Project Report

On

Design and Analysis of a Cross structure Bowtie Nanoantenna

Submitted in partial fulfillment of
the requirements for the award of the degree of

Master of Technology
in
Microwave and Optical Communication Engineering

Submitted by
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2K16/MOC/09

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CANDIDATE'S DECLARATION

I, Parul Goyal, Roll No. 2K16/MOC/09 student of M.Tech (Microwave and Optical Communication), hereby declare that the project Dissertation titled "Design and Analysis of a Cross structure Bowtie Nanoantenna" which is submitted by me to the Department of Electronics and Communication and Department of Applied Physics, Delhi Technological University, Delhi in partial fulfillment of the requirement for the award of degree of Master of Technology, is original and not copied from any source without proper citation. This work has not previously formed the basis for the award of any Degree, Diploma Associateship, Fellowship or any other similar title or recognition.

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CERTIFICATE

I hereby certify that the Project Dissertation titled "**Design and Analysis of a Cross structure Bowtie Nanoantenna**" which is submitted by Parul Goyal, Roll No. 2K16/MOC/09 [Electronics and Communication], Delhi Technological University, Delhi in partial fulfillment of requirement for the award of the degree of Master of Technology in Microwave and Optical Communication Engineering, is a record of the project work carried out by the students under my supervision. To the best of my knowledge, this work has not been submitted in part or full for any Degree or Diploma to this University or elsewhere.

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ABSTRACT

Optical nanoantennas are a developing concept in physical optics. They enhance the interaction of light with nanoscale matter because of their ability to convert the freely propagating optical radiations into localized optical fields and vice-versa. They can be used in ultraviolet (UV), infrared (IR) and visible region. Optical nanoantennas are analogous to the radio antennas but there is slight difference in their scaling properties. This is because of the fact that at optical frequency, metals do not behave as perfect conductors. The most claimed advantage of optical nanoantenna is that it can be used for a wide range of wavelength as its tunability depends on the dimensions of the nanoantenna.

A metallic resonant optical antenna of a four-fold symmetric ‘cross’ geometry consisting of two perpendicular nanosized gold bowtie antennas with a common feed gap in between them has been designed. It is able to convert the freely propagating fields of any polarization state into localized field at the feed gap of the nanoantenna.

The designed metallic cross bowtie nanoantenna exhibits high radiation enhancement and localization of the field in the feed gap at the resonant wavelength of 500 nm. This nanoantenna has been made using gold, and its properties have been enhanced through geometry optimization to provide highly localized radiation enhancement at the resonant wavelength. The geometric parameters that are used for optimization of the designed nanoantenna are length of the antenna arm and the flare angle of the bowtie. The reason behind using wavelength of 500 nm is that at this wavelength solar radiation is maximum. Thus, the designed nanoantenna can be significantly used for solar energy harvesting. The antenna is modeled and its spectral analysis is carried out through finite element method (FEM) simulations using the ‘COMSOL Multiphysics’ software package in the visible regions. The effect of antenna arm length and flare angle of bowtie on resonance wavelength, scattering cross-section, field enhancement, far-field pattern, directivity and radiation efficiency are analyzed in detail.

Thus, the proposed nanoantenna can be utilized for applications requiring strong radiation localization along with optional polarization control in the visible region. So, the designed nanoantenna has immense scope in the techniques such as surface enhanced Raman spectroscopy (SERS), fluorescence spectroscopy, and solar energy harvesting.

ACKNOWLEDGEMENT

I would like to express my sincere gratitude to my project supervisor, Dr. Yogita Kalra, for her supervision, invaluable guidance, motivation and support throughout the extent of the project. I have benefited immensely from her wealth of knowledge.
I express my deepest thanks to Mr. Nishant Shankhwar for giving helpful advice and guidance. I choose this moment to acknowledge his contribution gratefully.

I extend my gratitude to my university, Delhi Technological University (formerly Delhi College of Engineering) for giving me the opportunity to carry out this project.

This opportunity will be a significant milestone in my career development. I will strive to use the gained skills and knowledge in the best possible way, and I will continue to work on their improvement, in order to attain desired career objectives.

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Chapter 1

Optical Antennas

In this chapter, the basic idea about an optical antenna, the properties of an optical antenna and the electromagnetics of metal has been presented.

1.1. Introduction

An antenna is a device which is used for receiving or transmitting the electromagnetic waves[1]. When an incoming electromagnetic radiation causes the distribution of electric current on an antenna, it will work as a receiver and when an externally driven dynamic current distribution causes radiation from the antenna, it will work as a transmitter[3]as shown in Fig 1.1. Most antennas are reciprocal i.e. they can be used as a transmitter or a receiver. Moreover, some antennas focus both on incoming as well as outgoing electromagnetic waves simultaneously.

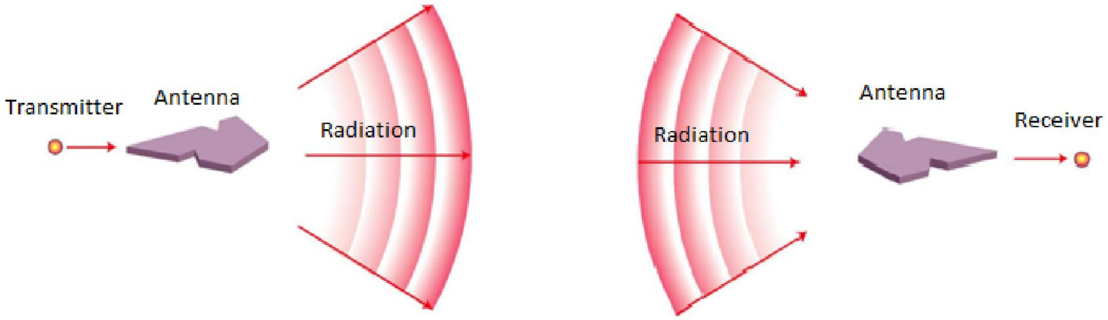


Figure 1.1: Antenna as a transmitter and a receiver. (a) Transmitting antenna. (b) Receiving antenna. Arrows indicate the direction of the energy propagation[3].

When an electric charge accelerates, energy is radiated by it in the form of electro-magnetic waves. Thus, Hecht explained that the main reason of the radiation from an antenna is the acceleration or deceleration of the free charges. In other words, time varying current on the antenna provides radiation into the surrounding medium[4]. This radiation field is transverse to the charge velocity. For transmission of current from a source to an antenna, the main requirements are an electronic circuitry that can generate a time varying current and a guiding device.

Antennas are characterized with the parameters: radiation pattern, radiation power density, radiation intensity, beamwidth, directivity, gain, bandwidth, polarization, input impedance [5].

1.1.1. Radiation pattern

The radiation pattern shows the directional variation of the parameters of a transmitter antenna. It can be a plot of the amplitude of the electric field or the magnetic field or the electric and magnetic power density. If the plot shows the variation of the amplitude of the electric and magnetic field, it is called the amplitude field pattern and if the plot shows the variation of the electric and magnetic power density, it is called as the amplitude power pattern. The radiation pattern has two types of lobes: Main lobe and side lobe as shown in Fig 1.2. The lobes having greater power strength in the desired direction are known as the main lobes and the lobes other than the main lobes are known as the side lobes. The side lobes having power distribution in the opposite direction of the main lobe are known as the back lobes. The side lobes show the unwanted radiations [1,5].

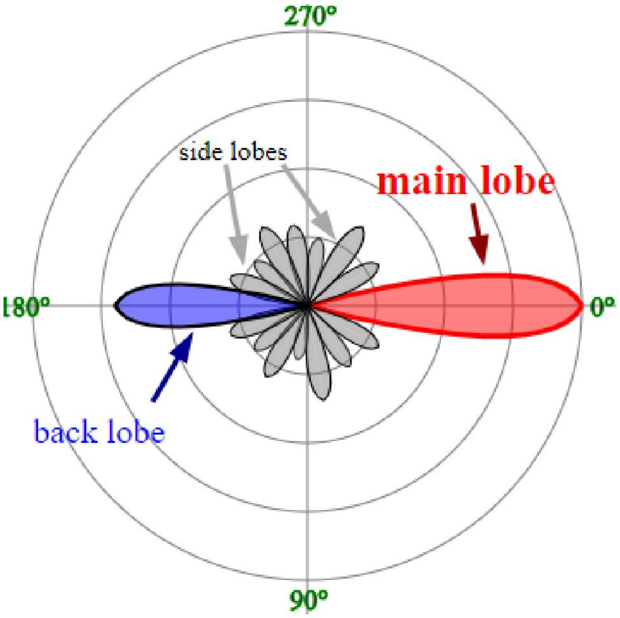


Figure 1.2: General radiation pattern of an antenna showing main lobe, side lobes and back lobe.

The radiation pattern of an antenna changes with change in the distance from the antenna. Due to change in the field pattern around an antenna with distance, the space around an antenna is divided into three regions: reactive near field, radiating near field (Fresnel) and far field (Fraunhofer)[1,2]. The reactive near field region is the region in which the energy decays very rapidly with distance. This region starts from the radiating surface of the antenna and terminates about a wavelength of the transceived wave. The radiating near field region is the region that lies between near field and far field regions. In this region, the field pattern significantly depends on the distance from the antenna and it begins from forming the lobes. If the dimensions of the antenna are very small as compared to the wavelength, this region diminishes. The boundary between radiating near field and far field regions is defined as the distance $2d^2/\lambda$ where d is the largest dimension of the antenna. After this distance, a far field region starts which does not vary with distance from antenna. In this region, the field pattern is formed and the energy decays with the square of distance from the antenna.

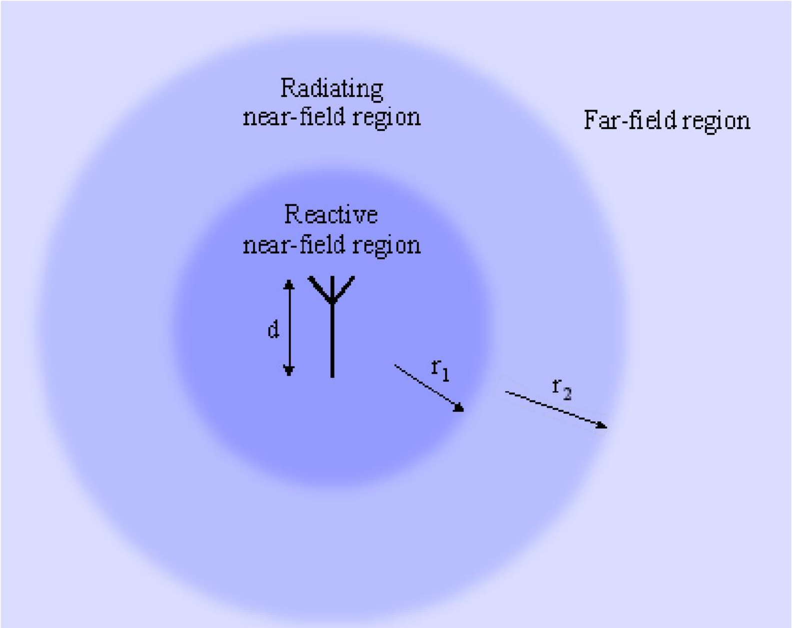


Figure 1.3: Field regions of an antenna depending on the distance from its surface.

The radiation power density W of an antenna is defined as the time average of the Poynting vector and the radiation intensity U is defined as the directional power radiated from the antenna per unit solid angle. Radiation intensity U is a far field parameter and it is obtained by multiplying the radiation power density by the square of distance, $U=r^2W$.

The beamwidth of an antenna is defined as the angular distance between two identical points on the opposite sides of the radiation pattern. We use another term half power beamwidth (HPBW) in an antenna which is defined as angle between the two sides of a radiation pattern where intensity of the radiation becomes half of its peak value in the direction where the radiation is maximum. Furthermore, first null beamwidth (FNBW) is defined as the angle between first nulls of the radiation pattern[1,5]. Fig 1.4 demonstrates radiation pattern, lobe and beamwidth concepts.

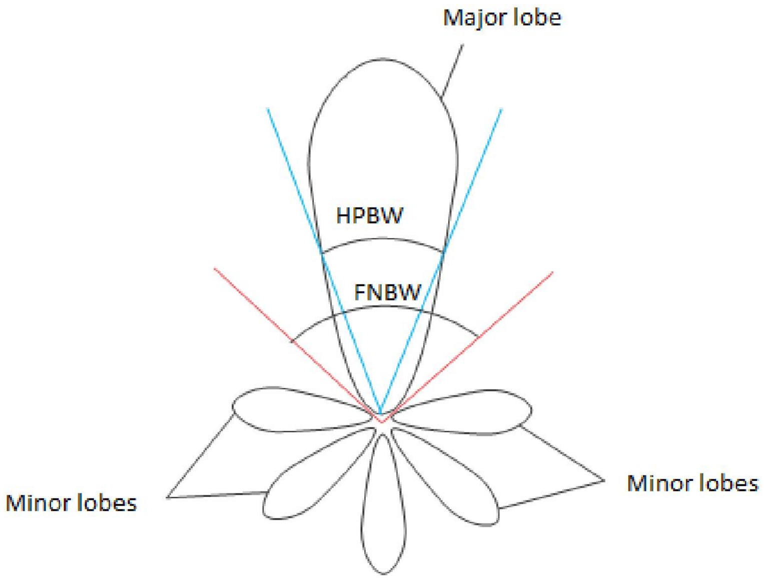


Figure 1.4: A typical radiation pattern of an antenna showing major lobe, minor lobe, half power beamwidth (HPBW) and first null beamwidth (FNBW).

1.1.2. Directivity and Gain

The directivity D of an antenna is defined as the ratio of the radiation intensity U in a particular direction to the radiation intensity averaged over all directions, $U_0 = P_{rad} /4\pi$. The direction of maximum radiation is taken as a reference if a particular direction is not mentioned [1,5].

$$D = \frac{U}{U_0} = \frac{U}{P_{rad}/_{4\Pi}}$$

The gain G of an antenna is defined as the ratio of the radiation intensity U in a particular direction to the antenna input power intensity averaged over all directions. Like directivity, the direction of maximum radiation is taken as a reference if a particular direction is not mentioned. In order to provide a relation between input power and radiated power, a term known as the radiation efficiency, e_{cd} is used i.e. $P_{rad} = e_{cd} P_{in}$. Radiation efficiency includes the conduction and dielectric losses of the antenna but it does not include the mismatch losses between source and the antenna[1,5]. Thus,there is a relation between directivity and gain.

$$G = \frac{U}{P_{rad}/_{4\Pi}} = e_{cd}D$$

1.1.3. Bandwidth and Polarization

The bandwidth of an antenna is the range of frequencies in which an antenna can operate significantly[1,5].

The polarization of an antenna is the direction of the electric field vector. It can be categorized as linear, circular and elliptical. If the electric field vector of the radiated wave is directed along a line at every instant of time, it will be linearly polarized. Circular polarization is a state in which electric field vector has a constant magnitude but its direction is always perpendicular to the direction of the wave.

1.1.4. Input Impedance

The input impedance, Z_A of an antenna is the ratio of voltage and current at the input terminals of the antenna. $Z_A = R_A + jX_A$. Here, R_A is the input resistance and it includes radiative and ohmic losses and X_A is the input reactance and it represents the reactive power losses. The input impedance of an antenna is purely resistive at the resonance.

Due to reciprocity theorem, the above defined parameters like radiation pattern, radiation power density, radiation intensity, beamwidth, directivity, gain, bandwidth, polarization and input impedance of an antenna are identical while using an antenna as a transmitter or as a receiver.

1.2 Electromagnetics of Metals

Maxwell's equations are used to describe how the metals interact with the electromagnetic field[6].There is no requirement of quantum mechanics even for the nanometer sized metals. This is due to the availability of large amount of free electrons in metals. Due to the high density of free electrons, electron energy levels will be very close and it will help in exploring the nanometer sized meals.

Metals reflect the incident electromagnetic waves whose frequencies are in optical regime i.e. UV, IR and visible region. In visible frequency and near IR regime, metals conductivity is very high and a small amount of incident electromagnetic wave penetrates into the metal. But at higher frequencies, the penetration of incident wave into metals becomes noticeable due to dielectric behavior of metals at such a high frequency. This dispersive behavior of metals can be explained with the complex dielectric function $\varepsilon(\omega)$ as all phenomena related to electromagnetics depend on $\varepsilon(\omega)$. The dispersive nature of metals is due to the phase difference between oscillations of free electrons and the electromagnetic wave.

1.3 Metal Nanoparticle Dielectric Functions

At optical frequencies, metals do not have high conductivity and thus the dispersion of metals becomes very crucial at optical frequency. The dielectric function of metal is determined by various methods like the Drude model, the Lorentz model, the Drude-Lorentz model and the Debye-Lorentz model [7]. These methods are used for semiconducting materials, metals, and dielectrics at optical frequencies, where strong resonances take place. It means that the optical properties of nanoparticles mainly depend on the dielectric function which is frequency dependent and the medium characteristics that surround it.

The constants of metals used at optical frequencies can be taken from various sources e.g., Drude-Lorentz model by Bora Ung[8], the values for dielectric function tabulated by Johnson-Christy[9] and Palik[10]. Above all methods, the Drude-Lorentz model is more accurate method that is used to describe the dispersion properties of different metallic nanoparticles as compared to the two other methods as it considers both the harmonic oscillations of bound electrons and free electron contributions. So, in this work, the Drude-Lorentz model is used to describe the complex permittivity of the used metal i.e. gold as given by equation 1.1.

$$\varepsilon_{\text{Drude}} = 1 - \frac{{\omega_p}^2}{\omega^2 + i\omega\omega_c} \qquad (1.1)$$

where ω_p is the plasma frequency and ω_c is the collision frequency.

The real part of this dielectric function of metal can be negative due to either contribution of free electrons or if the frequency is close to the resonant frequency of harmonic oscillator. The second condition occurs when the electrons in deeper bands are excited to the conduction band which is known as inter band transition. As compared to the contribution of free electrons contribution, this phenomenon is more responsible for the negative sign of the real part of the metal dielectric function due to shifting of optical frequencies close to resonance. The size and shape of the optical nanoantenna are responsible for the absorption losses in the nanoantenna but at the resonance frequency, the imaginary part of the permittivity of the metal plays an important role in these losses [7].

1.3.1 Drude, Lorentz and Drude-Lorentz models

The **Drude model** is mainly used for metals which have the free electrons moving through the material e.g. gold and silver. So, it can be used when there is no harmonic oscillation in the material. At optical frequencies, the bounded electrons in the valence band of a metal can be excited to the conduction band with the help of external light source and can cause the generation of the free charge carriers. The presence of these charge carriers provides a polarizable medium in metals and semi-conductors which can be excited with the help of a light source. If the size of a nanoparticle is smaller than 100 nm, it shows surface plasmon resonances [7].

The **Lorentz model** is used for the metals in which there is no contribution of the free electrons. It is completely due to the harmonic oscillations of the bounded electrons. Thus, this model is also known as harmonic oscillator model. Also, in this model, each atom has more than one resonant frequency[7].

The **Drude Lorentz model** considers both the harmonic oscillations of bound electrons and free electron contributions in calculating the permittivity of metals and thus is more accurate method than the above two methods [7].

Chapter 2

Types of Optical Antennas

This chapter presents the types of optical antennas based on materials used and the function of antenna.

2.1. Based on Materials Used

Optical nanoantennas can be fabricated using different materials e.g. metals, dielectrics or combination of both. On the basis of material used, optical nanoantennas can be classified as plasmonic nanoantennas, dielectric nanoantennas and hybrid nanoantennas.

2.1.1. Plasmonic Nanoantennas

For an antenna to be resonant at optical frequency, the small value of both inductance and capacitance is required[11]. In order to obtain this, the dimensions of the antenna can be reduced i.e. scale the dimensions of antenna according to the operating wavelength[12].

When high frequency electromagnetic radiation e.g. UV, IR or visible radiation is made incident on metals, the electrons in the metals get excited and their amplitude and phase lag increases with increase in amplitude. The amplitude will be a maximum at a phase lag of 90°, and this phenomenon is known as surface plasmon resonance (SPR). SPR occurs due to the finite effective mass of an electron [13]. This phenomenon explains the operation of optical nanoantennas which are made from metals such as Ag, Au, and Cu, which have their surface plasmon resonance in the visible region. These types of optical antennas are known as plasmonic nanoantennas.

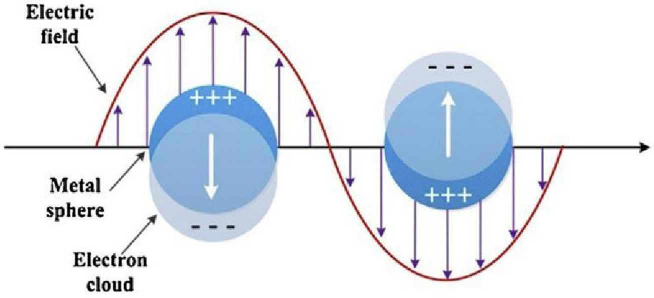


Figure 2.1: Excitation of a localized surface plasmon resonance [7].

The amplitude of oscillation at resonance is limited by ohmic and radiation losses which cause the internal damping of the system. Thus, the optical antennas can overcome the drawback of the RF antennas.

The idea about the plasmonic nanoantenna was firstly given by John Wessel in 1985[14]. He showed that due to the presence of a single plasmonic particle, the diffraction limit in resolution of optical devices can be overcome and predicts its value up to 1 nm. After some time, it became clear that the near field in the gap of two or more than two nanoparticles can have magnitude greater than in the vicinity of an elongated plasmonic particle because energy confinement in the gap of plasmonic particles occurs on small spatial scales. It shows that the electric field enhancement in the gap of plasmonic particles mainly depends on the geometry of nanoparticle, gap between nanoparticles and the material used for nanoparticle. Due to these parameters, it is possible to obtain the electric field enhancement in the gap between nanoparticles at the desired range of wavelength[15]. The main advantage of plasmonic nanoantennas is that they can be easily tuned and optimized for the desired range of operation by varying the parameters of nanoantenna. Some examples of plasmonic nanoantennas are shown in Fig 2.2.

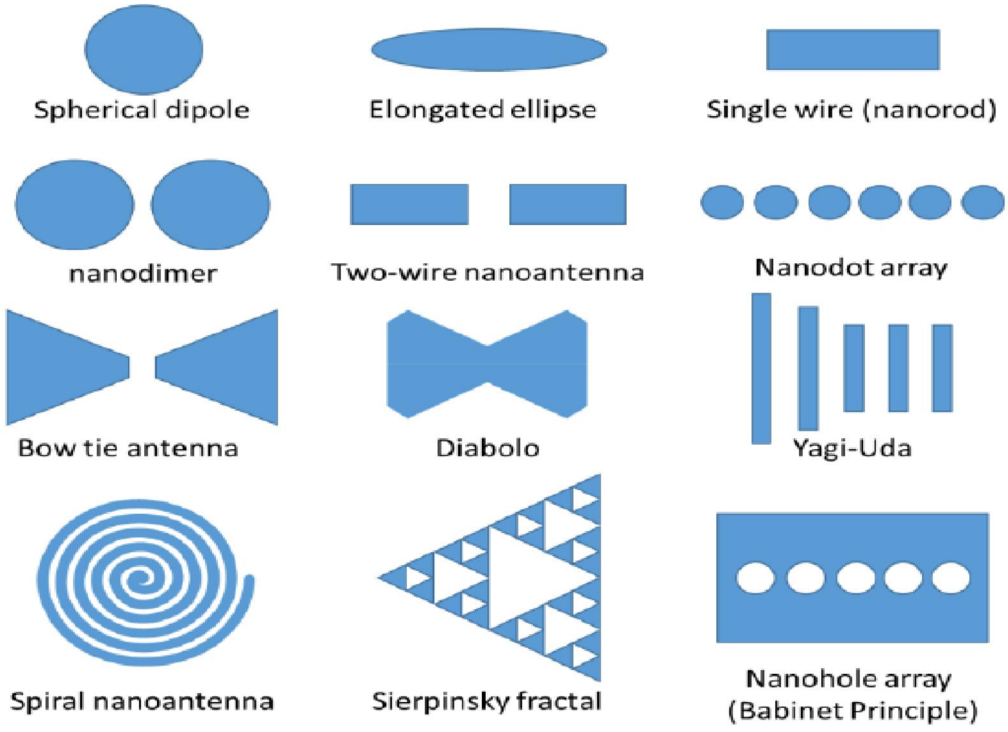


Figure 2.2: Different types of plasmonic nanoantennas.

2.1.2. Dielectric Nanoantenna

Although most of the optical antennas are designed using metallic materials whose working depends on surface plasmon resonances, there is one more type of optical antennas which are receiving great interest[13] – the dielectric nanoantennas. These nanoantennas are made using dielectric materials only, which have high refractive indices[13]. The fabrication of these nanoantennas is done using optically transparent materials whereas the fabrication of plasmonic nanoantennas is done using opaque materials. The dielectric nanoantennas exhibit resonance due to the formation of effective resonator inside the nanoparticle. Semiconductor materials are widely used as dielectric nanoantennas as they act as a transparent material in the visible regime.

There are a number of advantages of dielectric nanoantennas over plasmonic nanoantennas. Firstly, dielectric materials have low dissipative losses at the optical frequency. Secondly, the dielectric material can exhibit both electric and magnetic resonance simultaneously in a frequency range. Due to this, Huygens element can be created using single nanoparticle. This effect has a great importance in optics. The highly compact dielectric nanoantennas with a high directivity can be constructed using these Huygens elements due to their low losses and high directional properties e.g. Yagi-Uda nanoantennas [16-18]. The Huygens source made using Si nanoparticle and a Yagi-Uda nanoantenna are shown in Fig 2.3.

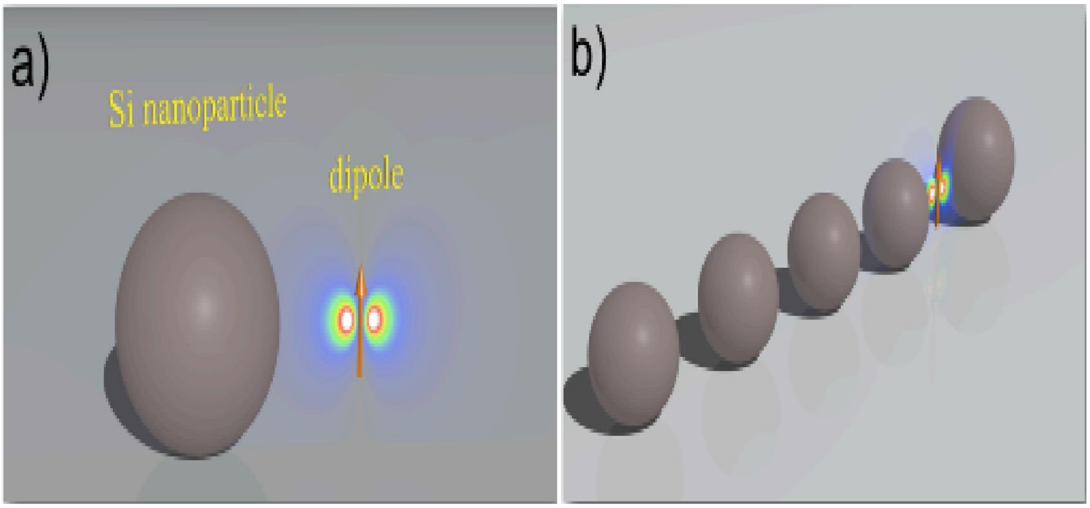


Figure 2.3: Schematic view of two types of all-dielectric nanoantennas. a) Huygens source b) Dielectric optical Yagi-Uda nanoantenna.

2.1.3. Hybrid Nanoantenna

Plasmonic and dielectric nanoantennas both have their own advantages. Plasmonic nanoantennas provide strong field enhancement at the feed gap whereas dielectric nanoantennas provide a large directivity with low dissipative losses. So, the nanoantennas that are made by combining these two types of nanoantennas on seeing their advantages are known as metal-dielectric nanoantennas or hybrid nanoantennas[19].

2.2. Based on Function of Antenna

On the basis of function of a nanoantenna, it is usually divided into two types, transmitting and receiving nanoantenna [13].

2.2.1. Transmitting Nanoantenna

For the transmitting nanoantennas, the source of radiation is the objects whose size is much smaller than the wavelength that they emit. These sources are known as quantum emitters. Due to their small size, they cannot radiate efficiently and hence cannot be used as nanoantennas. But if a nanoantenna is placed close to a quantum emitter, it will be excited by a strong localized emitter field and it will emit a high amplitude electromagnetic wave. From this, we can say that a nanoantenna enhances the radiation power of an emitter by few orders of magnitude. So, transmitting nanoantenna is a device which extracts the energy from an emitter and converts this energy into strong radiation. It also has the ability to redistribute the electromagnetic energy in the space.

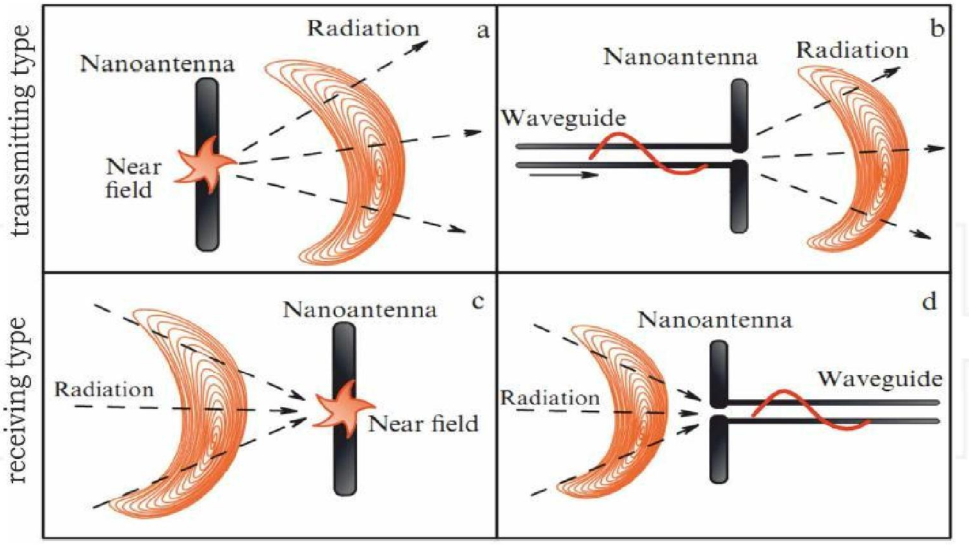


Figure 2.4: The basic principles of nanoantenna operation. Near field (a) waveguide mode (b) transformation into freely propagating optical radiation. (c, d) illustrate a reception regime [6].

2.2.2. Receiving Nanoantenna

The receiving nanoantennas convert the incident electromagnetic radiations into a strong localized field. They are designed in such a way that they are able to excite the quantum detectors of radiation that can absorb small power of radiations incident on them. These nanoantennas have high directivity which depends on applications of the device. Sometimes, the energy is concentrated to a narrow beam. The response of a receiving nanoantenna is characterized by specific unidirectional directivity; for example, the antenna is excitable by the waves coming from one half-space but poorly susceptible to the waves coming from another half-space.

Chapter 3

Optical Antenna Properties and Applications

This chapter presents the optical properties of the nanoparticles and applications of optical antennas.

3.1. Optical properties of nanoparticles

When the incident light interacts with nanoparticles, it results in refracted and reflected light which leads to absorption and scattering respectively. The scattering and absorption are of great importance at optical frequency as compared to reflection and refraction. But when there is a cluster of almost infinite number of nanoparticles such that it behaves as a macroscopic body, then the parameters transmittance and reflectance are still defined.

The absorption and scattering properties are highly affected by a number of parameters such as the shape and size of particle and also on the material constant like permittivity, refractive index etc. of the nanoparticles and the polarization of the medium that surrounds the nanoparticle. In short, we can say that the shape, size, distance between nanoparticle, material constants result in drastic change of the properties of optical nanoantennas [7].

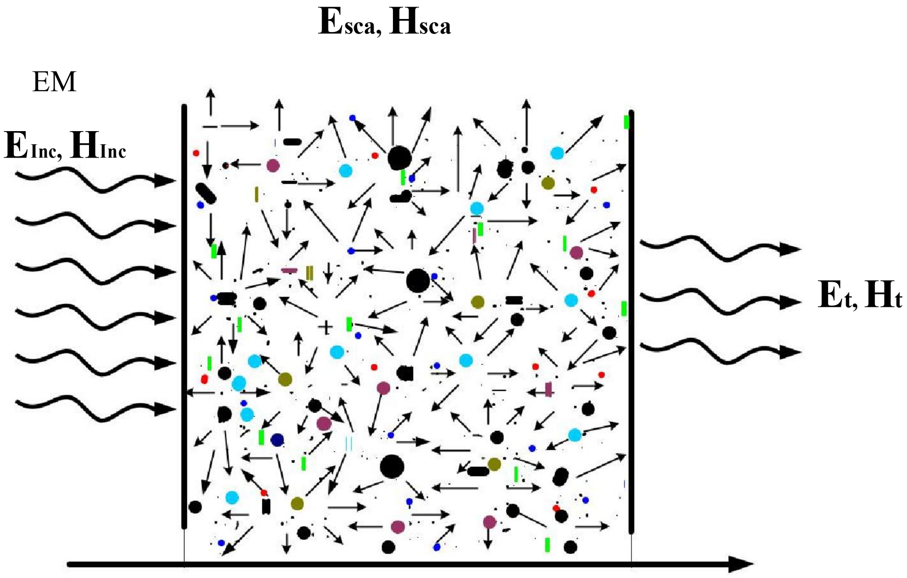


Figure 3.1: Scattering and absorption in a cluster of nanoparticles[7].

Figure 3.1 shows a cluster of nanoparticles that are illuminated by an electromagnetic wave. The electromagnetic fields i.e. electric and magnetic field of incident light (E_{Inc}, H_{Inc}) interact with nanoparticles, it is absorbed by the particles and scattered in the complete volume in a great extent. The reflected light contributes the scattering process whereas the refraction contributes the absorption process. As the light propagates in the direction of the incident light, transmitted light gets weaker due to the absorption and scattering process.

3.1.1. Effect of Nanoparticle Size and Shape

The absorption and scattering process determines the resonance features of nanoparticles which are referred as surface plasmon polariton resonances. On the basis of the ratio of the nanoparticle size and the wavelength of incident light, scattering can be classified as: the Mie scattering and the Rayleigh scattering. At optical frequency, the particles whose size is less than 300 nm undergo Rayleigh scattering which is a simple technique in the light scattering phenomenon. At the higher frequencies, the larger sizes particles undergo Mie scattering which is used to analyze the symmetric structures e.g. spherical nanoparticles. If the particle size is extremely small i.e. about 100 times less than the wavelength of incident light, then the particle is considered as a homogeneous material and the properties of the nanoparticle is determined with the help of a complex-valued dielectric function[7].

In semiconductors, nanoparticles size plays an important role in the optical properties during scattering of light. When the size of the semiconductor nanoparticles becomes smaller than a certain limit, the confinement of the electrons becomes more important and the energy levels become more quantized as compared to the valence and conduction band. At the plasmon resonance frequency, there is a strong absorption and scattering in metallic nanoparticles due to which strong colors are generated in noble metals. It is noticed that the changes in size of nanoparticles have a great effect on the ratio of the scattering to absorption. When the size of particles is small, the color of them is due to absorption i.e. absorption is more prominent than scattering in case of smaller nanoparticles. In case of metallic nanoparticles having size greater than 30 nm, the scattering process dominates over the absorption. So, we can say that absorption is dominant in case of smaller nanoantennas whereas scattering is dominant in large nanoantennas.

At nanometer scale, there are various factors that affect the shape of nanoparticles e.g. surface energy, proportion of corners and edges. The optimization of various parameters of a nanoantenna like resonant frequency, scattering cross-section, sensitivity, field enhancement, radiation properties etc. can be easily done by varying the shape, size and surface geometry of the nanoantenna[20]. Due to variation of the oscillation frequency of electrons, there is a shift in electric field density of the nanoparticles. This happens due to the variation in shape, size and surface geometry of nanoparticles which affects the absorption and scattering process in the nanoparticles.

The shape of nanoparticles depends on the characteristics of its atoms and molecules that form its corners, edges and surface geometry. The density of electrons is more at the corners and edges of a metallic nanoparticle. So, the different shapes of corners and edges may be a reason of difference in optical properties of metallic nanoparticles[20].

It is noticed that there is a trade-off between the reduction of the antenna size and performance of antenna e.g. bandwidth efficiency at optical frequency.

3.2. Optical Antenna Applications

Introduction of antennas at optical frequency has advent a number of advantages in various applications. Some of these applications are near field optics, spectroscopy, microscopy, solar energy harvesting, photo detectors, quantum light source, sensors, medicines, infrared and multi spectral imaging [21-26] etc.

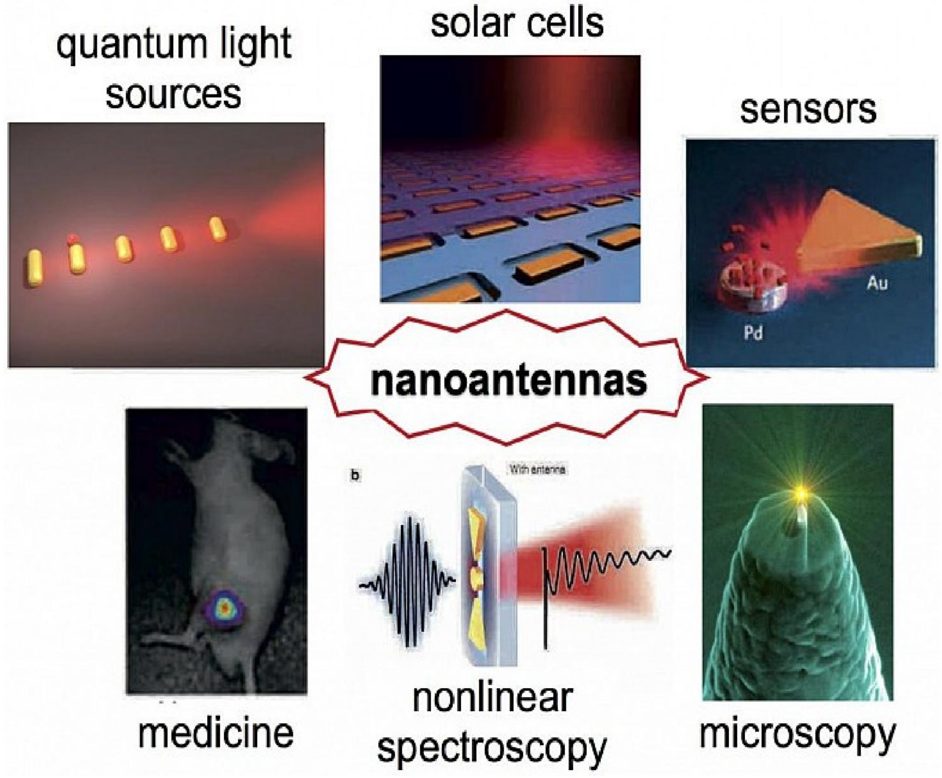


Figure 3.2: Various applications of optical nanoantennas

3.2.1. Infrared and Multi-Spectral Imaging

With the advent of optical nanoantennas, there is a significant progress in the IR detectors. In this technology, the first challenge was to couple the same kind of radio frequency antenna e.g. dipole, spiral, bow-tie antenna, micro strip, micro patch or arrays of them, to the existing conventional infrared multi-spectral imaging devices[25].

3.2.2. Near-Field Optics

Due to Near-field optics, the research and development has become possible in the optical microscopy. In optical microscopy, the properties of optical nanoparticles whose size are smaller than 100 nm have proposed [22,26]. The surface plasmon polariton resonance (SPPRs) plays an important role to induce currents in the wires of antenna and to propagate the signals at the optical frequency. At the optical frequency, the bounded electrons in the valence band excited to the conduction band and it contributes the finite conductivity and dispersive permittivity [27]. Although the conductivity of most of the metals is weakened by the excitation of surface plasmon polariton at the optical frequency, it allows the manufacturing of frequency dependent metallic nanoscale components in the optical regime. In this way, the surface plasmon polariton resonances and antenna resonances contribute to a strong localized field enhancement [15].

In scanning near-field optical microscopy, the resolution of an image is limited with the help of wavelength of incident light and numerical aperture property of objective lens system [28].

3.2.3. Optical Antenna Sensors

The advancement in the nano-technology has helped in manipulation of the light efficiently with the help of plasmonic materials in the nanoscale range. Even the minor change in the refractive index of a surrounding material can be detected easily due to the advancement in sensitive geometries in nanoscale technology [21]. It becomes possible due to the field enhancement at the surface of resonant noble metallic nanoparticles. The reason behind using the noble metallic nanoparticles as an optical sensor is that they observe the change in the density of electrons at the surface of a particle which changes the maximum absorption position of the surface plasmon polariton resonance. This technology is widely used due to its low cost, ease of design and fabrication.

Due to strong scattering or absorption, plasmonic nanoparticles have the ability to monitor the light signal easily. Due to their highly sensitive spectral response, they are used in biological and chemical sensing applications. They can also be used in spectroscopic applications due to their ability to detect the polarization.

3.2.4. Medicines

Optical nanoantennas can be used to kill the malignant tissues e.g. cancer cells. It is done by introducing the plasmonic nanoparticles at the affected site [29].When light radiation is incident on the nanoparticle, it heats these particles and burns it.

3.2.5. Photovoltaics

Solar cells are generally used to convert the solar radiation into electric current due to their low cost but they have a limitation in terms of the conversion efficiency. So, one alternative to remove this problem is the use of optical nanoantennas. They receive the solar radiation and convert it into localized field at the feed gap of nanoantenna[30,31]. With the help of a diode, this field can be converted into an electric current. The advantage of using optical nanoantenna over a solar cell is that the efficiency of optical nanoantenna is greater than a solar cell.

Chapter 4

Metallic Cross Bowtie Nanoantenna

In this chapter, the complete analysis of the cross bowtie nanoantenna i.e. design of nanoantenna, optimization of the nanoantenna by varying length of the nanoantenna and flare angle of the bowtie and various parameters of the optimized nanoantenna i.e. radiation efficiency, directivity and electric field distribution has been presented.

4.1. Introduction

In this project, a cross bowtie nanoantenna has been designed using gold as a material to obtain a strong electric field enhancement at the feed gap of the nanoantenna. When light radiation of certain frequency is made incident on the metallic nanoantenna, surface plasmon is generated on the surface of nanoantenna due to which an alternating current is produced on its surface which oscillate at the same frequency as that of the incident radiation leading to the generation of the voltage at the feed point of the nanoantenna. In this case, the feed point is at the centre of the nanoantenna where all field is localized and thus gives rise to electric filed enhancement at the centre of the designed nanoantenna. The nanoantenna is designed at a resonance wavelength of 500 nm. The reason behind using this wavelength is that the solar radiation is maximum at this wavelength as shown in Fig 4.1.

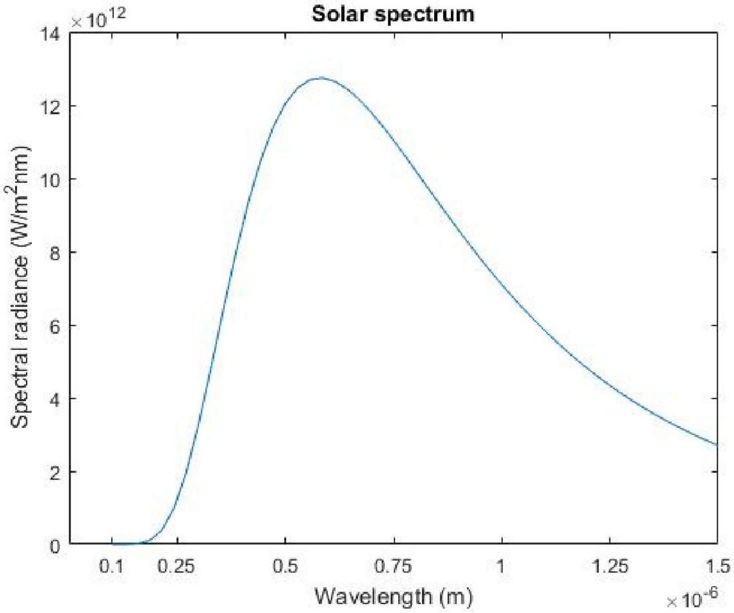
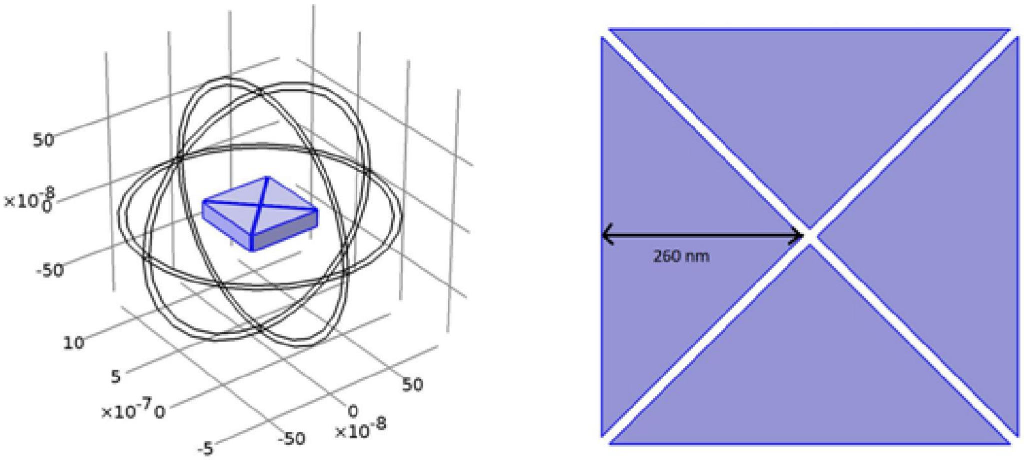


Figure 4.1: Solar spectrum which shows the maximum spectral radiance at a wavelength of 500 nm.

The concept behind using a cross bowtie nanoantenna is to make it polarization independent. The transverse electromagnetic wave with any arbitrary polarization can be decomposed into two linear components, each having an appropriate phase and amplitude. In the designed nanoantenna, two pair of perpendicular bowties with a common feed gap has the ability to sustain two such linear components, which add coherently in the feed gap of the designed nanoantenna.

4.2. Design of Cross Bowtie Nanoantenna

The cross bowtie nanoantenna has been modeled through finite element method (FEM) simulations using COMSOL Multiphysics. Firstly, the nanoantenna is designed for the bowtie with flare angle of 90^0 with length of each antenna arm as 260 nm and width of 50 nm and the feed gap between any pair of nanoantenna has been taken as 20 nm as shown in Fig 4.2.



(a) (b)

Figure 4.2: Geometrical design of a Cross bowtie nanoantenna. (a) 3D design. (b) 2D design

When an x-polarized wave is made incident on the nanoantenna and electric field distribution is analyzed that it has been found that electric field enhancement mainly occurs at the corners of the nanoantenna instead of the centre of the nanoantenna due to strong coupling between corners as shown is Fig 4.3.

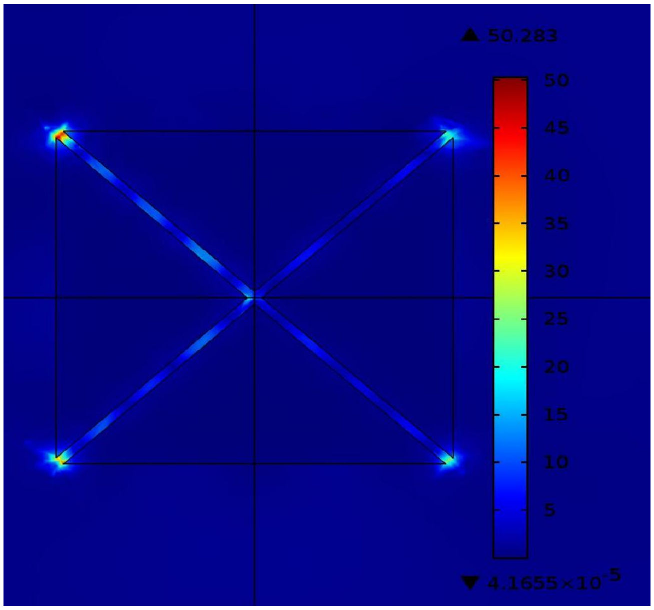


Figure 4.3: Electric field distribution in the cross structure bowtie nanoantenna with a flare angle of 90^0.

To reduce the coupling at the corners, the nanoantenna is designed for different flare angles (75^0, 60^0 and 45^0) but the length of each antenna arm is also varied in order to obtain the resonance at a wavelength of 500 nm because resonance of a nanoantenna depends on the dimensions of the nanoantenna in a great extent. The optimized length of antenna arm for the bowtie with flare angle of 75^0, 60^0 and 45^0 are taken as 265 nm, 270 nm and 258 nm respectively as shown in Fig 4.4.

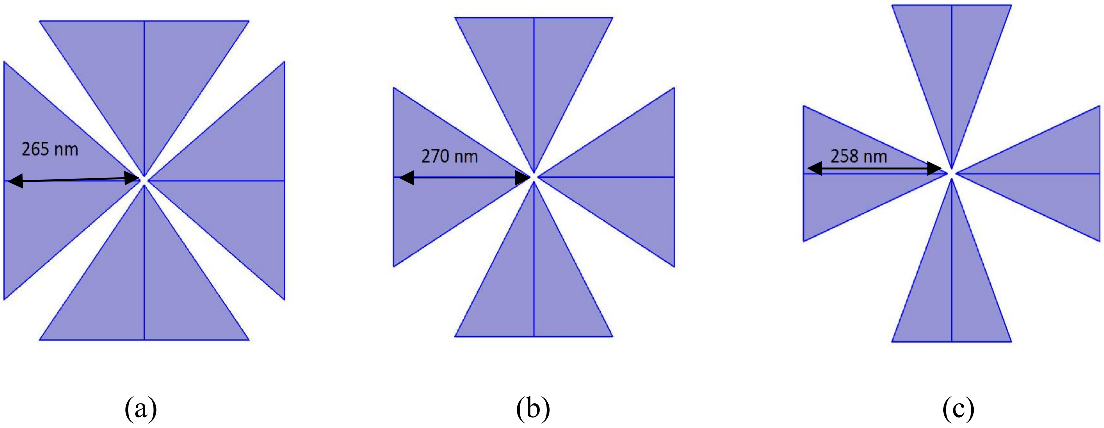


Figure 4.4: Design of cross bowtie with different flare angles. (a) Bowtie nanoantenna with flare angle of 75^0. (b) Bowtie nanoantenna with flare angle of 60^0. (c) Bowtie nanoantenna with flare angle of 45^0.

4.3. Results and Discussion

An input power is made incident on the antenna and the various characteristics like scattering cross-section and electric field enhancement at the feed gap of nanoantenna has been analyzed. The optimization of the nanoantenna has been by varying the length of the antenna arm and flare angle of the bowtie to obtain a electric field enhancement at the feed gap of the nanoantenna.

4.3.1. Scattering cross-section of the cross bowtie nanoantenna with different flare angles

The scattering cross-section of cross bowtie nanoantenna with different flare angles of 90^0, 75^0, 60^0 and 45^0 with length of each antenna arm as 260 nm is shown in Fig 4.5.

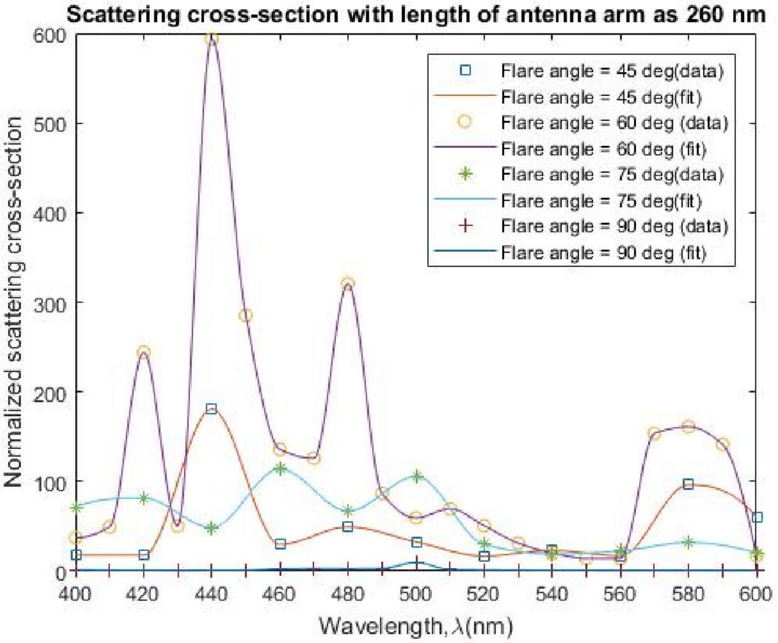


Figure 4.5: The scattering cross-section of cross bowtie nanoantenna with different angles with length of the antenna arm of each nanoantenna as 260nm.

From Fig 4.5, it is clear that if the length of the antenna arm is kept same for different flare angles, the resonance wavelength also changes. So, to keep the resonance at 500 nm wavelength, the length of the antenna arm is also be changed with change in flare angle of bowtie. The variation of the scattering cross-section of cross bowtie nanoantenna with flare angles of 90^0, 75^0, 60^0 and 45^0 at their resonant lengths is shown in Fig 4.6.

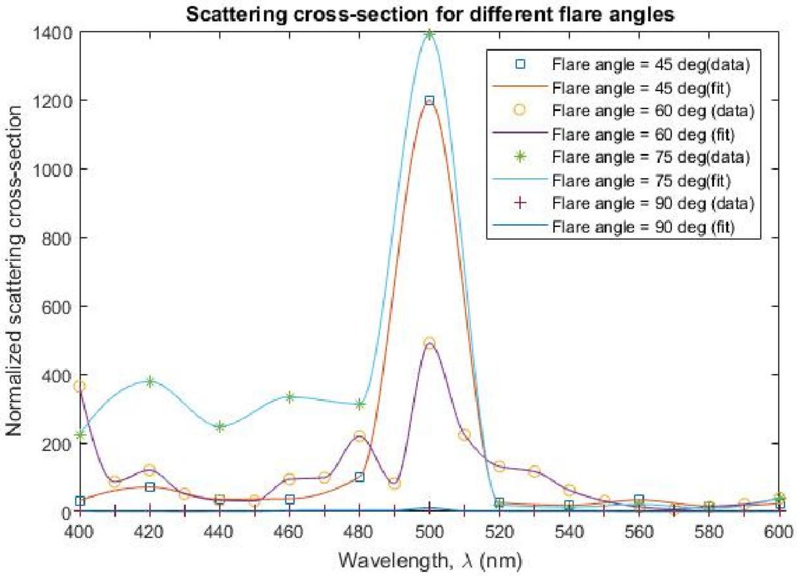


Figure 4.6: The scattering cross-section of cross bowtie nanoantenna with different flare angles with each nanoantenna has its arm length equal to its resonant length.

4.3.2. Electric field enhancement in cross cowtie nanoantenna

The electric filed enhancement in the cross bowtie nanoantenna with flare angle of 90^0, 75^0, 60^0 and 45^0 with length of antenna arm as 260 nm, 265 nm, 270 nm and 258 nm respectively is shown in Fig 4.7.

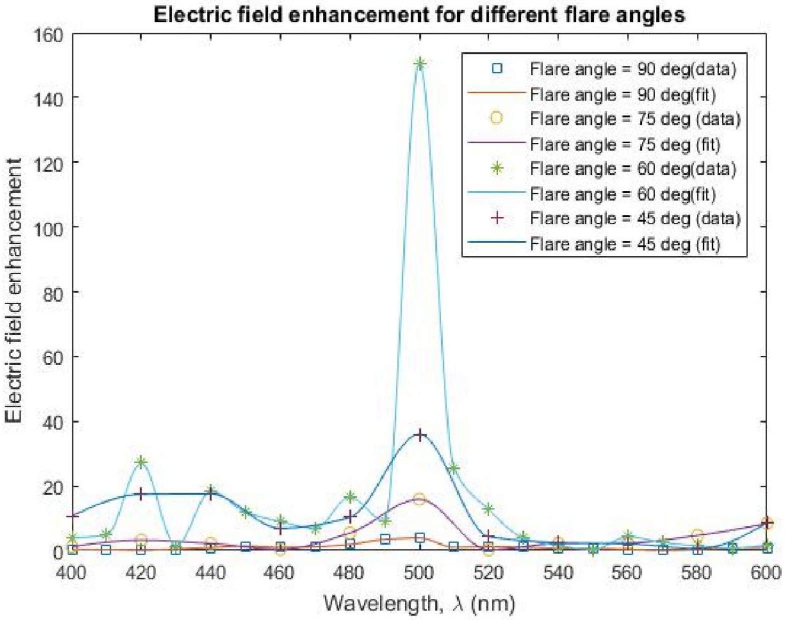


Figure 4.7: The electric field enhancement at the centre of cross bowtie nanoantenna with different flare angles with each nanoantenna has its arm length equal to its resonant length.

From Fig 4.6, it is clear that maximum electric field enhancement at the centre of cross bowtie nanoantenna has been obtained when the flare angle of bowtie is 60^0. Thus, the optimized flare angle of bowtie to obtain a strong field enhancement at the centre of designed nanoantenna is 60^0. There is a field enhancement of 150 times in the cross bowtie nanoantenna with flare angle of 60^0.

4.4. Analysis of Cross Bowtie Nanoantenna with flare angle of 60^0

The various parameters of optimized cross bowtie nanoantenna like radiation efficiency, directivity and electric field distribution have been analyzed.

4.4.1. Radiation Efficiency

Radiation efficiency of an antenna depends on that how much power is radiated by an antenna in the far zone of the total power delivered to that antenna[1, 9-16]. The radiation efficiency of cross bowtie nanoantenna with flare angle of 60^0 is shown in Fig 4.8.

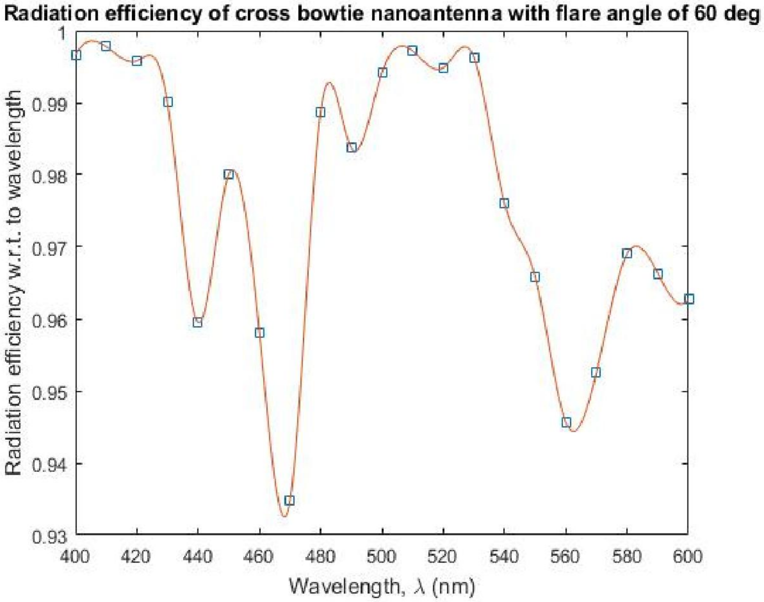


Figure 4.8: Variation of the radiation efficiency with wavelength of cross bowtie nanoantenna with flare angle of 60^0.

From Fig 4.8, it is clear the maximum radiation efficiency of cross bowtie nanoantenna with flare angle of 60^0 is 99.5 %. Such high radiation efficiency is due to the fact that the designed nanoantenna is made up of gold and there are very low losses in the gold at optical frequency.

4.4.2. Directivity

The directivity of cross bowtie nanoantenna with flare angle of 60^0 is shown if Fig 4.9 which shows that the maximum directivity of the designed nanoantenna is 3.8 at the resonant wavelength of 500 nm.

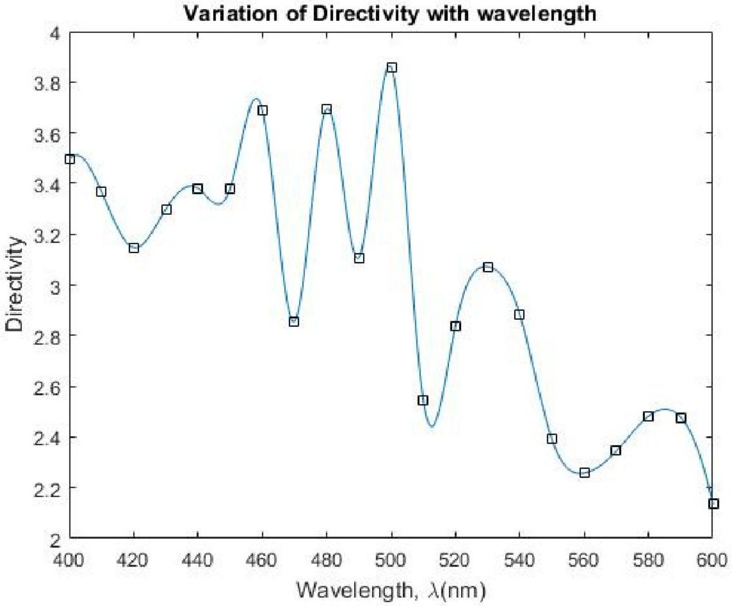


Figure 4.9: Variation of directivity of cross bowtie nanoantenna with flare angle of 60^0 with wavelength.

4.4.3. Electric field distribution

The electric field distribution in the cross bowtie nanoantenna with flare angle of 60^0 is shown in Fig 4.10 which shows that the maximum electric field is obtained at the centre of the nanoantenna.

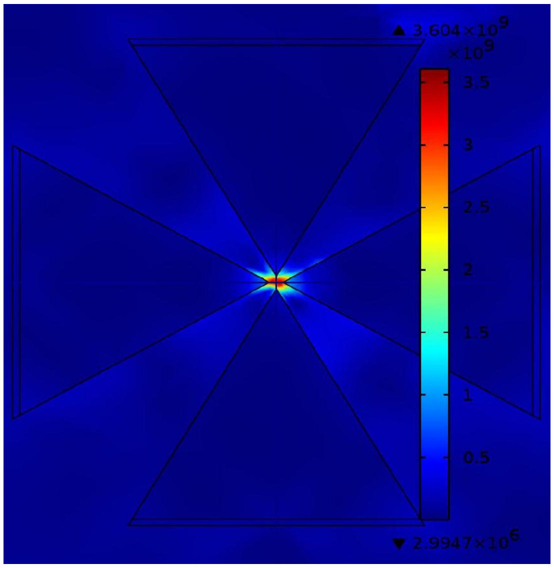


Figure 4.10: Electric field distribution in the cross bowtie nanoantenna with flare angle of 60^0.

Chapter 5

Conclusion

In this project, a metallic cross bowtie nanoantenna with different flare angles has been designed, optimized and analyzed. The optimization of the designed nanoantenna has done by varying the length of the antenna arm and flare angle of the bowtie in order to obtain a strong electric field enhancement at the centre of the designed nanoantenna at the resonance wavelength of 500 nm. As the nanoantenna is designed using gold, it will not corrode easily. During the design process, the metallic cross nanoantenna was successfully optimized with regards to length of the antenna arm and the size of the feed gap where the incident radiation is localized and enhanced. Therefore, the final resonant cross nanoantenna is designed as a gold nanoantenna with a 500 nm feed gap.

This optimized metallic cross structure nanoantenna can be used in the IR regime, for applications requiring high radiation localization, enhancement and good polarization control with moderate losses.

The optimized metallic cross structure nanoantenna designed in this project has applications in numerous fields that make use of highly localized IR radiation – including modern optical science and engineering, biological probing, and spectroscopic techniques.

For example, fluorescence spectroscopy – a technique that analyses the fluorescence of a sample, and is primarily used in biochemical, medical, and chemical research fields for analyzing organic compounds. In addition, Surface enhanced Raman spectroscopy (SERS) is a powerful vibrational spectroscopy technique that allows for highly sensitive structural detection, and recent research in the field has been geared towards the upcoming UV-SERS technique, which can allow for the probing of samples that cannot be studied through other spectroscopic techniques[15]. The metallic cross nanoantenna is a perfect candidate for use as a localized emitter of IR radiation, especially in IR-TERS (Tip Enhanced Raman Spectroscopy), in which the nanoantenna can be fabricated at the tip of the probe.

Chapter 6

Future Work

As the nanoantenna is designed at a resonance wavelength of 500 nm at which solar radiation is maximum, it can be used for solar energy harvesting if the nanoantenna is combine with a diode. The combination of a nanoantenna and a diode is known as rectenna.

6.1. Solar Energy Harvesting

The nanoantenna has been designed at a resonance wavelength of 500 nm in order to obtain electric field enhancement in the feed gap of nanoantenna. The next step that we can do is to use this field enhancement for collection of the solar radiation as the solar cells do. This can be achieved with the help of a metal-insulator-metal (MIM) diode which will rectify the oscillating current and will produce a dc power. The equivalent circuit of a nanoantenna which is coupled to a MIM diode is shown in Fig 6.1. The nanoantenna can be replaced with an equivalent circuit having an open circuit voltage with impedance in series and the diode with a parallel combination of a resister and capacitance.

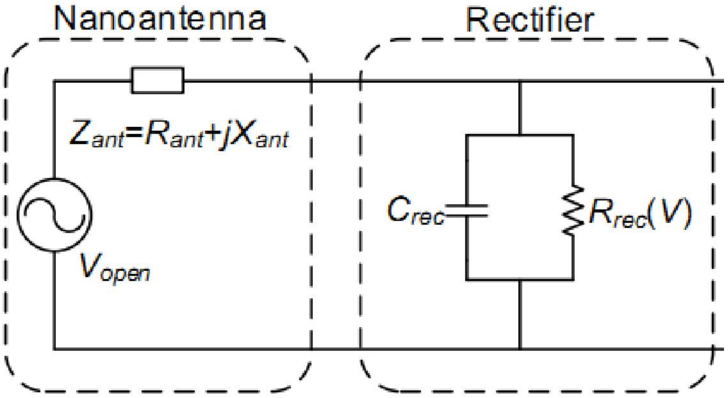


Figure 6.1: Equivalent circuit of a nanoantenna coupled to a MIM diode.

Following are the ideas that are supposed to do in the future:

Implementation of nanoantenna using different types of metal in order to obtain a strong field enhancement in the feed gap of nanoantenna.

To form an array of the designed nanoantenna in order to capture more and more solar radiation.

Couple the designed nanoantenna with a MIM diode to convert the solar radiation into dc power.

Fabricate the nanoantenna coupled with diode in order to calculate the conversion efficiency.

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List of Publications

- **P Goyal**, N Shankhwar, Y Kalra, Field Enhancement in a Victoria Cross type nanoantenna, IEEE International Conference on Photonics and High Speed Optical Networks (ICPHON 2018), ISBN 978-1-5386-3324-3

- **P Goyal**, N Shankhwar, Y Kalra, Design of a Cross structure nanoantenna, National Conference on Advanced Materials and Nanotechnology (AMN-2018)

- **P Goyal**, N Shankhwar, Y Kalra, Design and Analysis of a polarization independent Flower shaped nanoantenna, International Conference on Advances in Science and Technology (ICAST-2018)

- R Ranga**, P Goyal,** Y Kalra, Field Enhancement in a Tapered Cone Dipole Nanoantenna, IEEE International Conference on Photonics and High Speed Optical Networks (ICPHON 2018), ISBN 978-1-5386-3324-3

- **P Goyal**, N Shankhwar, Y Kalra, Near Field Enhancement in a Hollow Flower Shaped Nanoantennas, Frontiers in Optics/ Laser Science Conference (FIO/LS) (Accepted)