Project Report

on

Design and Analysis of V-shaped Nanoantenna

Submitted in partial fulfillment of

the requirements for the award of the degree of

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in

Microwave and Optical Communication Engineering

Submitted by

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CANDIDATE'S DECLARATION

I, Shanu Kumar, Roll No. 2K16/MOC/12 student of M.Tech (Microwave and Optical Communication), hereby declare that the project Dissertation titled "Design and Analysis of V-shaped 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 V-shaped Nanoantenna**" which is submitted by Shanu Kumar, Roll No. 2K16/MOC/12 [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

To convert the energy of free propagating radiation to localized energy and localized energy into free propagating radiation energy, we have always been reliant on radio wave and microwave antennas. But with the developments in physical optics, optical antennas are garnering attraction. Properties of metal nanostructures which behave as strongly coupled plasmas at optical frequencies forms the basis for the operation of optical antennas. Optical antennas can overcome the limitations of light-emitting devices, photovoltaics and spectroscopy by increasing the light-matter interaction. Televisions, cell-phones and other communication equipment which work on electromagnetic antennas, mostly use radio-wave or microwave ambit of the electromagnetic spectrum. Contrary to the electromagnetic fields, optical frequencies are controlled by re-directing the wave fronts of propagating radiation by means of lenses, mirrors, and diffractive elements. There are several current studies which have been undertaken to find ways of translating established radio wave and microwave antenna theories into the optical frequency regime and with few successes attained with the help pf nano-optics and plasmonics, optical antennas may soon be a thing of practical use. Once we are able to extend the concept of antennas into optical frequency regime, we can have major technological advancements ranging from enhanced absorption cross-sections and quantum yields in photovoltaics, releasing energy efficiently from nanoscale light-emitting devices, boosting the efficiency of photochemical or photophysical detectors, to improving spatial resolution in optical microscopy.

ACKNOWLEDGEMENT

I would like to express my sincere gratitude to my project supervisor, Asst. Prof. Dr. Ajeet Kumar, for his supervision, invaluable guidance, motivation and support throughout the extent of the project. I have benefited immensely from his wealth of knowledge.

I extend my gratitude to my college, 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

INTRODUCTION

This report consists of the design and analysis of V-shaped nanoantenna using gold as a material. This model demonstrates the calculation of the scattering cross-section and Electric field at feed gap of the nanoantenna. The scattering is computed for the optical frequency range, over which gold can be modeled as a material with negative complex-valued permittivity. The antenna is modelled and its spectral analysis is carried out through finite element method (FEM) simulations using the ‘COMSOL Multiphysics’ software package in the optical frequency range The scattering and Electric field enhancement are analyzed in detail. Furthermore, this design is improved through geometry optimization to provide strong radiation enhancement and localization.

1.1 OBJECTIVES

The main objectives of this report are as follows:

- Study the basic properties of optical nanoantennas and their applications in modern optical science and engineering.
- Study of the scattering and Electric field enhancement at the feed gap of nanoantenna.

CHAPTER 2

OPTICAL NANOANTENNA

Mirrors, diffraction elements and lenses can be used to direct and control the wavefront of the incident radiation of light. These operations rely on making use of the wave nature of electromagnetic field and hence can be used for the manipulation at the scale of subwavelength.

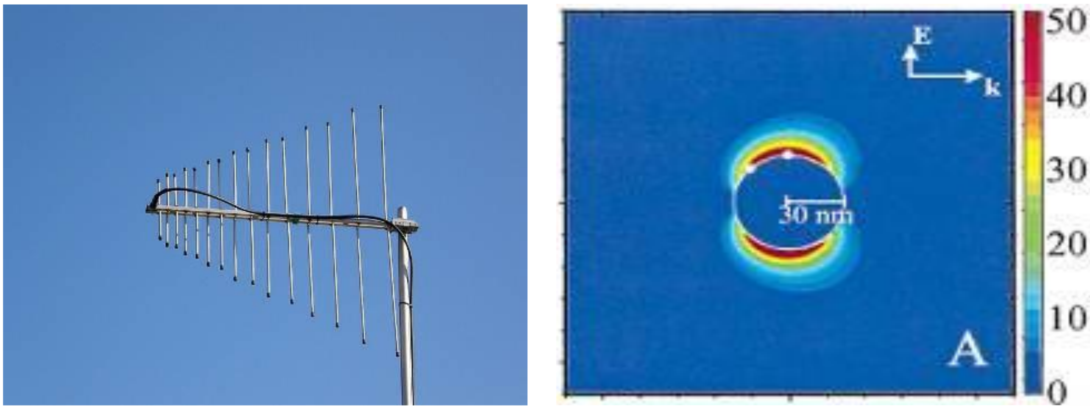


Figure 2.1: Example of RF antenna and optical antenna

Antennas constitute an important aspect of devices like radios, television etc. which rely on making use electromagnetic waves in microwave and radio wave spectrum. Optical nanoantennas have been able to attract considerable attention for applications ranging from near-field microscopy to molecular and biomedical sensors, solar cell, optical communication, and optical tweezers [1-7]. Contrary to light emitting devices, where electron and hole combine to release a photon, the reverse process takes place in photovoltaics. Optical antennas can enhance the absorption efficiency in photovoltaics and help in efficient release of energy in light emitting devices.

An optical antenna has characteristic dimensions of the order of wavelength of light and hence its fabrication requires accuracy in the range of 10 nm. Unlike conventional fabrications, the fabrication to such a small scale can be done only by using nanoscience and nanotechnology. The two methods of above technologies applicable for it are top-down or bottom-up method. Processes involved in top-down methods are ball milling [11, 12] electron beam lithography [13, 14] etc. whereas processes involved in bottom-up method include sol-gel technique, atomic layer deposition etc. There are various challenges in nano-scale fabrication, one of them being the size related properties that come into being due to fabrication being at nano-scale. Although, optical antennas have great acceptability, the fabrication of such a scale has made their application rather non-existent till date.

Edward Synge [8] developed the concept of antenna in the year 1928 when he localized optical radiations on a sample surface by colloidal gold particles. Later, in the year 1985 John Wessel, for the first time suggested [9] that gold particle can work as an antenna. However, it was only in 1995 that Dieter Pohl and Ulrich Fischer [10] were experimentally able to demonstrate the idea. Many studies were later carried out by various other researchers that led to the development of optical antennas of various shapes and sizes.

2.1 OPTICAL ANTENNA

Antennas are crucial to any modern day communication system, as they are the elements that convert propagating fields into electric currents and vice versa. They also act as transducers between localized fields and freely propagating radiations [15]. Nano optics is a branch of physics that deals with control and manipulation of optical signals by some specifically designed nanostructures. Nano optics requires radiations to be efficiently directed and transmitted between the nano elements which can be either transmitters or receivers. They have been developed in various shapes i.e. cylindrical, conical, cuboidal etc. They can be used in as a single nano object or in a cluster. Unlike radio wave and microwave antennas, optical antenna is a device that can effectively convert freely propagating optical radiations to localized energy at subwavelength scales. Due to their higher operating frequency, as compared to their radio wave counterpart, their characteristic size is very small (down to few nanometers) which poses a major challenge in its fabrication.

Efficiency and directivity are the two main and desirable feature of an antenna. Efficiency is defined as the transfer of currents to freely propagating waves or vice versa. On the other hand, directivity is defined as concentrating the electromagnetic energy in desirable regions of space and blocking the coupling of these radiations in undesirable regions of space. By optimizing spatial distribution of currents, both high efficiency and high directivity can be achieved.

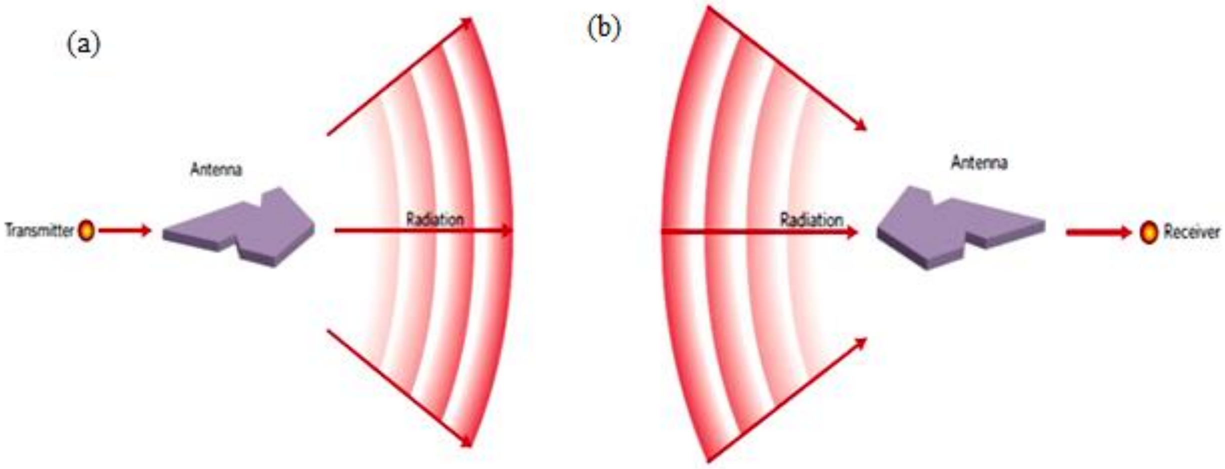


Figure 2.2: Optical antenna (a) transmitter antenna (b) receiver antenna. Each antenna can be used as a transmitter or receiver antenna simultaneously. [3]

Optical nanoantennas can be either of receiving type or radiating type. Receiving nanoantennas convert freely propagating fields into near fields, whereas, those nanoantennas which convert near fields to freely propagating fields are called transmitting type. In a microwave antenna a waveguide is used to deliver energy. Due to very small size of optical nanoantennas, plasmonic-waveguides are used. Plasmonic waveguides find applicability due to its ability to achieve subwavelength scale confinement and relatively long propagation. Nanoantennas can transform waveguide modes to freely propagating radiations in transmitting nanoantennas whereas, receiving nanoantennas transform freely propagating radiations to waveguide modes or they can transform optical radiations to strongly confined fields.

Optical nanoantennas can be classified into two types – plasmonic nanoantennas and dielectric nanoantennas. Plasmonic nanoantennas are made of metal nanoparticles, usually Gold and Silver. Some of the examples of plasmonic nanoantennas include dipole nanoantenna, bowtie nanoantenna, Yagi-Uda type nanoantenna etc. The study of nanoantenna began due to the success achieved in their fabrication using metals which supported plasmonic resonance.

2.2 APPLICATIONS OF OPTICAL NANOANTENNAS

Due to their ability to bridge the size and impedance mismatch between nano-emitters and freely propagating radiations, nanoantennas are being perceived as a promising area of research under the field of science called nano optics. They also can also be used to manipulate light on a scale smaller than the wavelength of the incident radiations or at sub-wavelength scale. Presently, nanoantennas find application in the near field microscopy and high resolution biomedical sensors. With the development in nano-optics, nanoantennas, in the near future may find applications in solar cells, biomedical and molecular sensors, optical tweezers etc.

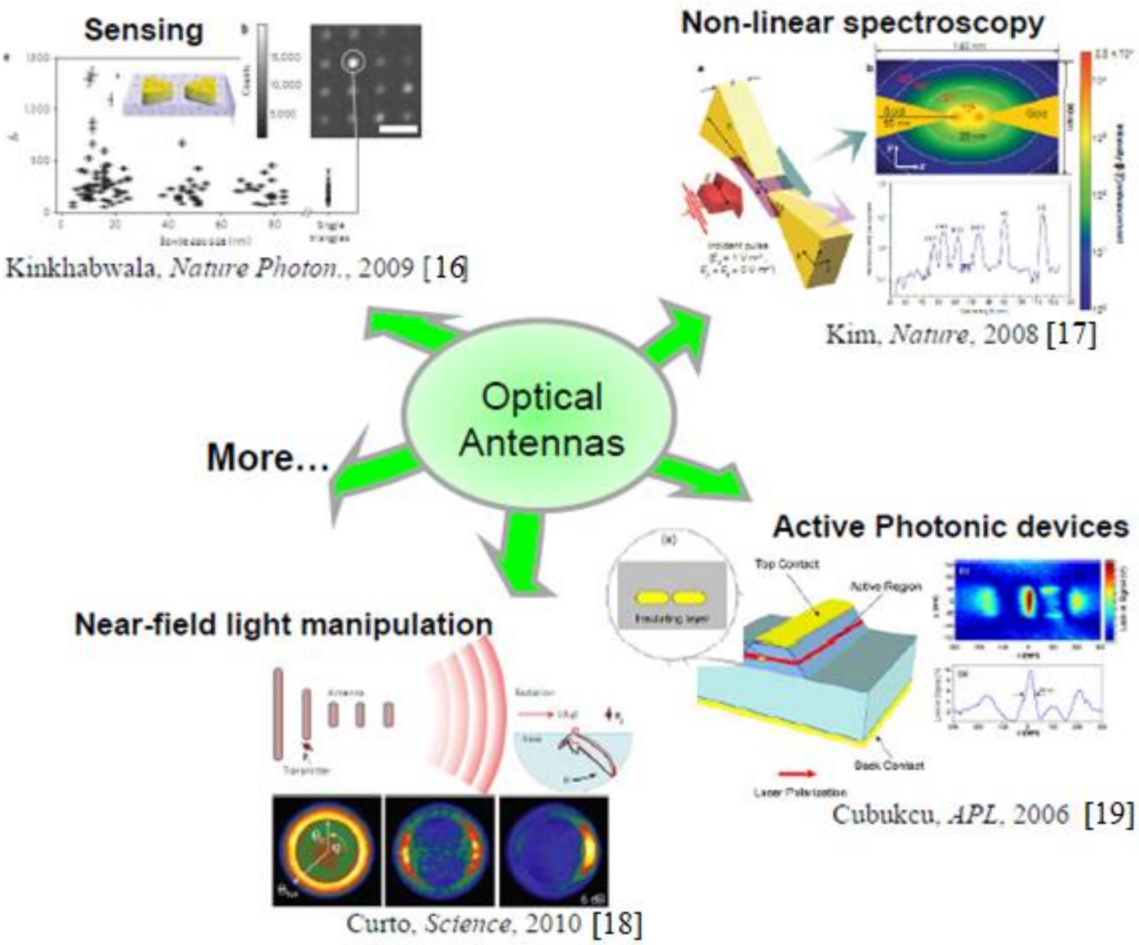


Figure 2.1: The research in optical nanoantenna is driven by wide range of applications. Some of these are shown in this figure.

Research in the field of optical antennas has brought out a range of possible applications that have great advantages to enhanced light-matter interaction. Till now most of the applications have been discussed in reviews of plasmonic and optical antennas [20-24]. Optical nanoantennas find a huge scope in nanophotonic applications. In this section we shall highlight some of the most important nanoantenna applications.

2.2.1 Scanning near field optical microscopy

Near field optical microscopy methods can be used to measure topography and optical properties like fluorescence. Some of the nanoscale imaging tools include microscopic methods such as scanning probe microscope, electron microscope etc. For capturing image of materials having size below 100 nm, optical microscopes are not well suited because of inherent large probe apertures (nearly three times the size of the material to be imaged). To compensate for this problem, optical nanoantenna can be used. Nanoantenna needs to be fabricated on the tip of the scanning probe to achieve very high resolution imaging. Here the resonance of the antenna is driven by the localized field of small aperture. By the use of bowtie antenna [25] and λ/4 [26] antenna, single molecule images of resolution nearly 25 nm (in the latter case) has been achieved. Many experiments have been carried out in this area. Highly controlled probes were manufactured by attaching single or multiple gold nanosphere to the dielectric tip of the optical fiber near-field probe. Such probes can produce images of single molecules of resolution less than the sphere diameter. Using these probes, high resolution images of proteins in their native cells have also been achieved [3, 27, 28].

2.2.2 Spectroscopy

Spectroscopy is the field of science which deals with the measurement of spectra when matter interacts with the electromagnetic radiations or emits it. Nanoantenna can be used to obtain highly enhanced and efficient spectroscopy. During spectroscopy process where some nano-object is investigated, nanoantenna is used to enhance both the emission and excitation. Surface enhanced spectroscopy [29] and tip enhanced spectroscopy [30, 31] are the traditionally developed techniques for measurement of light- matter interaction. The Raman scattering involves the absorption and emission of photons which are nearly identical in energy. The total scattering enhancement is usually proportional to the fourth power of the field enhancement. Many modifications have been made to this techniques since 1970's. Metallic nanostructures are capable of enhancing the local electric field and hence increase the interactions between incident light and specimen placed in its ambit. It has been observed in various studies that localization of electric field by single nanoantenna structures but arrays of nanoantennas can even work more efficiently in detecting signals very easily in the far-field. This is caused by various short and long range interactions occurring between the neighboring nanoantennas which leads to changing of resonance characteristics of the array. By moving from isolated nanoantenna to an arrays of nanoantenna, coupled end-to-end through nano gap, it is possible to increase the localization of the electric field even further in these gaps. [32]

2.2.3 Superemitter

Research in the field of quantum and classical information technology is being used to study light emission, detection and amplification at few photon levels. Another field of application is the use of optically resonant antenna in the experimental study of single emitters coupled to optical antennas. Quantum system can be represented by combination of single photon nanoantenna and a nano structure by placing the nanoantenna in the near field of the fluorescent quantum system. Emission and absorption of precisely single photon at a time can be ensured by the quantum system whereas the nano structure ensures the manipulation of the coupling of the emitter to the far-field radiation channels [3, 33]. To control emission, detection and amplification of light at the level of one or more photons at a time, nanoantenna based single photon superemitters are used. The manipulation of light in such a way can help us achieve submicron length scales and subpicosecond time scales. In order to strongly enhance the light-matter interactions, the nanoantenna in the vicinity of the emitter, modify the electromagnetic mode structure around the emitter itself. Emitter placed in the 'hot spot' of the resonant antenna is the source of creation of single plasmons in the resonant mode of the antenna instead of the creation of freely propagating photons. These plasmons are radiatively decayed to produce photons that have the properties of the antenna resonance e.g. its emission spectrum, resonance spectrum, polarization etc.

2.2.4 Optical tweezing

Optical tweezers are the instruments that use light to manipulate microscopic objects as small as a single atom [34]. In latest researches, it has been established experimentally that the optical trapping in well-controlled hot spots in the gap of nanoantennas can be used to allow trapping with lower excitation power and higher efficiency and stability [35, 36]. Since the momentum associated with light or electromagnetic radiations is linear in nature therefore the transfer of this momentum to an object leads to the production of forces which are radiative in occurrence. A scientist named Arthur Ashkin extensively worked on this theory to design optical tweezers, and later went on to develop optical manipulation technique on microscopic level [37]. Conventional optical tweezers consisted of microscopic objectives or optical lens and were based on far-field technique but the confinement of light is limited due to diffraction. By enhancing optical tweezing with nanoantennas, the limitations imposed by diffraction can be eliminated [48, 49]. Nanoplasmonics and optical tweezing combined to further formulate the idea of plasmonic optical tweezers, which unlike optical tweezers work in the range of microns. The plasmonic optical tweezers have the ability to extend the particle trapping range down to nanometers. For capturing and detection of biomaterials like viruses and vesicles, plasmonic optical tweezers integrated with lab-on-a-chip is a promising technique [50].

2.2.5 Photovoltaics

With the ever increasing demand for energy and our reliance on conventional sources to meet these requirements has resulted in degradation of environment both from their extraction as well as their consumption. This has led to a recent change in the outlook of people who are exploring other sources of clear energy. One such hot topic is photovoltaics which is derived from the latin word ‘Photo’ means light and ‘voltaic’ means voltage so, photovoltaics are the devices which are used to convert light energy to electrical energy [38]. Among the many possible ways to generate energy, solar cells are the ones that have the capability to use sun’s heat energy to generate electrical currents. However they are being limited due to less efficiency, complex structures and high costs. Practically, an isolated solar cell is nearly 20% efficient and a multijunction solar cell is nearly 30% efficient. With the application of nanoantenna in this field, the absorption efficiency can be increased to nearly 85%, which is much higher [70]. However, the biggest advantage of using nanoantennas lies in the fact that these devices can be engineered to absorb any frequency of light. By changing the size of the nanoantenna in the array, we can engineer the nanoantennas to absorb any wavelength of light. Plasmonic photovoltaics is one of the most recent fields in nanophotonics which can confine incident radiation in subwavelength range [51]. Standard solar cells are combined with metallic nanostructures, which concentrate and guide light at the nanoscale, leading to a reduction of the semiconductor thickness required, as well as enhancing the broadband absorption of the incident light, which is one of the crucial challenges to modern solar cell technologies [52].

2.2.6 Optical sensors

At visible frequency range, some metals specifically gold and silver, show plasmonic properties. When these materials interact with visible light, group of electrons start vibrating perpendicular to the surface of the material. This creates a wave of oscillating electrons called plasmons. Size of nanoantenna, dielectric material in the vicinity of nanoantenna and nanoantenna material are the factors affecting the wavelength of plasmon oscillations. In sensing applications, the molecules of material to be sensed get adsorbed near the nanoantenna and cause a shift in the resonant frequency peak. This is how nanoantenna sensors work by showing the resonant frequency peak change. Nanoantenna finds application in biological sensing, chemical gas sensing etc. with efficiencies increasing multiple times. Many plasmonic sensors were demonstrated in past for example, sensing based on particle arrays on a fiber facet [39] or on a substrate [40] with sensitivities down to the single-particle level [41, 42]. Mona zaghloul et.al showed a shift of 12 nm in the resonant peak of grapheme covered plasmonic nanoantenna when exposed to sense water vapors [43]

2.2.7 Lasing

Laser is a device that radiates coherent light or other electromagnetic radiation by the emission of photons. A plasmonic nanoantenna implemented to these lasers is known as ‘SPASER’. Spaser is a device that produce stimulated emission of plasmons. Pumping efficiency and intrinsic losses in cavity are the two factors influencing lasing threshold in conventional lasers. Nanoantenna size and geometry can be engineered to resonate at pumping wavelength, emission wavelength or both [44, 45]. Nanoantenna arrays of such particles can efficiently increase absorption, field enhancement [46] and can also tailor the electromagnetic radiations in well-defined patterns [47]. Nanoantenna structure combined with a nanocavity can efficiently refuel pumping energy in nanocavity.

2.2.8 Plasmonic circuits

Semiconductor and microelectronic are the two technologies for circuit designing. Both these technologies face serious problems of speed and data transmission rates. With the advancement in the field of nano-optics, these problems can be eliminated. If the electrons in circuits can be replaced by light then speed of operation of the circuits can be significantly increased. Surface plasmons are of two types- localized type and propagating type. Propagating surface plasmon polaritons can be considered for nanophotonic circuits and data transmission. Photonic devices of size smaller than the wavelength of light suffer through limitations of diffraction in fabrication processes. Plasmonic nanoantennas have an advantage due to presence of surface plasmon polaritons which surpass this diffraction limitation. Different metallic nanoparticle structures such as grooves [53], chains [56-59], sharp metal wedges [54], metal slits [55] etc. have been designed for guiding these propagating type plasmons to nanophotonic circuits.

2.2.9 Thermal fields

Thermally active fields can be easily created by the use of metallic nanoantennas, also called plasmonic nanoantennas. Metallic nanoantennas support localized surface plasmon resonance. Due to this phenomenon local heating of nanoantennas occur. Metals undergo considerable amount of ohmic losses when subjected to radiations of high or optical frequencies. Although, this is considered as a drawback and is the reason behind widespread use of dielectric nanoantennas but in some areas of science, this turns into dramatic advantage. This localized heating plays a vital role in many areas like vapor generation [60, 61], cancer treatment [62], catalysis [63-65], nano-fabrication [66, 67] and nano-manipulation [68, 69] etc. metallic nanoantennas can act as nanolocalised sources of thermal energy which can be switched on or off easily by employing low power optical means. Studies show that vapors can be generated by employing the thermal field of the metallic nanoantenna. For instance, Au nanoparticle was studied by Fang Z [60] to demonstrate the formation of nanobubble around the nanoparticle when it is illuminated by resonant light of sufficient intensity. By varying the size of the nanoantenna, micro sized bubbles can be achieved and hence light induced vapor generation is possible by implementing the theory of heating caused by surface plasmon resonance in metallic nanoantennas.

2.3 TYPES OF OPTICAL NANOANTENNA

Optical nanoantennas are broadly of two types and that are (1) metallic nanoantennas and (2) dielectric nanoantennas. Metallic nanoantennas are fabricated by metallic nanoparticles and support surface plasmon resonances. They are also known as plasmonic nanoantennas. On the other hand, dielectric nanoantennas are fabricated by semiconductor material of very high permittivity. Although, plasmonic nanoantennas suffer from various drawbacks such as considerable losses at optical frequencies but they find applications in various fields of science as well. In this section, both types of the nanoantennas are discussed in detail.

2.3.1 Metallic nanoantenna

The research on metallic nanoantennas started in 1928 after a scientist named Richard Hutchinson Synge for the first time suggested the use of metallic nanoparticles for confinement of optical field. Later, in 1985 John Wessel explained the use of monopoles as nanoantenna, suggesting that a monopole can overcome the diffraction limits and tune the resolving power up to 1 nm. In these nanoantennas, the excitation of surface plasmon resonances of different order occur which cause the confinement of optical fields in their vicinity.

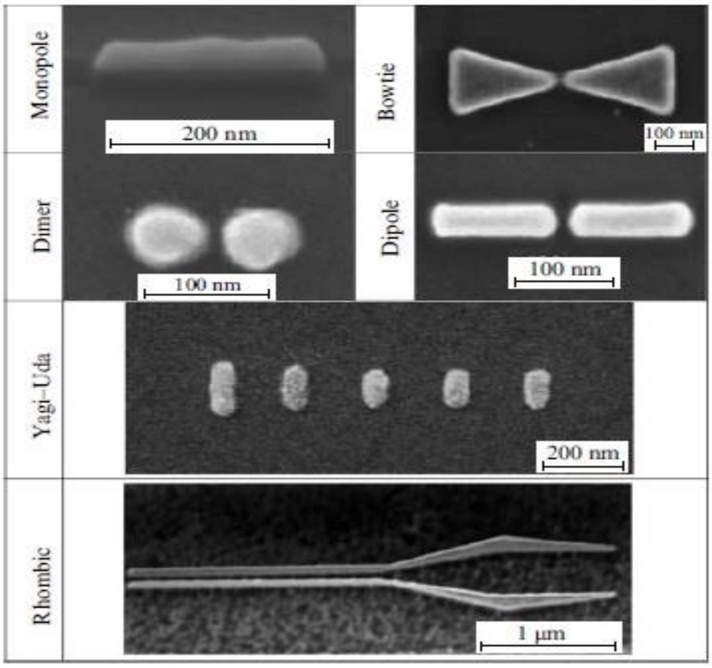


Figure 2.2: Various types of plasmonic nanoantennas. [70]

Metallic nanoparticles confine electromagnetic radiations (incident on them) in their vicinity. Later, it was observed that the magnitude of strength of the confined electromagnetic field is higher in the gap between two or more plasmonic nanoparticles as compared to single elongated nanoparticle. This occurred as the confinement in case of two or more plasmonic nanoparticles occurs at a smaller spatial scale. There exists a wide variety of plasmonic nanoantennas e.g. monopole, dipole, bowtie, Yagi-Uda etc. Each of them having a specific property and a specific design.

Plasmonic monopole nanoantenna is the simplest of all the nanoantennas. The factors affecting the characteristics of this nanoantennas include shape, size, material and the dielectric environment. These nanoantennas find special application where high precision fabrication of nanoparticle arrays is required. Plasmonic dipole nanoantenna, also called dimer, have the ability to confine electromagnetic field of very high magnitude in the gap between nanoparticles. Research by various authors show that the dipole nanoantennas can be tuned to work in desired operating regime by introducing materials of different permittivity in the gap. Bowtie nanoantenna finds application in solar cells and ideal absorption coating because they enhance the absorption efficiency. They also possess a high value of fluorescence. Plasmonic Yagi-Uda nanoantenna consists of a reflector and one or more directors. These types of nanoantenna show very high directivity.

Plasmonic nanoantennas are fabricated by metal nanoparticles and can be of variable shapes and sizes. They offer benefits such as small size, can confine the electromagnetic radiations with very strong magnitude and show high directivity. However there exist some disadvantages of using plasmonic nanoantennas. In classical antenna theory, it is considered that the electromagnetic field is restricted to the boundary of the metallic nanoantenna. The electromagnetic radiations penetrate into the plasmonic nanoantenna at optical frequency regime. The penetration is described by the skin depth and depends on the permittivity of the material used. So, at optical frequencies the concept of perfect conductor fails. Hence metals suffer considerable amount of losses at optical frequencies. Also, gold and silver (which are major plasmonic materials) are not compatible with CMOS nanofabrication technology. To overcome these disadvantages, nanoantennas made of high dielectric constants came into existence.

2.3.2 Dielectric nanoantenna

These nanoantennas are fabricated using semiconducting materials such as silicon, germanium etc. which are transparent at optical frequencies consequently leading to the term dielectric nanoantennas. Unlike plasmonic nanoantennas where electric resonance of high magnitude is obtained and weak magnetic resonance occurs, in dielectric nanoantennas, both electric and magnetic resonances of high magnitude are obtained. These nanoantennas have gained importance over the past years as it enables us to achieve both magnetic and electric response at visible frequency range and very low losses in optical regime. Hygen’s element is created in these nanoantennas. Many nanoantenna structures can be created by the use of this Hygen’s element e.g. Yagi-Uda nanoantenna.

2.3.2.1 Hygen’s element

Hygen’s element is a dielectric nanoparticles which is fabricated with material of very high permittivity, of the order 10-20. These elements show electric resonance and magnetic resonance in the visible region of electromagnetic spectrum. Both the dipole moments i.e. electric dipole moment and magnetic dipole moment are induced when Hygen’s element [71] is excited by an emitter. At a particular frequency, the polarizabilities of both the dipole moments has an equal magnitude. Thus with the help of Hygen’s element, fully dielectric nanoantennas can be fabricated with improved directional properties.

2.3.2.2 Optical magnetism

An electric dipole is a separation of positive and negative charges and therefore, oscillating electric charges of opposite signs can be called an oscillating electric dipole. This oscillating electric dipole is the source of electromagnetic radiations similar to the source of magnetic field in nature is the magnetic dipole. Magnetic monopoles or isolated magnetic poles (i.e. either North Pole or South Pole) do not exist in nature. A loop in which the current shrinks to a point can be used for the calculation of magnetic field of a dipole. The split ring resonator or SRR is also an artificial source of magnetic dipole as shown in the fig. 5(a) below.

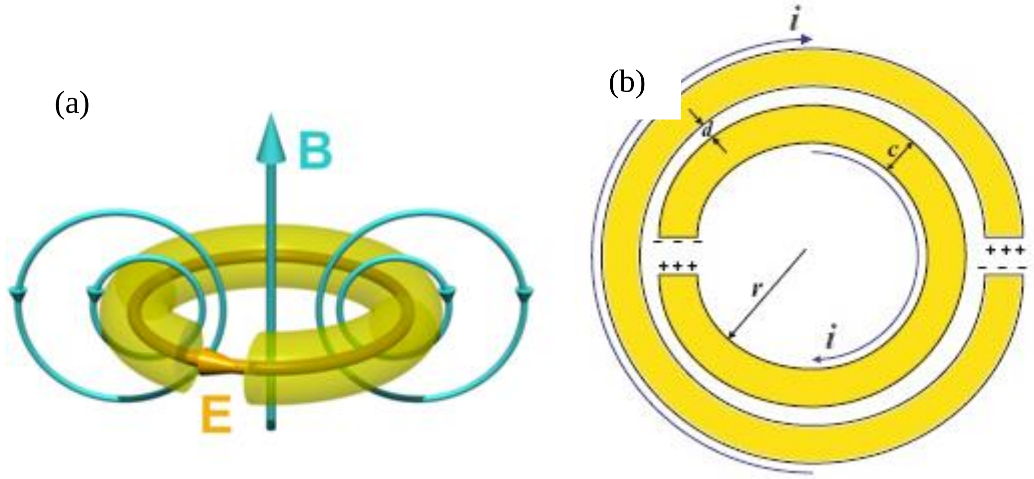


Figure 2.3: (a)Production of magnetic dipole by split ring resonator (SRR) [72], (b) schematic of split ring resonator showing the direction of currents carried by the two concentric ring.

Split ring resonator is a device that has been developed to produce exceptional effects which otherwise are very difficult to produce. It consists of two concentric rings with slits etched in them and placed such that the two slits are opposite to each other or as shown in the fig.5 (b). When electromagnetic radiations interact with this current carrying structure, magnetic dipole is produced which oscillates up and down in a transverse manner at the center of the ring. Split ring resonator finds application in metamaterials.

These type of artificial systems have grown in popularity and interest due to the below mentioned reasons:

- When incoming electromagnetic radiations interact with these artificial systems, they respond to the magnetic component of the radiations.
- At optical frequencies, they show negative or non-unity magnetic permeability.

- The above characteristics are hard to find in naturally existing systems.

Negative refraction [76], clocking [73, 74] and super lensing [75] are some of the material properties which can be achieved with the help of these artificial systems. At visible or optical frequencies, intrinsic losses in metals are considerable and cannot be neglected which a major hindrance to their use in antenna is designing. An alternative approach is to use a dielectric materials for this purpose. Dielectric nanoparticles of high refractive index show very low or negligible losses at visible range of frequency spectrum. Also, they show strong magnetic response at optical frequencies. High refractive index spherical nanoparticles were used to explain the above mentioned both the phenomenon. Magnetic dipole resonance of very high magnitude can be attained for a specific range of parameters. Oscillating magnetic field can be achieved at the center of the spherical dielectric nanoparticle as shown in the fig. 6

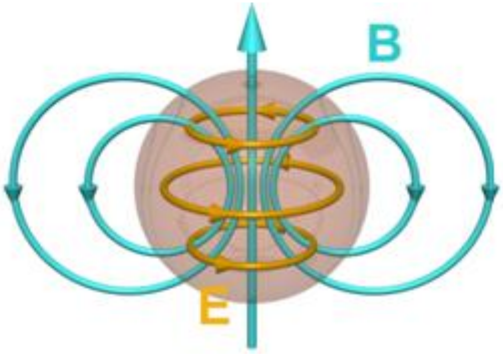
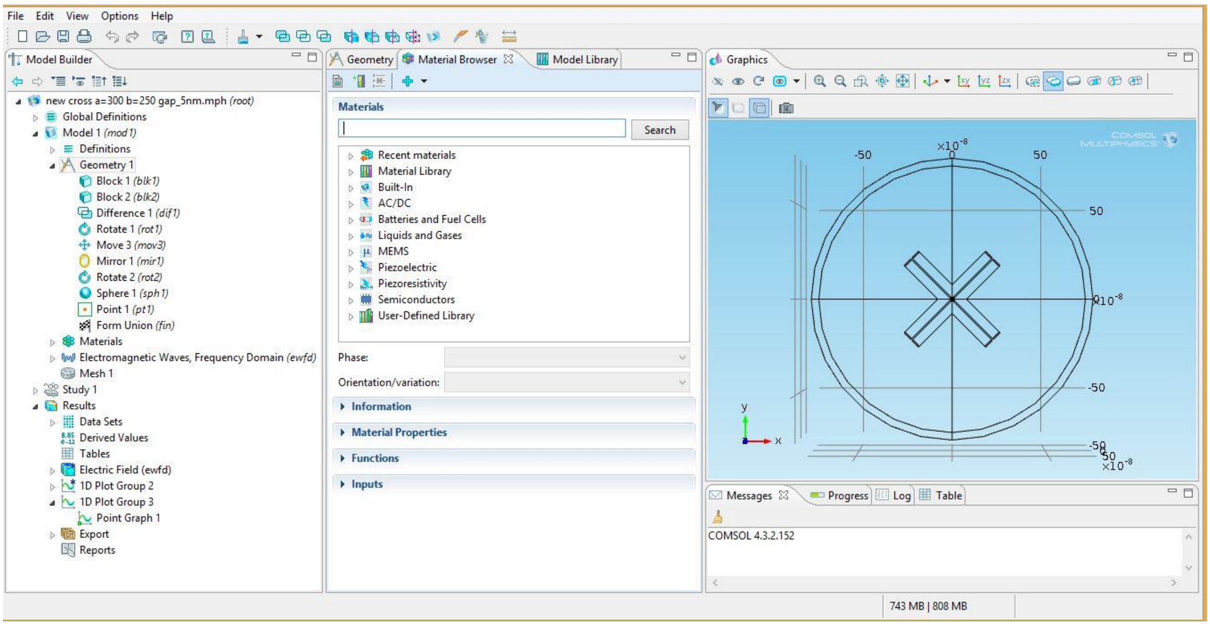


Figure 2.4: Electromagnetic wave distribution in spherical dielectric nanoparticles [72].

CHAPTER 3

SOFTWARE AND CALCULATION METHODS

COMSOL Multiphysics is a dynamic multi-dimensional correlative tool used to synthesise and simulate various kinds of modern and classical scientific and systematization problems. The Model Builder environment of the software gives us a vivid account of the model and ingress to all its possible outcomes. Having access to COMSOL Multiphysics enables us to extend the conventional models of one type of physics to Multiphysics models that are capable of solving coupled physical phenomena and do so simultaneously. In-depth knowledge of mathematics or numerical analysis is not required for accessing the features of the software.



COMSOL 4.3.2.152

Figure 3.1: COMSOL Window

Using the user friendly interface based on physics and coupled with advanced support for material having different properties, one can easily simulate models by distinctly defining the relevant physical parameters—such as properties of material , load on each source, constraints, type of sources, and fluxes—rather than having to define a definite equation for for each underlying variable. With COMSOL we have the flexibility to apply the above mentioned parameters directly to solid and fluid domains, boundaries, edges, and points independently of the computational mesh. A set of equations is then internally compiled by COMSOL which represents the complete model.

The complete functionality of COMSOL can be accessed as a standalone product through a extensible graphical user interface (GUI) or by script programming in Java® or the MATLAB® language (Live Link is required for accessing MATLAB). With the help of such physics interfaces, a number of studies can performed. Some of it includes: Stationary and time-dependent (transient) studies, Linear and nonlinear studies.

While solving the model with given set of parameters, COMSOL uses a definite set of advanced numerical analysis tools which are embedded into it. For the realisation of output, the software runs the analysis in conjunction with adaptive meshing (not set by default and needs to be enabled if user wishes to) and error control using a variety of numerical solvers. The studies has the capability to access multiprocessor systems and cluster computing, thereby enabling it to run batch jobs and parametric sweeps.

In COMSOL an array is created that record all steps leading to the creation of mesh, geometry, studies and solver settings, and visualization and results presentation. It thus provides a handy way to assign a framework for any part of the model: By easily changing a node in the model tree and re-running the previously fed commands again. The program stores the entire data from previous simulation and reassigns it to the new set of parameters and data in the model.

Partial differential equations (PDEs) form the basis for the laws of science and provide the foundation for modelling a wide range of scientific and engineering phenomena. COMSOL can be used in a wide variety of applications. Some of them are mentioned below:

- Acoustics
- Bioscience
- Chemical Reactions
- Corrosion and Corrosion protection

- Diffusion
- Electrochemistry
- Electromagnetics
- Fluid dynamics
- Fuel cells and electrochemistry
- Geophysics and geomechanics
- Heat transfer
- Microelectromechanical systems (MEMS)
- Microwave Engineering
- Optics
- Multibody dynamics

Many practical usage require synchronous couplings in a system of PDEs—Multiphysics. For example, the case of electric resistance of a conductor where electrical resistance frequently changes with temperature, and a model of a conductor carrying current must be inclusive of resistive-heating effects. Multiphysics modelling techniques: A range of predefined user friendly system design helps provide convenient access for common Multiphysics applications. In its unmodified configuration, COMSOL provides modelling and analysis options for a wide variety of application areas. It also supports many other optional modules for other key applications. These application-specific modules use terminology and solution techniques directed to a particular discipline, which facilitates creating and analysing models.

Wave Optics Module: The Wave Optics Module is used for solving problem occurring in the field of electromagnetic waves at optical frequencies (relating to wavelengths in the nano- to micrometre range). The fundamental equations for electromagnetics are by default present in all of the physics interface—a feature unique to COMSOL Multiphysics. This also makes nonstandard modelling readily approachable. The module is beneficial for simulations and design of optical applications in practically all domains where one can find electromagnetic waves, such as:

- Optical fibers
- Photonic waveguides
- Photonic crystals

- Nonlinear optics
- Laser resonator design
- Active devices in photonics

The physics interfaces subsumes the following domains of electromagnetic field simulations and handle time-harmonic, time-dependent, and Eigen frequency/Eigen mode problems in-plane, axisymmetric, and full 3D electromagnetic wave propagation and full vector mode analysis in 2D and 3D.

Material properties incorporated include inhomogeneous and fully anisotropic materials, media with gains or losses, and complex-valued material properties. In addition to the customary post processing features, the module provides for direct computation of S-parameters and far-field patterns. You can add ports with a wave excitation with specified power level and mode type, and add PMLs (perfectly matched layers) to synthesise electromagnetic waves that travel into an unbounded domain. For time-harmonic simulations, you can use the scattered wave or the total wave.

Using the Multiphysics proficiencies of COMSOL Multiphysics, you can couple simulations with heat transfer, structural mechanics, fluid flow formulations, and other physical phenomena. With the Wave Optics Module you can do time-harmonic simulations of systems that are much larger than the wavelength. This situation is typical for optical phenomena, components and systems. Due to the relatively weak coupling between waves in optical materials, the interaction lengths are often much larger than the wavelength. This applies to linear couplers, like directional couplers and fibre Bragg gratings, and nonlinear phenomena, like second harmonic generation, self-phase modulation, etc. With the Wave Optics Module, these kinds of problems are directly addressable, without huge computer memory requirements.

The module accommodates any case of nonlinear, inhomogeneous, or anisotropic media independent of the structure size. It also accommodates materials with characteristics that vary as a function of time as well as frequency-dispersive substances.

CHAPTER 4

METALLIC V-SHAPED NANOANTENNA

In this chapter, the complete analysis of the V-shaped nanoantenna i.e. scattering cross-section field enhancement has been analyzed.

4.1 INTRODUCTION

In this project a V-shaped and a double V-shaped nanoantenna has been designed using gold as a material as shown in Fig. 1. A plane transverse electromagnetic wave is incident on nanoantenna and the scattering cross section and Electric field in the feed gap has been computed using the finite element method. The modelling and optimization of the nanoantenna have been done using COMSOL Multiphysics Software.

4.2 DESIGN OF V-SHAPED NANOANTENNA

A V-shaped nanoantenna using gold as a material with length *l* = 300 nm and Width *w* = 250 nm. Perfectly matched layer (PML) of thickness 50 nm is used. The most important property of PML is that it absorbs reflection coming out from the incident material and thus do not interfere with the incoming radiation wave which distinguishes it from non-PML material.

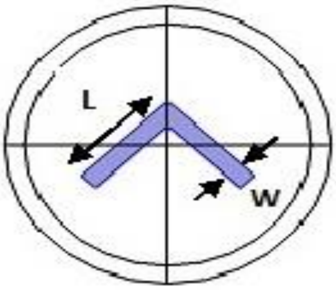


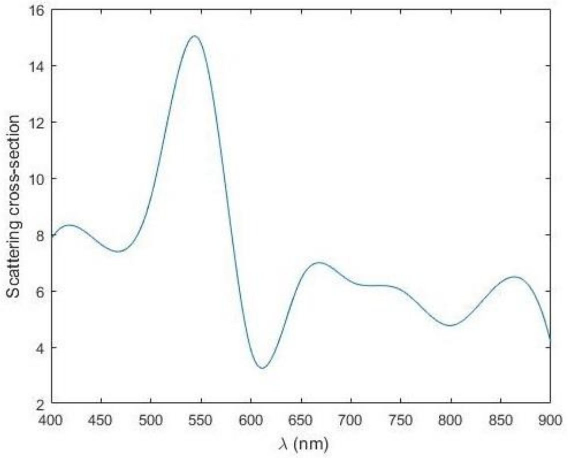
Figure 4.1: Geometrical design of a V-shaped nanoantenna (2D design)

4.3 RESULTS AND DISCUSSION

An input power is made incident on the antenna and the electric field enhancement is observed at the tip of the nanoantenna and the scattering cross-section is analyzed whose resonant wavelength is 550 nm.

4.3.1 Scattering cross-section and Electric field of V-shaped nanoantenna

The scattering cross-section of V-shaped nanoantenna with length *l* = 300 nm and width *w* = 250 nm



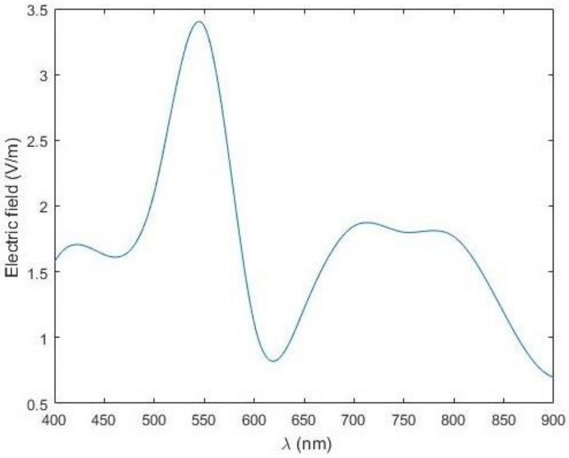


Figure 4.2: Variation of scattering cross section with wavelength

Figure 4.3: Variation of Electric field with wavelength

From the above figure we can analyze that the maximum scattering cross-section and Electric field is at the resonant wavelength of 550 nm.

CHAPTER 5

METALLIC DOUBLE V-SHAPED NANO-ANTENNA

In the previous chapter, we designed and analyzed V-shaped nanoantenna in this chapter we will be designing double V-shaped nanoantenna with same length and width and varying the feed gap for optimization of V-shaped nanoantenna.

5.1 DESIGN OF DOUBLE V-SHAPED NANOANTENNA

The double V-shaped nanoantenna has been modeled through finite element method (FEM) simulations using COMSOL Multiphysics. Firstly, the nanoantenna is designed for the feed gap of 5 nm with length of each antenna arm as 300 nm and width of 250 nm and then feed gap is varied.

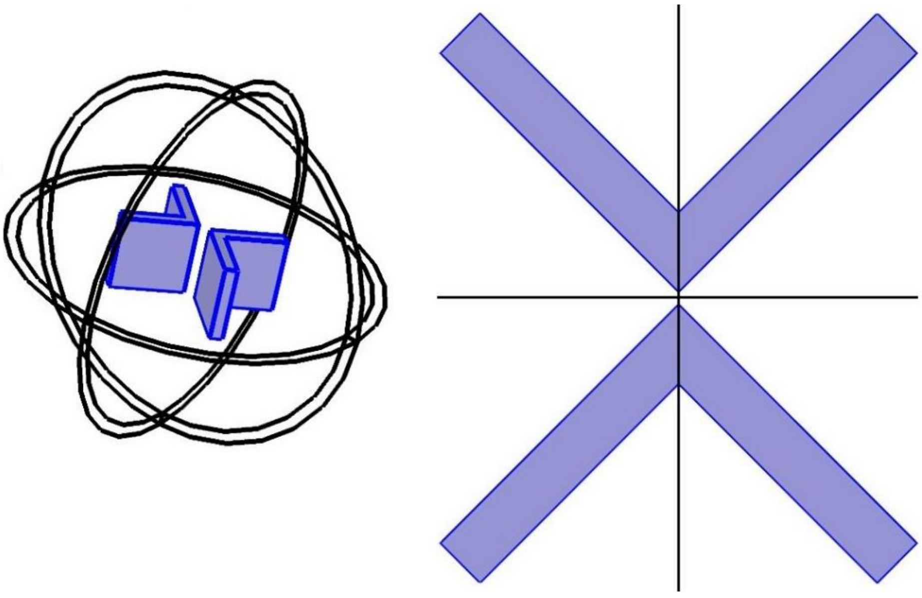


Figure 5.1: Geometrical design of a double V-shaped nanoantenna. (a) 3D design. (b) 2D design.

5.2 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 feed gap.

5.2.1 Scattering cross-section of double V-shaped nanoantenna with different feed gap

The scattering cross-section of double V-shaped nanoantenna with different feed gap of 5 nm, 10 nm and 15 nm with length *l* = 300 nm and width *w* = 250 nm is shown in Fig. 5.2

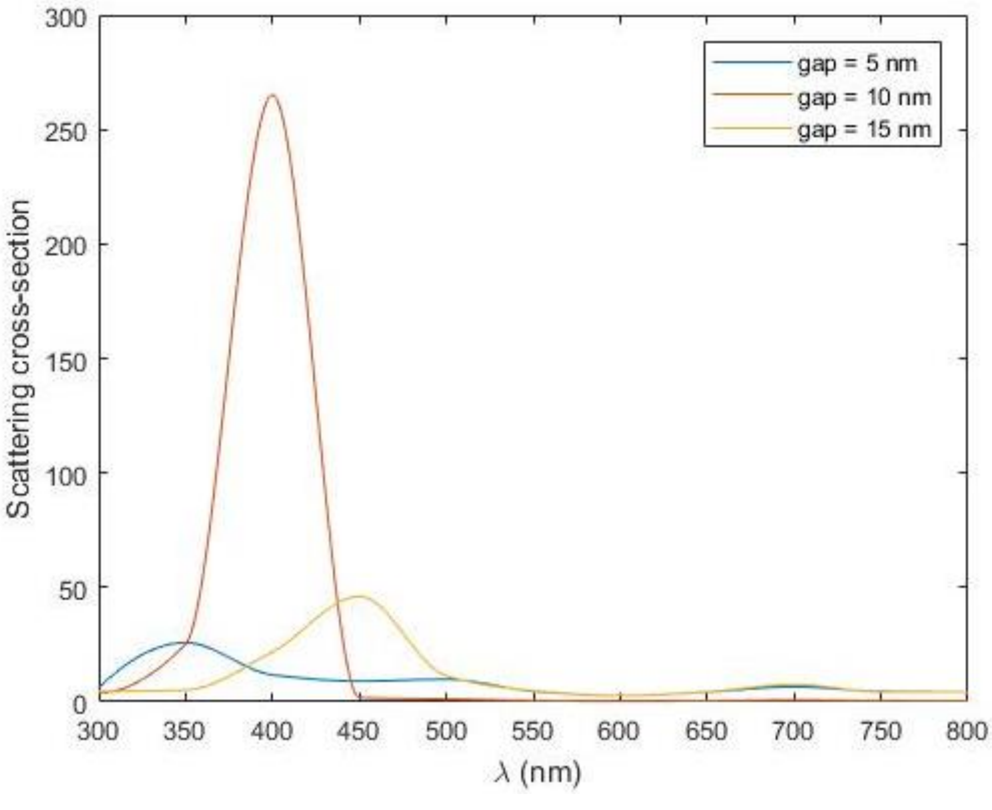


Figure 5.2: The scattering cross-section of double V-shaped nanoantenna with different feed gap.

From the Fig. 5.2 it is clear that as the feed gap is varied the resonant wavelength is also increasing and maximum scattering is at resonant wavelength of 400 nm with feed gap of 10 nm.

5.2.2 Electric field of double v-shaped nanoantenna with different feed gap

The electric field with different feed gap of 5 nm, 10 nm and 15 nm with length *l* = 300 nm and width *w* = 250 nm is shown in Fig. 5.3

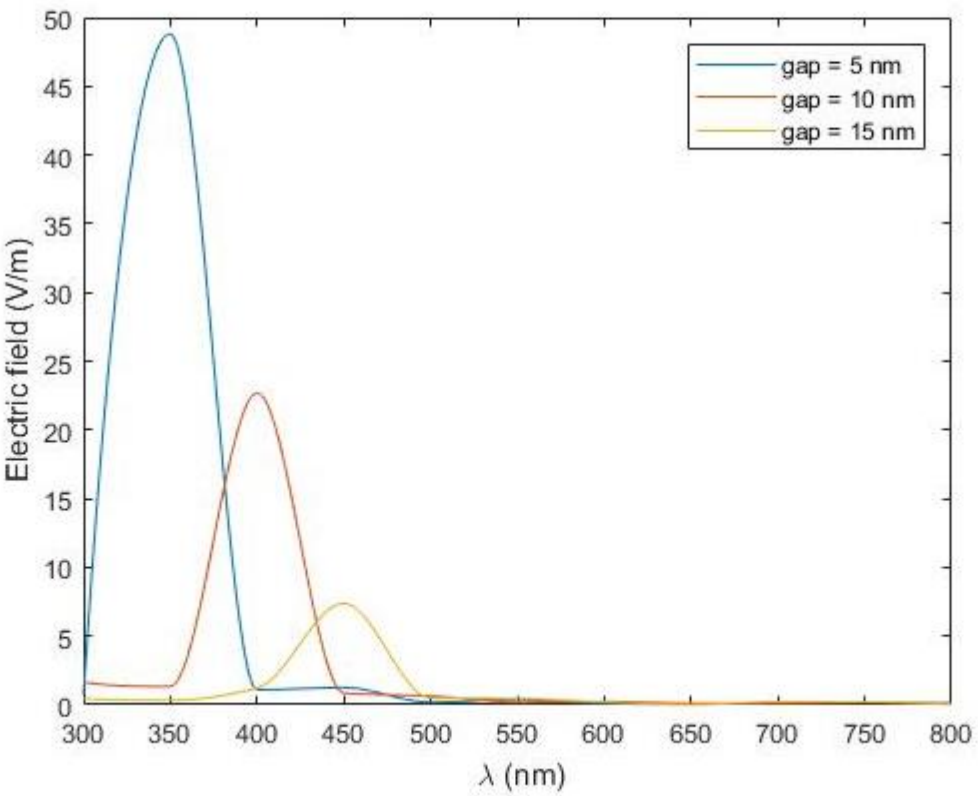


Figure 5.3: The electric field enhancement of double V-shaped nanoantenna with different feed gap.

From Fig. 5.3, it is clear that maximum electric field is at the feed gap of 5 nm and as the gap is increasing the electric field is decreasing and the maximum field is at 350 nm and as the gap is varied the resonant wavelength is also increasing.

5.3 ANALYSIS OF CROSS V-SHAPED NANOANTENNA WITH OPTIMIZED LENGTH AND WIDTH

The various parameters of optimized cross V-shaped nanoantenna like scattering cross-section Electric field have been analyzed.

5.3.1 Design of cross V-shaped nanoantenna

A cross V-shaped nanoantenna using gold as a material with length *l* = 500 nm and Width *w* = 100 nm and the feed gap between them is 10 nm as shown in Fig. 5.5

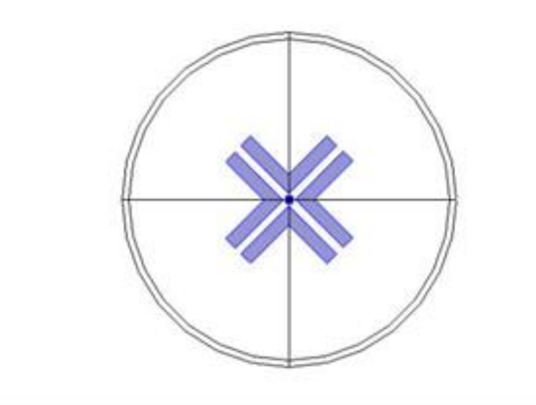


Figure 5.4: Design of cross V- shape nanoantenna

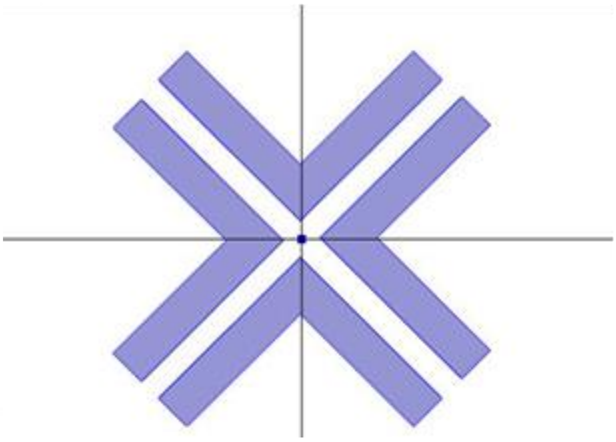


Figure 5.5: Zoomed in view with feed gap of 10 nm

5.3.2 Scattering cross-section and Electric field of cross V-shaped nanoantenna with feed gap of 10 nm

An input power is made incident on the antenna and the various characteristics like scattering cross-section and electric field at the feed gap of nanoantenna has been analyzed.

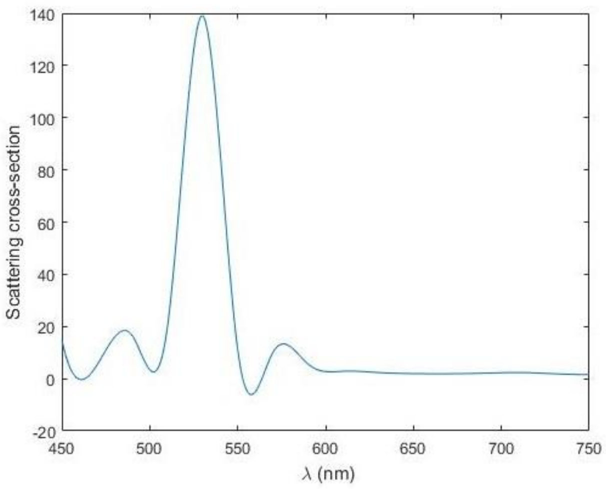


Figure 5.6: Variation of scattering cross section with wavelength

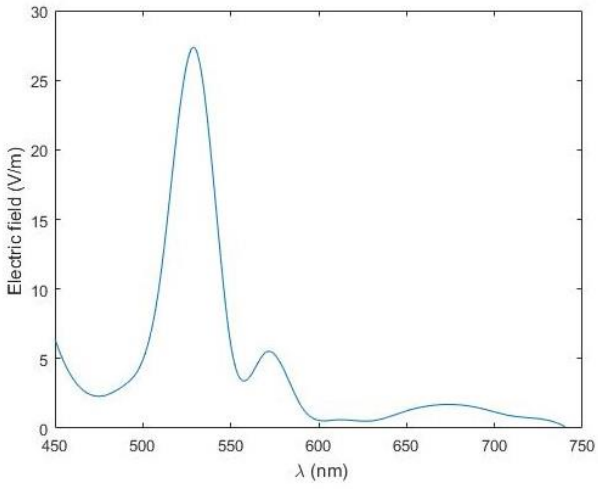


Figure 5.7: Variation of Electric field with wavelength

From the Fig. 5.6 it has been observed that it has high scattering cross-section and Electric field at resonant wavelength of 530 nm and this can be used for solar energy harvesting which has high radiation efficiency as compared to single V-shaped and double V-shaped nanoantenna.

CHAPTER 6

CONCLUSION AND SCOPE FOR FUTURE WORK

6.1 Conclusion

In this dissertation, scattering cross–section of V-shaped double V-shaped and cross V-shaped nanoantenna is being studied. The capability to tailor the scattering response of nanoantennas with the help of double V-shaped has been ascertained. An important result regarding the cross V-shaped over single V-shaped is that it has higher scattering cross-section and electric field enhancement as compared to the single V-shaped nanoantenna. These results are important in tuning of the resonant wavelength in visible region of electromagnetic spectrum.

Further this report brings forth various prospects related to the study of optical nanoantennas. Because of their nanoscale size, both fabrication and characterization of optical antennas present us with obstructions in harnessing their exclusive properties for an ambit of applications. Therefore, a wider perspective patterning, characterization and applications is taken. This should empower forthcoming studies of optical antennas by providing fundamentally essential understanding of their behavior as well as simple methods of fabricating them.

Moreover, optical nanoantennas can be used to aggrandize the efficiency of photovoltaic devices, and can be used in spectroscopy for killing cancer cells. Another field where these could find practical application would be biological imaging.

6.2 FUTURE PROSPECTS

There are multiple avenues for further exploration of this project. There are a wide variety of material that can be tested for improvements in scattering cross-section, and Electric field in the feed gap of nanoantenna. Furthermore, there are various aspects of the antenna geometry that can be varied, for tuning the far field over the entire optical range, depending on the specific application.

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LIST OF PUBLICATIONS

- **Shanu Kumar**, Pooja Chauhan, Ajeet Kumar ,Design and Analysis of a Double V-shaped Nanoantenna, International Conference on Advances in Science and Technology (ICAST-2018)

- **Shanu Kumar**, Pooja Chauhan, Ajeet Kumar, Design and Analysis of a Cross V-shaped Nanoantenna for Visible Region, Frontiers in Optics/ Laser Science Conference (FIO/LS) (Accepted)

Design and Analysis of a V-shaped Nanoantenna

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Abstract
Scattering and coupling of electromagnetic wave by a double V-shaped nanoantenna in the feed gap have been reported and the tuning of resonance is in the visible range and in the infrared region of the electromagnetic spectrum has been analyzed.

Keywords Scattering, Field enhancement, Resonant, Perfectly matched layer

1. Introduction

The objective of an optical antenna is to convert the energy of free propagating radiation to localized energy, and vice versa. Optical antenna's make use of unique properties of metallic nanostructures which behaves as a strong coupled plasma at optical wavelength which can increase the efficiency of light matter interaction in many applications such as photovoltaic and spectroscopy [1]. Metallic nanoparticles are one of the promising candidates in capturing, focusing, and manipulating light at nanoscale dimensions by virtue of their surface plasmon resonances. Scattering of the light is one of the phenomena which is used in nanoantennas [2].

In this paper, a double V-shaped nanoantenna has been designed using gold as a material as shown in Fig 1. The scattering cross section and field enhancement in the feed gap has been computed using the finite element method [3]. The modelling and optimization of the nanoantenna have been done using COMSOL Multiphysics Software

2. DESIGN

A double V-shaped nanoantenna using gold as a material with length 'l = 500 nm' and Width 'w = 400 nm' and the feed gap between them is 10 nm as shown in Fig 2. Perfectly matched layer (PML) of thickness 50[nm] is used. The most important property of PML is that it absorbs reflection coming out from the incident material and thus do not interfere with the incoming radiation wave which distinguishes it from the ordinary non-PML material

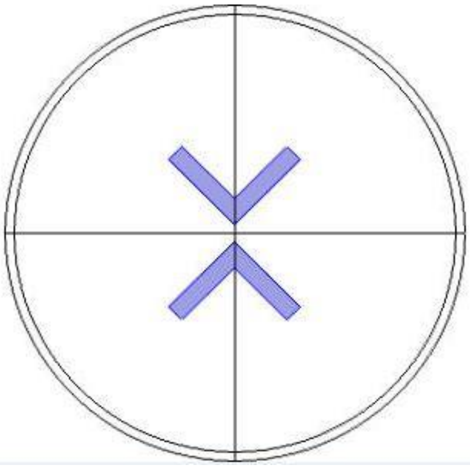

Fig 1: Design of double V- shape nanoantenna

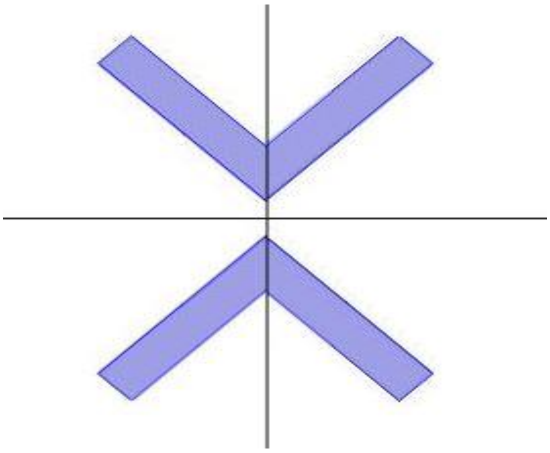

Fig 2: Zoomed in view of double V- shaped nanoantenna with feed gap of 10 [nm]

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3. Results and discussion

An input power is made incident on the antenna and the field enhancement is observed in the feed gap region of the nanoantenna. The various parameters of nanoantenna like scattering cross section, effect of antenna arm length and width on scattering cross section and resonance wavelength has been analyzed.

3.1 Variation of Scattering cross section with antenna arm length and width

The variation of scattering cross section with wavelength of the nanoantenna of arm length with ‘l = 500 nm’ and width ‘w = 400nm’ is shown in Fig. 3

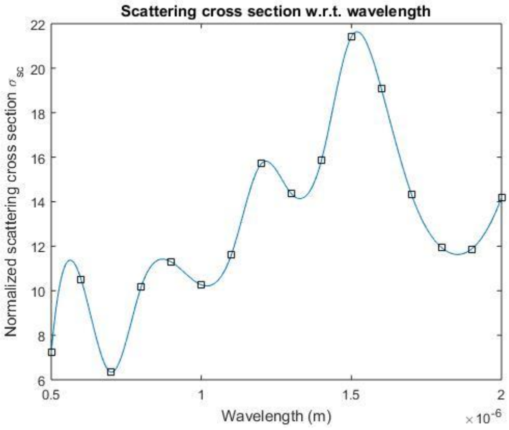

Fig 3: Variation of scattering cross section with wavelength

Now taking the antenna arm length and width as ‘l = 300 nm’ and ‘w = 250 nm’ scattering cross section is shown in Fig. 4

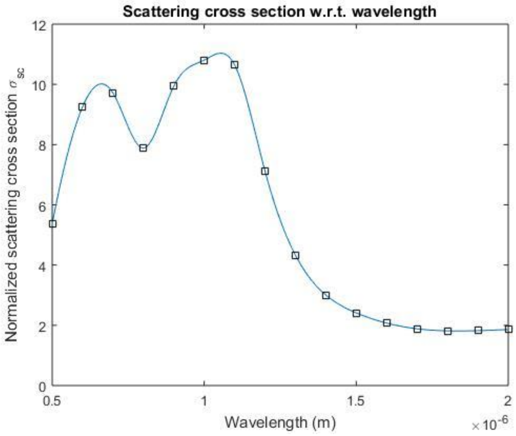

Fig 4: Variation of scattering cross section with wavelength

Now taking the antenna arm length having ‘l = 250 nm and width ‘w = 175 nm’ scattering cross section is shown in Fig. 5

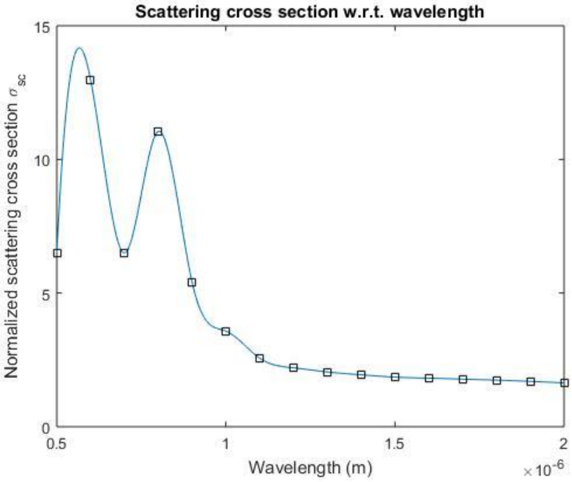

Fig 5: Variation of scattering cross section with wavelength

3.2 Electric field in the feed gap of nanoantenna

The field in the feed gap of nanoantenna with length ‘l = 500 nm’ and width ‘w = 400 nm’ is shown in Fig. 6

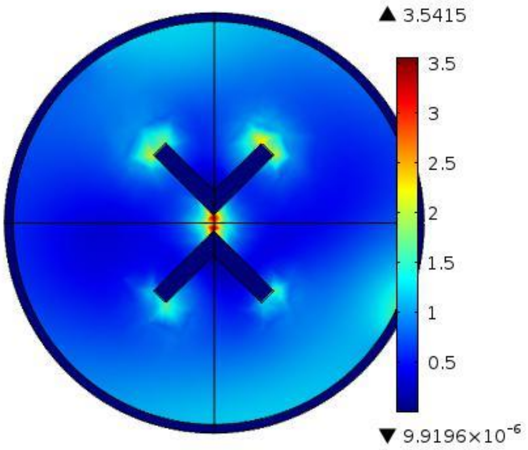

Fig 6: Electric field distribution in feed gap of nanoantenna

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4 Conclusion

A V – shaped nanoantenna has been successfully designed and analyzed. It has been observed that as the antenaa arm length and width of the nanoantenaa is changed the resonnat wave length varies from infrared region to visible region

Acknowledgement

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Design and Analysis of a Cross V-shaped Nanoantenna for Visible Region

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Abstract: A cross V-shaped nanonoantenna has been designed using gold as material with gap of 10 nm. The scattering cross-section and the Electric field at the centre has been obtained with optical resonant wavelength of 530 nm which lies in visible range.

OCIS codes: (260.5740) resonance, (290.0290) scattering.

Introduction:

Optical nanoantenna are just analogous to microwave antenna but the region of operation of optical nanoantenna is in optical range and size of nanoantenna is in nanometre range [1]. Metals at optical region behaves at strong coupled plasma which can increase the efficiency of light matter interaction at nanoscale [2].

In this paper, a cross V-shaped nanoantenna has been designed using gold as a material as shown in Fig 1. The scattering cross section and Electric field in the feed gap have been computed using the finite element method [3]. The modelling and optimization of the nanoantenna have been done using COMSOL Multiphysics Software.

Design of Nano-antenna:

A cross V-shaped nanoantenna using gold as a material with length ‘l = 500 nm’ and Width ‘w = 100 nm’ and the feed gap between them is 10 nm as shown in Fig 1. Perfectly matched layer (PML) of thickness 50[nm] is used. The most important property of PML is that it absorbs reflection coming out from the incident material and thus do not interfere with the incoming radiation wave which distinguishes it from the ordinary non-PML material.

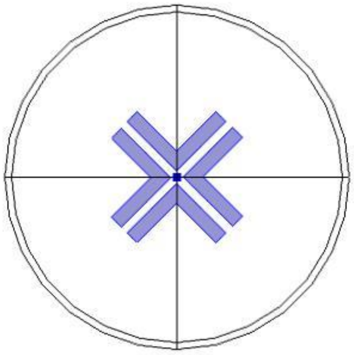

Fig 1: Design of cross V- shape nanoantenna

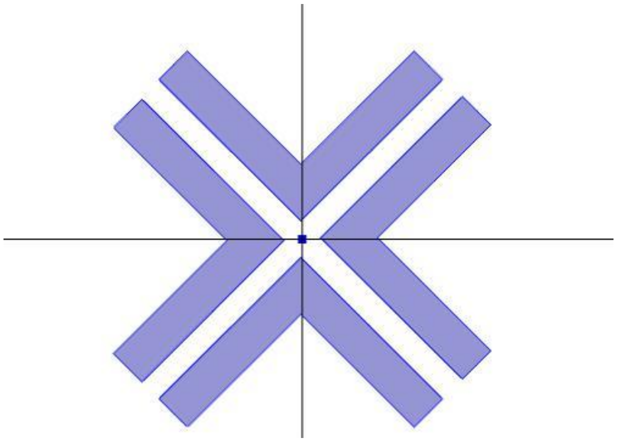

Fig 2: Zoomed in view with feed gap of 10 [nm]

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Simulated results:

An input power is made incident on the antenna and the field enhancement is observed in the feed gap region of the nanoantenna.The different parameters of nanoantenna like scattering cross section and Electric field in the centre feed gap at resonance wavelength have been analysed.

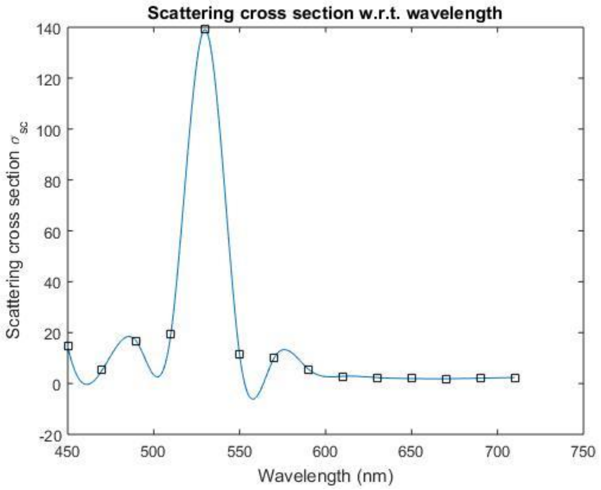

Fig 3: Variation of scattering cross section with wavelength

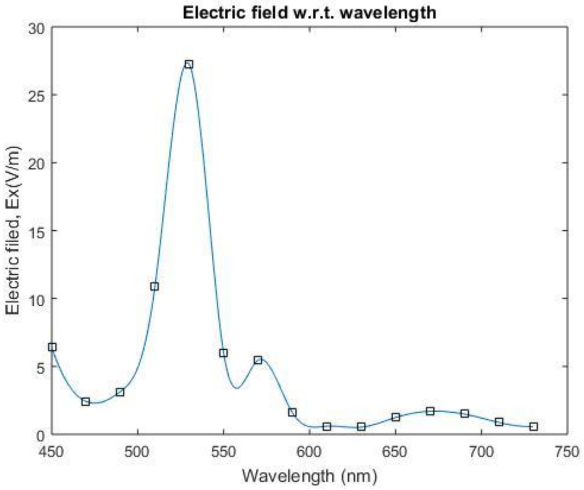

Fig 4: Variation of Electric field Ex with wavelength

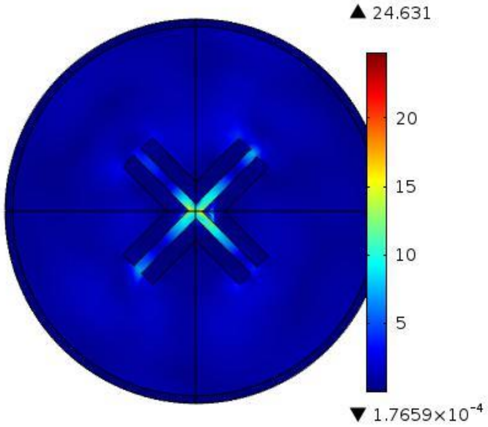

Fig 5: Electric field distribution in feed gap of nanoantenna

Conclusion

A cross V – shaped nanoantenna has been successfully designed and analysed. It has been observed that it has high scattering at resonant wavelength of 530 nm and Electric Peak at 530 nm.

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