radiation energy, and *vice versa*. For this purpose, optical antennas utilize the distinctive properties of metal nanostructures, which are strong plasmonic coupling elements at the optical regime. The concept of optical antennas is being advanced technologically and they are projected to be substitute devices for detection in the millimeter, infrared, and visible regimes. At present, their potential benefits in light detection, which include polarization dependency, tunability, and quick response times have been successfully demonstrated.

Keywords: optical nano-antenna

Introduction

The optical antennas, which represent unique optical detectors equivalent to radio frequency (RF) antennas, are a novel concept in the field of physical optics [1]. The optical antenna is an helping tool for influencing and regulating radiation in the optical regime. Nowadays, optical antennas are subjected to an increasing amount of technical research. This technology has potential in the enhancement of the efficiency of sensing, light emission, photo-detection, spectroscopy, and heat transfer [1]. Conventionally, optics and photonics are involved in the regulation of optical propagation using fibers, lenses, mirrors, and different diffractive components. In almost all areas, antennas are universal, covering satellite to toys. As optical antennas have numerous prospects, the key benefits of this type of antennas can be précised as follows:

Optical antennas:

* (i) are point detectors which secure a recognition space of almost the square of the wavelength [2].

* (ii) combine optical radiation into minute volumes for *generating currents* in the wire which are identified by a rectifying component of almost 0.02 μm^3 volume. This minute material volume permits one to achieve faster responses. Initial assessments of this response time are about 100 ns for devices without optimization [3]. Conversely, one of the rectifying tools employed in detecting the signal is constructed on the basis of a tunnel effect, which has a response time of approximately 10–14 s, 10–15 s [4].

* (iii) are known as polarization-sensitive sensors like the RF versions [2].

* (iv) are capable of being tuned to a particular wavelength region. At optical frequencies, the metallic structures have a lossy character and as a result, the resonances are likely to be widened, which possibly limits the tuning ability (5].

* (v) are directionally sensible subject to the metallic structure design and the addition of peripheral optical devices [6].

Though the optical antenna has use possibilities in numerous fields, it has a great possibility for use as a biosensor and this review only highlights the biosensing application. This review provides a clear overview of optical biosensors to the reader, a concept that arises from the contact of visible light with free electrons at a metal-dielectric boundary [7].

History of Optical Antennas

The root of the theory of optical antenna can be found in near-field optics [8]. The proposal of using a colloidal gold nanoparticle for optical radiation concentration on a model surface to overcome the restrictions of diffraction in imaging is first made by Synge in 1928 [9]. The concept of using gold nanoparticles as an antenna was first presented in 1985 by Wessel [10] and it was first demonstrated experimentally by using a gold-coated polystyrene particle by Fischer *et al*. in 1995 [11]. In the succeeding years, sharply pointed optical antennas were used in microscopy and spectroscopy [12,13,14]. Tip-enhanced near-field optical microscopy is the result of these experiments. In early 1968, optical antennas were utilized as whisker diodes in infrared radiation recognition and combination [15,16,17] and as a continuation of these studies, various investigations about infrared antenna structures have been done [18,19,20].

In 1997, after proof of principle experiments, bow-tie type antennas have been suggested as optical probes for the near-field regime [21]. Later investigations presented the fabrication of bow-tie type antennas on tips [22]. After the establishment of the similarity of optical antennas with near-field optical probes [8], tip-on-aperture probe techniques become popular to grow the antenna structures [23,24]. As a result of these advances, many researchers head off to explore various antenna geometries with both experimental and theoretical approaches. As an example, Figure 1 displays several antenna shapes fabricated using different techniques. Nowadays, the use of surface plasmon resonance in optical antennas makes them more efficient for selected frequencies which holds potential for sensing and detection in the field of biology.

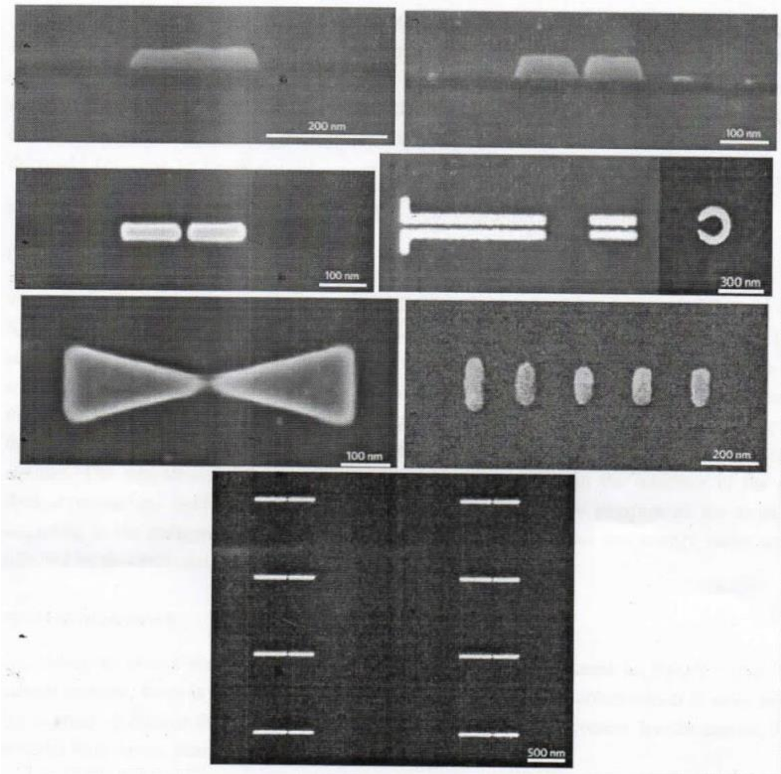

Figure 1

Optical antennas of different shapes.

Physical Properties of Optical Antenna

Before entering in depth into the field of optical antennas, we should know their basics. The main parameters for designing optical antennas are:

Local Density of Electromagnetic States (LDOS)

In the discussion of antennas, one of the most significant parameters is impedance. According to circuit theory, impedance is defined as *Z= V/I*, where *I* is current and *V* is voltage. According to this definition, the antenna is connected to the source through a transmission line, but this definition of antenna input impedance needs to be modified due to the feeding of optical antennas by confining light emitters rather than real currents. A practical replacement of this definition comprises the LDOS. This LDOS is the cause of the dipole energy dissipation in a random inconsistent environment. The allowance of a clear relationship of quantum conventional formalisms is the main benefit of using the LDOS. LDOS is represented by p and the total LDOS can be found as [28]:

$$\rho(r0,\omega=\langle\rho\rho(r0,\omega)\rangle\equiv Z\omega\pi c2lm\{Tr[G\leftrightarrow(r0,r0,\omega)]\}$$

(1) where *Tr* indicates the trace, ρ_ρ is the partial LDOS, ω is the transition frequency, G is the Green function tensor,*c* is the velocity of light, and r_0, is an arbitrary location. Therefore, the LDOS accounts for the existence of the antenna and is an extent of its

properties. In the absence of an antenna in free space, we achieve $\rho_\rho = \omega^2 / (\pi^2 - C^3)$ and $\Gamma 0 = \omega 3 \left| \left\langle g \middle| p \wedge \middle| e \right\rangle \right| 2/3(3\pi\varepsilon 0 hc3)$. Purcell observed the dependency of the amount of atomic decay on the indigenous atmosphere in 1946. Since then, it has been used for different systems, such as near interfaces of molecules or atoms in cavities. The adaptation of atomic decay rates has a foundation in the interface of the atomdistinct secondary field. This distinct field attains the rear of the position of the atom after scattering in the indigenous surroundings. The transition frequencies and energy states are also infected by this back-action.

Antenna Impedance

According to circuit theory, the antenna resistance can be calculated as Re{Z} = P/I^2. In an optical antenna, there is a governing dipole rather than a physical current which is more suitable for expressing Z according to the current density, $j \sim i\omega p$, as a replacement for the current, *I*. The antenna impedance, thus, can be defined as in by the expression:

$$\mathrm{Re}\{Z\} = \pi 12 \varepsilon \rho \rho (r0, \omega)$$

(2) Therefore, the antenna resistance Re{Z} can be linked with the LDOS. The unit of antenna impedance is Ohm per area in place of the typical Ohm. *Here*, *Z* is mutually dependent on the position r_0, and alignment n_ρ of the dipole. According to Greffet *et al.* , the stored energy can be found by the imaginary part of Z.

Antenna Efficiency

A basic problem in antennas is demonstrated in Figure 2. This figure contains dipoles p1 and p2, which are represented as a transmitter (*Tx*) and receiver (*Rx*). Here, the function of the antenna is to boost the *Tx* to *Rx* transmission efficiency, which can be achieved by raising the *Tx* radiation, for which a suitable figure of merit is the antenna efficiency and this antenna efficiency can be found as in [1]:

εrad=PradP=PradPrad+Ploss

(3) where *P* is the total antenna dissipated power and P_{rod} and P_{loss} means radiated power and power loss, respectively.

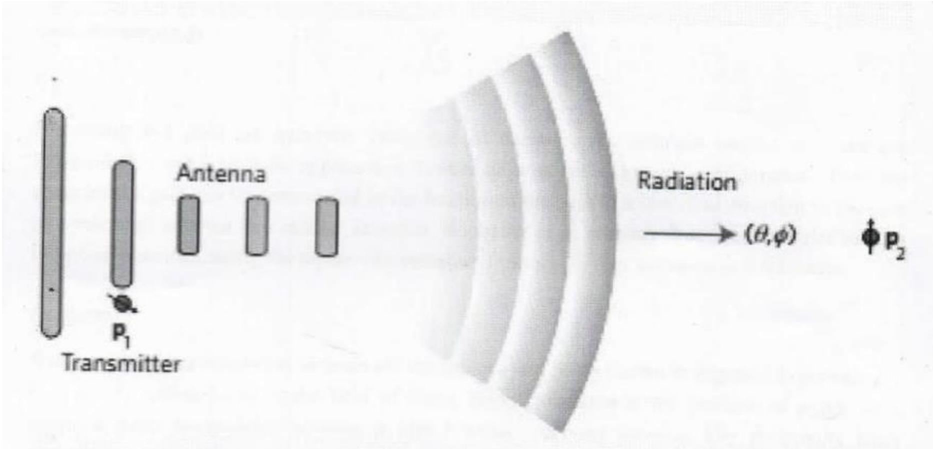

Figure 2

Enhancement of the transmission efficiency from the *Tx* to *Rx*.

Directivity

The capacity of focusing the radiated power into a definite route is known as the directivity of the antenna, which represents the density of the angular power in relation to an isotropic radiator. The improvement of the efficiency of transmission can be accomplished by guiding the radiation towards *Rx*. Directivity is a measure of the proficiency for this system which can be represented as [1]:

$$D(\theta,\varphi)=4\pi Pradp(\theta,\varphi)$$

(4) where both θ and ϕ denote the direction of observation and $p(\theta, \phi)$ denotes the angular density of power.

Gain

Antenna gain is the result of the combination of antenna efficiency and directivity. The definition of antenna gain is similar to that of the directivity, but here the normalization is done in comparison with power P instead of the radiated power P_{roud}. It can be mathematically represented as [1]:

$$G = \varepsilon radD = 4\pi P\rho(\theta\varphi)$$

(5) Directivity and gain are generally calculated in decibels. As isotropic perfect radiators are impractical, a more realistic approach is to state an antenna of known configuration. Then the comparative gain can be demarcated as the fraction of the gain in a specified direction to the gain of a reference antenna in a similar direction. Bouhelier *et al*. recently described the relative gain of optical antennas, using the dipole-like radiation from single nanoparticles as a reference.

Reciprocity

Reciprocity makes it possible to trade off the sources and fields shown in Figure 2 to provide p_1 E_2= $P_2 \cdot E_1$, where E_1 (E_2) is the field of dipole p_1(p_2) calculated at the position of p_2(p_1). As a result, a noble transmitting antenna is also a noble receiving antenna. The reciprocity leads towards a correlation of emitter's stimulation rate (Γ_{exc}) with the impulsive discharge rate (Γ_{rad}) for a two-state quantum emitter which can be presented as:

$$\Gamma exc, \theta(\theta,\varphi) \Gamma oexc, \theta(\theta,\varphi) = \Gamma rad \Gamma rado D\theta(\theta,\varphi) D\theta o(\theta,\varphi)$$

(6) where the meaning of the superscript "*o*" is the nonexistence of the antenna, while the subscript “θ” specifies the nature of polarization; explicitly, the points of the electric field in the direction of unit vector θ. An alike equation can be formed for polarization in the direction of ϕ. It is interesting that the excitation in high directivity direction allows Γ_{exc} to be boosted more intensely than Γ_{rad}. From Equation (6), it is clear that the relation of Γ_{exc} and Γ_{rad} due to the existence of the antenna is proportionate and has been included qualitatively in several studies.

Antenna Aperture

Antenna aperture is another significant antenna parameter, which is similar to the absorption cross-section σ. Let, a dipole with σ_o, cross-section as an *Rx* and the *Rx* is not connected to an antenna, n_p, is a directional unit vector, and E_0, is the receiver incident field. The receiver field increases to E after its connection with the antenna and antenna aperture (or absorption cross-section) can be found as

$$\sigma = \sigma o |nP.E| 2 |nP.Eo| 2$$

(7) Therefore, the antenna aperture changes with the indigenous intensity improvement factor. Many studies have revealed that 10^4-10^6 intensity enhancements are possibly attainable and therefore, a layer of molecules (all molecules are attached to an optical antenna) situated 0.1-1 µm apart are capable of absorbing all of the incident radiation for distinctive molecules with 1 nm^2 free-space cross-sections. Obviously, this evaluation has a limited validity because it overlooks the coupling among the antennas.

Effective Wavelength

In case of the radio wave antennas, the radio frequency (RF) counterpart of optical antennas, the wavelength of the incident radiation, λ relates to its design rules. For instance, the length of a half-wave antenna *L* is $\lambda/2$, and the separation between elements of a Yagi-Uda antenna corresponds to some fraction of λ. Therefore, the scaling of RF antenna design from one wavelength to another is very straightforward because of its proportionality to λ. Conversely, this scaling is not applicable to the optical regime where the diffusion of emission into metals has to be considered. The delay after supplying the driving field to get the electronic response due to a finite electron density results in the skin depth and this skin depth is usually bigger than the antenna element diameter. Hence, the electrons of a metal react to an effective wavelength λ_{eff} instead of the wavelength λ. This effective wavelength can be determined as:

$$\lambda eff = n1 + n2(\lambda \lambda P)$$

(8) where n_1 and n_2 are geometric constants and λ_ρ, is the wavelength of the plasma. Applying the new wavelength calculation rule, the wavelength of a half wave antenna for an optical regime becomes $\lambda_{eff}/2$ instead of $\lambda/2$. The difference between λ and λ_{eff} is influenced by the geometric constants, but is normally between 2 to 5.

Conductivity of Antenna Materials

As the conductivity of metals drops considerably when the diameters become less than 5 nm, metals are possibly not the best selection for antenna elements. In the case of diameters of less than 5 nm, carbon nanotubes are superior conductors than metals. Therefore, on a small scale, carbon materials have wide possibilities to be the materials of choice for optical antenna elements.

Antenna Resonance

The resonantly excited nanostructures behave as optical antennas similar to RF antennas, especially in IR (infrared) that concentrate the energy of electromagnetic radiation to a confined volume of the sub-wavelength scale. Thus, nanorods, with μm-sized lengths *L* that show plasmonic resonances in the IR spectral range are termed nanoantennas. However, the simple $\lambda/2$-dipole behavior known from RF antennas, where the relationship betweenL and the resonant wavelength λ_{res} is given by $2L = \lambda_{ress}$ does not hold for nanoantennas at optical frequencies. Moreover, the finite penetration depth of the light into the metal, and the non-negligible diameter *D* of the antenna lead to the modified relation.

$$2L = C2[\lambda res \lambda p] - c1$$

(9) In this equation, λp denotes the plasma wavelength of the antenna's material, whereas the coefficients c_1, and c_2 rely on *D* and on the static dielectric constant ε, of the surrounding medium. The basic assumption in this model is a high aspect ratio of the antenna (*D*<< *L*) and the metal is described as a free-electron gas, as stated by the Drude model with negligible relaxation rate compared to photon frequencies. Since these conditions are adequately satisfied for gold nanorods with *L/D* > 10 in the mid-IR region, Equation (9) can delineate the resonance behavior of isolated or at least non-interacting nanoantennas.

Conclusion

Optical antennas are the prevailing tool for the manipulation of light on a nanometer scale and they are also capable of delivering optimum control over transduction in the far-field region. Present optical antenna research is being motivated in particular by developments in nanofabrication technology and RF antenna analogies. Though various antenna conformations are currently being appreciated in the optical regime, it is going to be fascinating to observe how different antenna parameters, such as the impedance matching, are going to be redefined for different types of optical sources, like atoms and molecules. Optical antennas unite the quantum methods and photon sources by including fascinating new physics, for instance the breach of selection procedures and unconventional ways for robust pairing. The ideas of focused radiation and focused reception can be pragmatic to the photon emitters.

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