CHAPTER - 1

INTRODUCTION

1.1 Brief Background

Antenna has been an integral part of RF and microwave spectrum devices from the very commencement of use of these spectrums. However, in the optical spectrum as it is only in the recent years that researchers have thought about antenna in optical frequency domain. Although, the idea of the optical antenna has its foundations in nearfield optics [1]. In 1928, Edward Synge proposed the utilization of a colloidal gold molecule for confining optical radiation on specimen surface and along these lines outperforming diffraction boundary in optical imaging [2]. At that point, in 1985, John Wessel proposed interestingly that a gold molecule could work as an antenna [3]. The principal test exhibits of this followed in 1995 by Dieter Pohl and Ulrich Fischer, who utilized a gold-covered polystyrene particle [4]. In the next years, optical antennas as strongly pointed metal tips were utilized as a part of close field microscopy and spectroscopy [5]. These analyses brought forth what is today known as 'tip-improved nearfield optical microscopy'. These reviews proceeded, what's more, from that point forward, different infrared antenna geometries have been meticulously investigated [6,7].

However, these investigations and studies were concentrated towards use of metals which supported plasmonic resonances in construction of optical nanoantenna. Diverse types of plasmonic antenna analogous to designs of antenna in RF and microwave range were designed to perform numerous tasks for example, dipole, bow-tie, Yagi-Uda etc. [8-31]

Regardless, in spite of various focal points of plasmonic nanoantennas related with their subwavelength size and solid localization of the electric field, such nanoantennas have extensive dissipative losses bringing about low radiation productivity. To conquer such constraints, another kind of nanoantenna were proposed considering dielectric nanoparticles with a high index dielectric constant, for instance Huygens optical components and Yagi-Uda nanoantennas [32–39]. Such all-dielectric optical nanoantennas suffers less from the dissipative losses with improved magnetic response in the optical domain. The key for such novel functionalities of high dielectric constant nano-photonic components is the capacity of subwavelength dielectric nanoparticles to bolster at the same time both electric and magnetic resonances, which can be controlled freely. This sort of nanoantennas has a few extraordinary advantages, for example, low optical losses at the nanoscale furthermore, super-directivity which was never talked about in metal nanoantenna.

1.2 Motivation

These intriguing advantages over metallic partners settle on dielectric nanoantennas as well-known decisions for directional dissipating in optical spectrum of visible and near IR frequencies. This thesis comprises of an outline of ultra-directional, all-dielectric optical nanoantenna. The first design is inspired by the theory given by Kerker et al for forward and backward scattering of light with the help of subwavelength nanoparticle. The cuboid shaped dielectric nanoantennas bolster azimuthally symmetric forward dissipating for innovative nanophotonic applications in visible and near infrared regions. A dielectric nanoparticle bolsters both electric and magnetic resonances. The forward dissipating by dielectric nanoparticle is seen at first summed up Kerker's condition.

The second design is inspired by the theory of directional Fano resonance shown by subwavelength nanoparticles. Fano resonance has been seen in metallic particle oligomers and recently in dielectric nanoparticles as well. [40-51]. This Fano resonance is established from the distinct asymmetric line shape or a narrow resonance drop created by the interference between an overlapping broad bright mode and narrow dark mode resonances.

COMSOL MultiPhysics programming is used for studying the scattering properties of these dielectric nanoantennas, broke down utilizing Finite Element Method in software. The impact of change in dimension of these nanoantenna keeping the material persistent has been additionally contemplated. Further, the impacts of nanoparticle parameters on disseminating properties of dielectric nanoantennas are likewise examined.

1.3 Thesis Objective

The principle goals of the proposition are as per the following:

- To bring out the essence from the essential ideas of optical nanoantennas, its attributes, sorts and nanoantenna applications. Further, to study the current progressions in the field of dielectric optical nanoantennas.

- To take in the numerical systems to demonstrate nanoantennas i.e. Finite Element Method.

- To design and study parameters of two different dielectric nanoantenna structure they are a Silicon cuboid and Silicon linear spherical quadrumer dielectric nanoantenna based on two different theories of Generalized Kerker's condition and directional Fano resonance for advanced nanophotonic applications in visible and near infrared frequencies.

- To compile the scattering properties of above mentioned all-dielectric nanoantenna in detail. Further, to analyze the impact of change in dimensions and gap of these nanoparticles.

1.4 Thesis Outline

The rest of the report is organized as follows:

Chapter 2 includes the literature review of the research papers and survey papers that were studied during the project work. In this chapter, optical nanoantennas have been discussed in brief, along with their applications and fabrication techniques. Further, two types of optical nanoantennas-plasmonic and dielectric nanoantennas were discussed.

Chapter 3 dwells in detail about all-dielectric optical nanoantennas. The principles on which dielectric nanoantennas are designed are discussed in detail.

Chapter 4 includes the calculational method and software tools used for design and analysis of the dielectric nanoantenna. FEM method for finding numerical solution for complex PDEs has been explained in detail.

Chapter 5 includes the design, simulations, and results of the proposed dielectric structure. This chapter includes the thorough analysis of scattering behaviour of the proposed design. The impact of gap in nanoantenna array and increase in directivity with number of nanoantenna elements is also discussed in this chapter.

Finally, Chapter 6 concludes the work done during the course of this project work and gives out the Future Scope.

CHAPTER - 2

OPTICAL NANOANTENNA

2.1 Introduction

The antenna is a transducer intended to transmit or accept electromagnetic waves. Antennas can also be referred as to the devices converting electric current into the propagating radio waves and, vice versa [52]. As a commonly utilized device in the present-day society, antennas have been broadly utilized in the RF and Microwave systems, for example, radar, the radio and TV broadcasting, and space investigation. Therefore, the conventional studies and development of antenna were limits to radio frequency and microwave range. The applications of most well-known antennas are chiefly confined to the radio/microwave frequency in the electromagnetic (EM) range especially for remote communications.

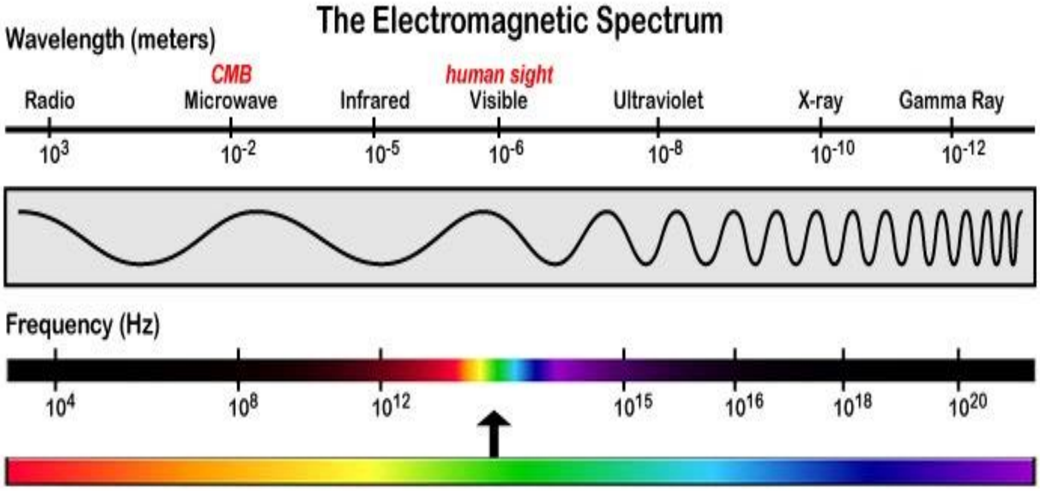


Fig. 2.1 The whole Electromagnetic Spectrum.

The development for antennas supporting shorter and shorter wavelength did not reach optical regime. One of the reasons is that before antennas could reach optical frequencies in a reliable way, optical fibers had removed the need to develop optical antennas for telecommunication applications. As of late, because of the improvement in the field of nano-optics, another branch of material science, the idea of the antenna has been stretched out to optical range. The nano-optics manages the transmission and gathering of optical signals by subwavelength nanoparticles.

2.2 Review of studies on Nanoantenna Theory

The optical antenna, otherwise called nanoantenna, is a light coupling device comprising of nanometer scale particles, which works in the optical range.

The receiving nanoantenna is a device successfully changing over incident light (in optical frequency) into a firmly bound field. Alternately, on the transmission end the nanoantenna changes over the emphatically bound field in the optical frequency made by a specific (feebly emitting or nearly non-emitting) source into optical radiation. By a confined field one comprehends an electromagnetic field amassed in a smaller area contrasted with the wavelength of light. [8]

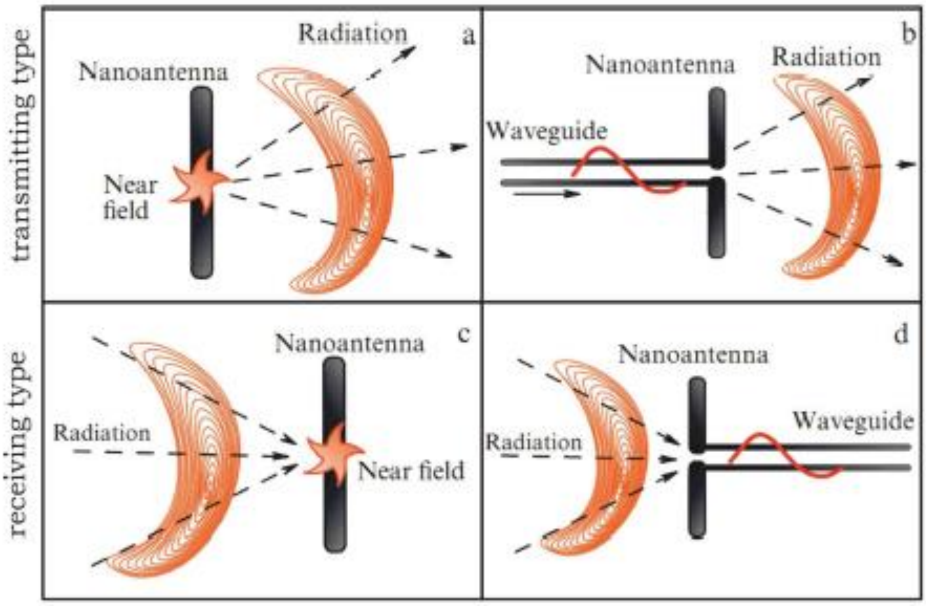


Fig. 2.2 The basic principles of nanoantenna operation. (a, b) Transmitting nanoantenna- the waveguide mode and transformation into freely propagating optical radiation; (c, d) explains a reception process [8].

Optical nanoantennas are like their radiowave and microwave partners, yet there are significant contrasts in their physical properties and scaling conduct. The distinctions are for the most part because, at optical frequencies, metals are not impeccable conductors, but rather unequivocally related plasmas depicted as a free electron gas. This means the metals as optical frequencies show dielectric properties. The electromagnetic reaction is managed by aggregate electron motions (surface plasmons, SP) normal for firmly coupled plasma. These aggregate excitations make a direct downscaling of conventional antenna design incomprehensible. Subsequently, at optical frequencies an antenna at no time in the future reacts to outside wavelength however to a shorter viable wavelength, which rely on upon material properties. Further with these changed material properties, the dielectric constant also becomes frequency-dependent, which needs special characterization in case of nanoantenna. In the dimensional aspect, as the particles' size decreases to the nanometer scale, the continuous band structures of the bulk materials transit to the discrete localized energy level and the quantum effects become apparent.

The idea of the "nanoantenna" was right off the bat proposed for the nanoparticles' full qualities as the resonators for local field improvement [53], and once appeared imaginative. The uncommon impacts of surface plasmon of metallic nanoparticles incited by light and the collaboration between them have drawn broad research enthusiasm over recent years. The nanoparticles are equipped for centering and restricting visible and near infrared (NIR) lights into nanometer scale measurements by utilizing surface plasmon reverberation, along these lines producing nearby upgraded fields with significant size [54].

In perspective of the nearby field focus and upgrade impacts, these metallic nanoparticles have been proposed to be utilized as the optical nanoantennas or plasmonic full antennas [55] and examined broadly [56]. Specifically, the nanoantenna is celebrated for their capacity to give sub-diffraction resolution in near field optics and photonics, which brings about overwhelming change over the other near field probes.

The initial advances in the field of nanoantenna and nano-optics was done with metallic materials which supported plasmonic resonances. However, the high dissipative losses in these metallic materials encouraged the scholars to search for materials which had low dissipative losses. It was only recently that the answer was found in materials with high dielectric constant. Nanoantenna designs taking advantage of the optical response of dielectric and semiconducting particles have appeared in the last few years in addition to metallic (plasmonic) nanoantennas.

2.3 Types of Nanoantenna

As of now explored nanoantennas incorporate different designs as far as various material constitutions, designs, and arrangements. Right off the bat, the nanoantenna plans include diverse material constitutions: there are the outlines which were halfway stacked with various sorts of materials like the multi-layered materials [57,58,59], the sectional materials [60] and single material like gold, silver, and semiconductors. Furthermore, the nanoantenna designs have distinctive setups which comprise of particles of many shapes. For a single molecule, monopole [61], the sphere [62], ellipsoid [63], cylinder (counting wire [64, 65, 66], triangular cylinder [67], triangle [68], pentagon [69] have been considered. For two coupling particles, the spheres [70], dipole [55], nanorod [71,72], disks [73,74], elliptical sets [75], and bowtie [76] have been investigated. Thirdly, the nanoantenna plans have distinctive courses of action from single antenna section to antenna particle chain [77,78] and cluster [59, 79, 80, 81, 82].

However, based on the material used the nanoantennas can be classified into three main broad categories. They are:

- Metallic or Plasmonic Nanoantenna
- Metal-Dielectric Nanoantenna
- Dielectric Nanoantenna

The first two types of nanoantenna are briefly explained in the subsequent paragraphs as they are beyond the scope of this thesis. The principle of operation and designing of metallic nanoantenna are based on surface plasmon generation and Purcell factor which is completely different from the dielectric nanoantenna. Dielectric nanoantenna have a strong magnetic resonance along with electric resonances which can be independently controlled.

2.3.1 Metallic Nanoantenna

The material used in these antennae are the ones which exhibit generation of surface plasmons in the optical regime and are opaque. In 1985, John Wessel [3] showed that a metallic nanoparticle behaves as an antenna. He revealed that the presence of a single plasmonic particle makes it possible to overcome the diffraction limit in the resolution of optical devices and to predict their resolving power up to 1 nm. Soon, it became clear that the strength of the near field in the gap between two or more plasmonic nanoparticles can be an order of magnitude higher than in the vicinity of an elongated nanoparticle. It is because the energy confinement in the gap occurs on smaller spatial scales. It turned out that the enhancement of the electric field in the gap between nanoparticles strongly depends on the metal used, the geometry of nanoparticles, the gap width, the radius of the curvature of the nanoparticle surf ace within the gap, as well as on the properties of the environment.

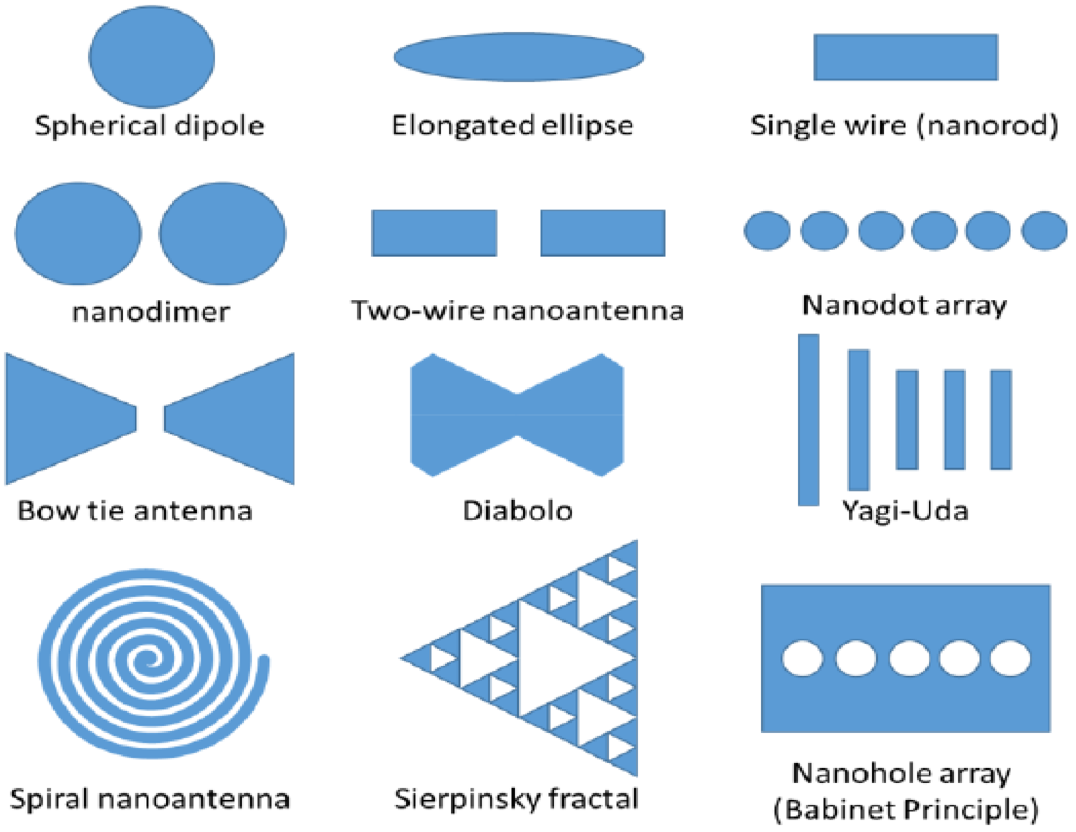


Fig. 2.3 Schematic of Plasmonic/Metallic Nanoantenna

The engineering of these parameters within a given range makes it possible to control the position and amplitude of frequencies at which the maximum of the enhancement of the confined field strength occurs. Such a wide range of opportunities for tuning these nanoantennas and optimizing their performance in a desired regime has led to the creation of a great variety of nanoantennas having similar geometries and operation principles. The dimer nanoantennas that consist of two nanoparticles are of interest. This large class includes dipole nanoantennas and `bowtie' nanoantennas, so named for their similarity to well-known garment. The problems facing nanophotonics frequently require that a given emitter can radiate in the desired direction. This requirement is met using Yagi Uda nanoantennas. These nanoantennas are look and operate similarly to Yagi Uda radio-frequency antennas (widely known in the Russian language literature as `wave channel' antennas).

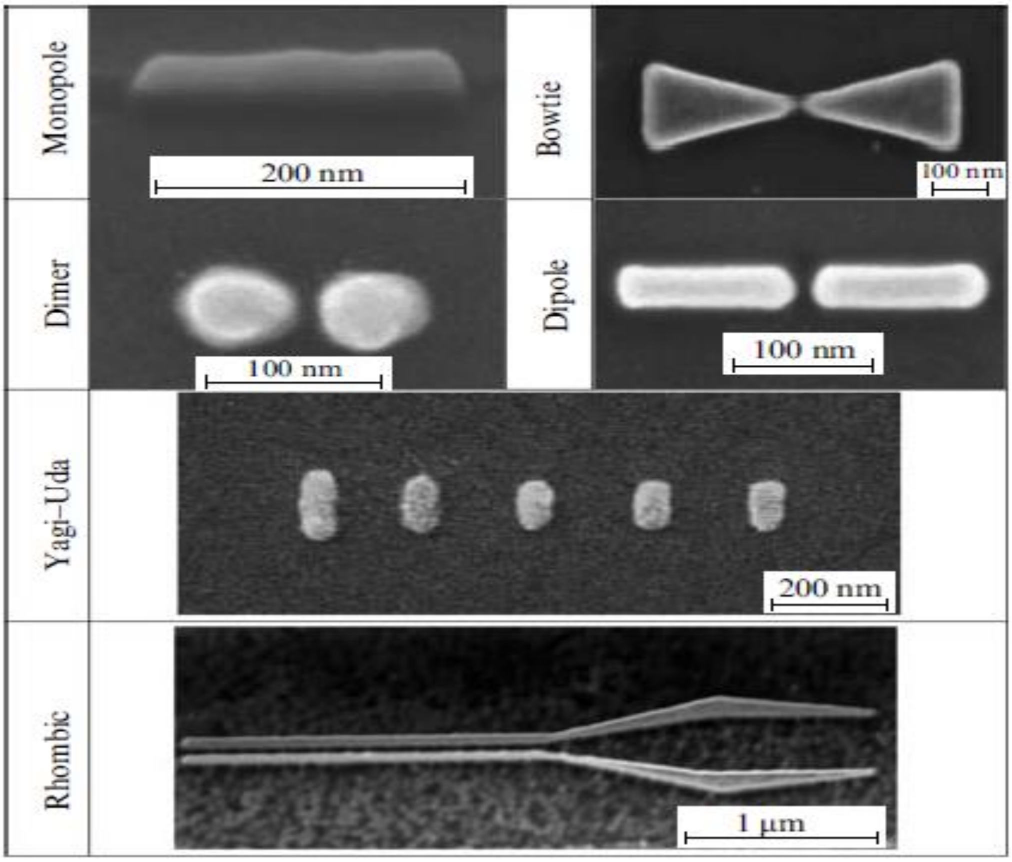


Fig. 2.4 SEM image of Plasmonic/Metallic Nanoantenna

The geometric similarity in design of plasmonic antenna with the antenna in the RF and Microwave regime can be clearly established. One metallic nanoparticle can operate as a receiving antenna due to its ability to enhance the electromagnetic field strength in its vicinity upon excitation of plasmon resonances of a dissimilar order. Dimers and so on to oligomers in plasmonic antenna are based on the fact that the field is confined in the gap between the two or more nanoparticles.

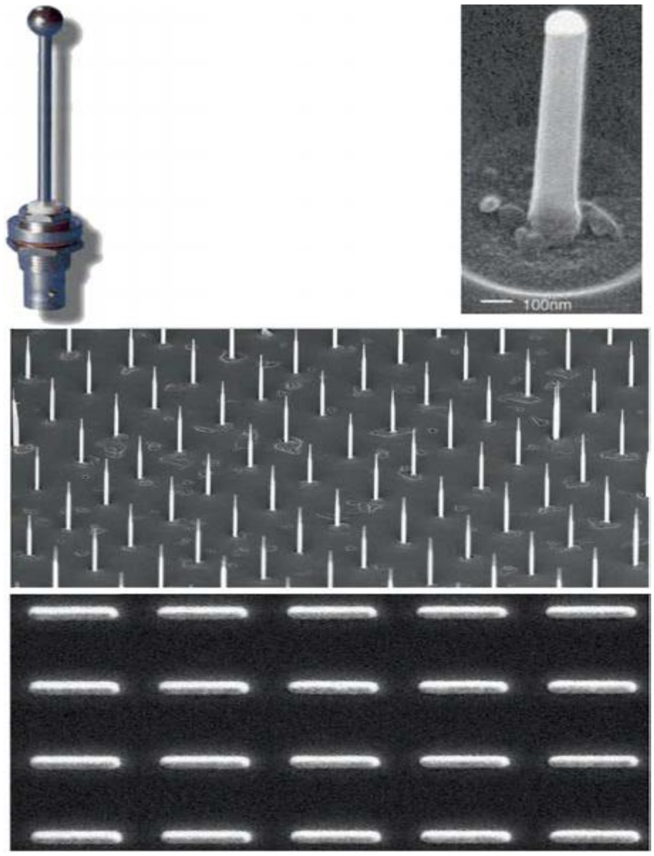


Fig. 2.5 Monopole nanoantenna. (a) Geometric similarity of the monopole nanoantenna and its radio frequency analog. (b) and (c) Images of monopole nanoantenna arrays.

2.3.2 Metal-Dielectric Nanoantenna

They are the hybrid of metallic and dielectric nanoantenna. Generally used in the core-shell designs or layered metal dielectric setting or substrate is added for the metal nanoparticle to enhance the scattered field by the nanoparticle [83,84].

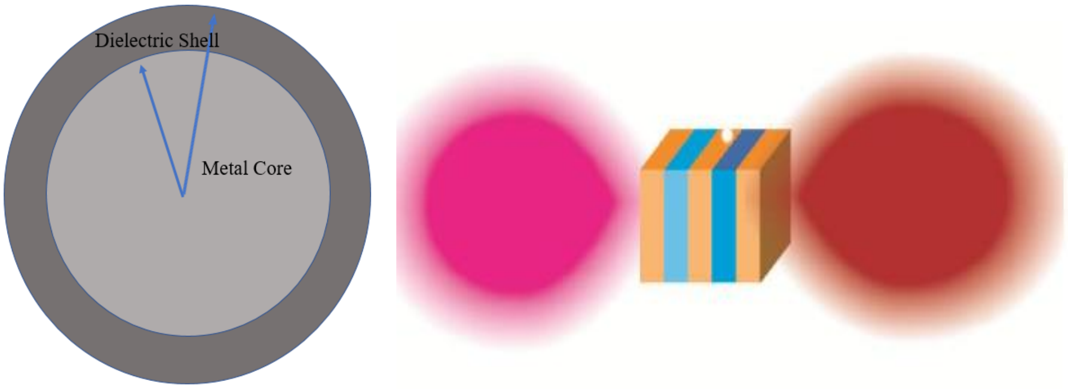


Fig. 2.6 Schematic of Metal-Dielectric nanoantenna

2.3.3 Dielectric Nanoantenna

Unlike metallic nanoantennas made from an opaque material having plasmonic behavior in the optical range, dielectric nanoantennas are fabricated from optically transparent constituents. Their resonant response is related to the formation of an effective resonator inside the nanoparticle. The antennas based on semiconducting particles are called dielectric nanoantennas, because semiconductors are sufficiently transparent in the visible frequency range. Nanoantenna designs exploiting the optical response of dielectric and semiconducting particles have showed up over the most recent couple of years, notwithstanding metallic (plasmonic) nanoantennas. Not at all like metallic nanoantennas produced using a opaque material having plasmonic behaviour in the optical range, dielectric nanoantennas are created from optically straightforward materials. Their successful response is identified with the development of a viable resonator inside the nanoparticle.

There are many benefits of using a dielectric nanoantenna. First, dielectric and many semiconductor materials are characterized by notably low dissipative losses in the optical range. Second, there is a wavelength range in which a submicron dielectric particle of high permittivity or dielectric constant like Si or Ge simultaneously exhibits both electric and magnetic resonant responses. It makes possible the creation of the Huygens element using a single particle. This effect is of primary importance to optics. Due to the directional properties and low losses, Huygens-element particles can be utilized to construct compact dielectric nanoantennas with very high directivity.

2.4 Characteristics of Optical Nanoantenna

The main characteristics of the optical nanoantenna can be said to be analogous to the antenna of RF and Microwave spectrum. Nevertheless, they are briefly described in the subsequent paras.

- Directivity: - A prime characteristic of any antenna or for that matter nanoantenna is its directivity. Directivity of nanoantenna can be defined as "the ratio of the radiation intensity in the given direction from the antenna to the radiation intensity averaged over all directions like in case of an isotropic antenna. The average radiation intensity is equal to the total power radiated by the antenna divided by 4π. If the direction is not specified, the direction of maximum radiation intensity is implied." The directivity diagram is a positive function coinciding in the spherical coordinate system with the Poynting vector distribution in the far field radiation zone. For an antenna, the concentration of radiation in a given direction is given by the directivity. Under mentioned expression define directivity [52]

$$\boldsymbol{D(\theta,\varphi) = \frac{4\pi p(\theta,\varphi)}{P_{rad}}} \qquad \textbf{(2.1)}$$

Where the total power radiated is given by P_{rad}, $\int \boldsymbol{p}\ (\theta,\varphi)d\Omega$, is the integral of the angular distribution of the radiated power $\boldsymbol{p}(\theta,\varphi)$ over the spherical surface, where (θ,φ) are the angular coordinates of the spherical coordinate, and $d\Omega$ is the element of the solid angle. The maximum value of directivity is given by

$$\boldsymbol{D_{max} = \frac{4\pi Max[p(\theta,\varphi)]}{P_{rad}}} \qquad \textbf{(2.2)}$$

Where, power transmitted in direction of the main lobe is given by Max $\boldsymbol{p}(\theta,\varphi)$.

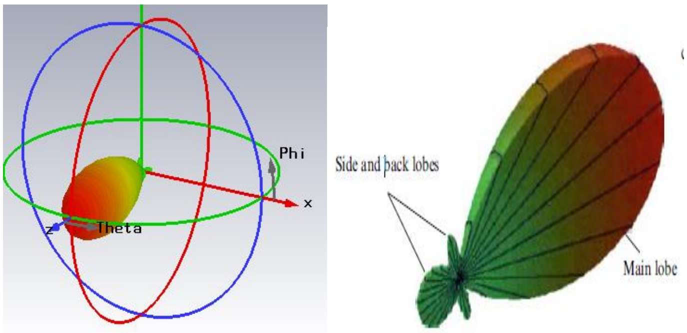


Fig. 2.7 Directivity diagrams for a Yagi-Uda nanoantenna.

- Efficiency: - The conduction, reflection, and dielectric losses determine the antenna efficiency of an antenna. The conduction and dielectric losses of an antenna are measured as they are very difficult to evaluate. Their separation is difficult even with the help of measurement. Hence, they are generally borne together to form the radiation efficiency.

$$\varepsilon_{rad} = \frac{P_{rad}}{P_{rad}+P_{loss}} \qquad (2.3)$$

where P_{loss} is the total power loss in antenna material. For a lossless antenna, one has radiation efficiency, $\varepsilon_{rad} = 1$. The maximum value of the gain is related to the maximum directivity of by

$$G = \varepsilon_{rad} D \qquad (2.4)$$

This quantity defines directivity, taking account of losses in the antennas.

- Absorption cross section of a quantum detector (Field factors): - Quantum sensors used in the optical domain have subwavelength spatial proportions. A trivial absorption cross section characterizes the quantum sensors σ equal to the ratio of the absorbed power P_{exc} to incident radiation intensity:

$$\sigma(\theta, \varphi . n_{pol}) = \frac{P_{exc}}{I} \qquad (2.5)$$

Where, n_{pol} is the direction of polarization of the incident field E. For a sensor which is described using dipole approximation, the absorption cross section can be written as [8]

$$\boldsymbol{\sigma = \sigma_0 \frac{(n_p E)^2}{(n_p E_0)^2}} \tag{2.6}$$

Where, n_p is the orientation of the absorbing dipole, σ_0 is the absorption cross section in the absence of a nanoantenna, and E and E_0 are the electric field strengths in the presence and absence of the nanoantenna, respectively. Nanoantennas has ability to enhance the near field in a certain space region, hence the absorption cross section of a detector placed in this region is also gets enlarged.

- Confined magnetic and electric field enhancement factors: - The absorption cross section of a sensor also depends on the enhancement factor of the confined electric field, which is given by

$$\boldsymbol{\delta^e = \frac{|E|}{|E_0|}} \tag{2.7}$$

Where, |E| represents the absolute magnitude of the electric field at a given point in the presence of a nanoantenna and $|E_0|$ is the absolute magnitude of electric field without a nanoantenna. The coefficient of enhancement factor may be either greater or less than unity. It must be greater than unity for practical applications, as only in such case the sensor efficiency increases with availability of the nanoantenna.

- Purcell effect: - It was assumed that the natural radiation is an intrinsic behaviour of molecules or atoms. Hence, the natural or spontaneous radiation of the molecule or atoms cannot be modified. It was only after EM Purcells [85] work it was known that the spontaneous relaxation rate depends partially on the environment of a light source, thus telling that by introducing light source in a distinct or special environment the emission behaviour of an atom and emitter can be modified.

An emitter's energy states have its own spectrum. As these energy states are fixed, when an emitter is excited to these states it must remain in that state for infinitely lengthy duration. But, due to emitters interaction with the environment an emitter in the excited state is branded by a short lifetime. This means special environment for a light source can change the rate of spontaneous emission. This effect was called the Purcell effect.

The Purcell factor F_P is given by the spontaneous emission rate of the emitter placed in a certain heterogeneous system, γ, compared with the spontaneous emission rate in the free space, γ_0.

$$\boldsymbol{F_P = \frac{\gamma}{\gamma_0} = \frac{P_{tot}}{P^0}} \tag{2.8}$$

The change in the total power $\mathrm{P_{tot}}$ emitted by the emitter as to the power $\mathrm{P^0}$ that the emitter radiated in the free space can be related to the Purcell factor. The course of improvement of spontaneous emission rest on the variation of the number of excitation acts and spontaneous emissions of the emitter per unit time. The total power $\mathrm{P_{tot}}$ is defined as the summation of two powers, one radiated by the system, and absorbed in the material and its environment.

2.5 Applications of Optical Nanoantenna

Nanoantennas might be utilized and coordinated into the high thickness optical circuits. That is on account of the optical frequency is substantially higher than the frequency utilized as a part of the remote interchanges. Above considered significant nanoantenna look into for optical correspondence reason nearly identifies with the antennas' radiation execution in the far-field, which is a greater number of researchers' worry with respect to the traditional antenna outline. Then again, the nanoantennas can create promising outcomes over the customary antenna, particularly in the near field applications. They are observed to be equipped for delivering goliath concentrated and exceedingly confined fields with the size as little as many nanometers, accordingly enhancing the size confuse between the diffraction constrained light spot energized by light source and fluorescent atoms which are considerably littler than the excitation wavelength.

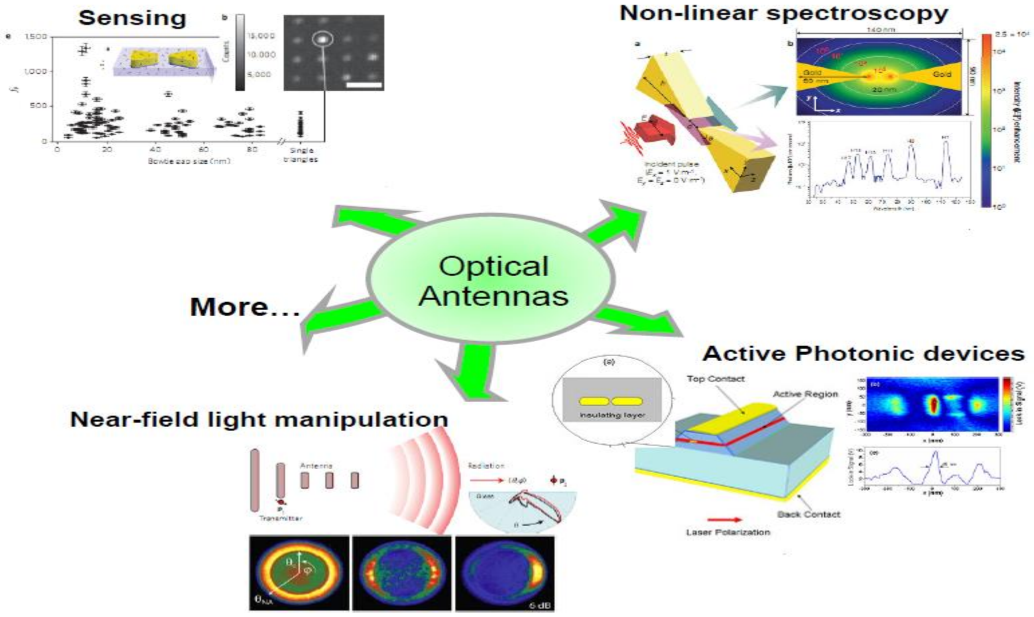


Fig. 2.8 A wide range of applications are driving the current research in optical antennas. Some of the applications reported in recent years include biological and chemical sensing, non-linear spectroscopy and high-harmonic generation, photonic devices, high density optical data storage, sub-diffraction lithography and imaging, and solar energy harvesting. [16, 72, 98, 99]

In the subsequent paragraphs, we briefly dwell open the various applications of optical nanoantenna. Nanoantennas in light of surface plasmon resonance have assorted applications in the near field test or atom location/emanation [16, 62, 82, 86, 87], surface upgraded Raman diffusing (SERS) [88], optical microscopy [78, 89, 90] or imaging [57, 91], spectroscopy [92], photonic applications for chemical and bio-detecting [93, 94, 95, 96], and optical circuits [97].

- <u>Scanning near field optical microscopy</u>: - Near field optical microscopy gives concurrent estimations of the geology and optical properties (fluorescence). Nanoantennas have been proposed as imaging and spectroscopic tests which help in light section through the test gap and to improve the impact of electromagnetic field close to the tip of a gap less test. Nanoantennas should be created at the tip of a filtering test. A fascinating case of near field spectroscopy is a solitary particle imaging which has been accomplished with bowtie [90] and $\lambda/4$ antennae [61], and determination down to 25 nm can be acquired in the last case. The optical radio wires help us to drastically build the effectiveness of light going through gap tests. It is exceptionally hard to outline the tests in light of optical nanoantennas in light of the fact that occasionally it is practically difficult to separate them on in light of nearness or nonattendance of the gap.

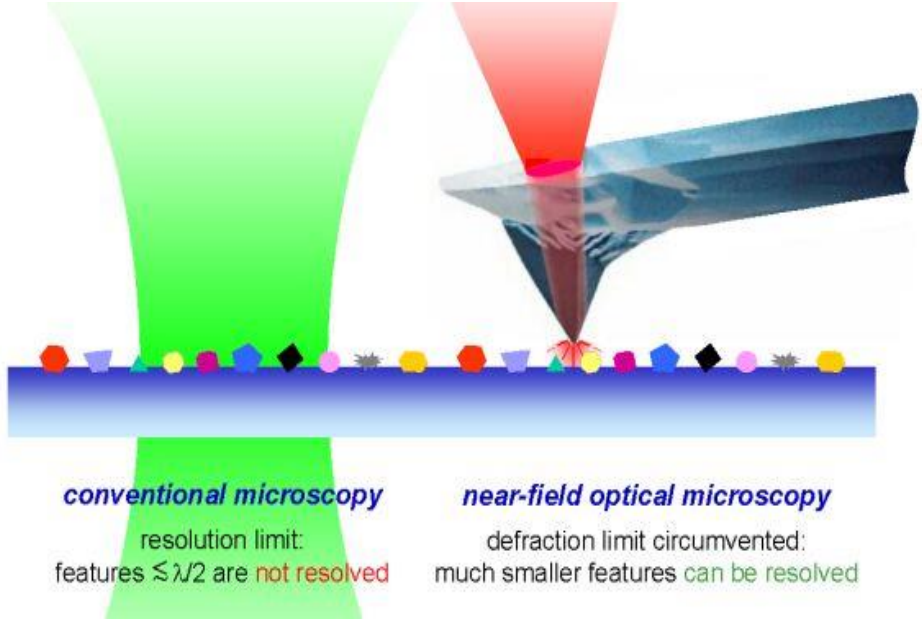


Fig. 2.9 Difference between conventional and near field microscopy

The work on probe antenna is fundamentally engaged to upgrade the dispersing of particles or quantum producers. The optical test nanoantennas are additionally utilized as a part of tip-improved Raman Spectroscopy which have muddled structures for instance, a mix of plasmonic waveguide and a photonic precious stone, coaxial structures and carbon nano-tube based structures [100-102].

➢ Spectroscopy: - SERS (Surface improved Raman spectroscopy) is the marvel in which comprise of growth of the dispersing cross segment of the atom put close to a hostile metal surface [102-105]. The historical backdrop of spectroscopy begun in a test in 1970s. The utilization of this impact was to production of substrates to concentrate the organic specimens. The signs can be to a great extent improved after the surface-upgraded and tip-upgraded Raman scattering as appeared in figure 2.10.

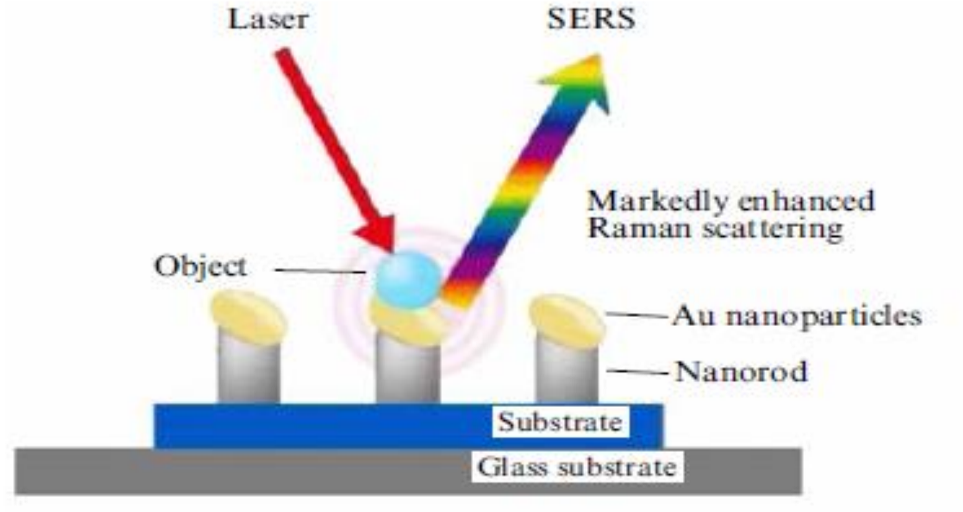


Fig. 2.10 Surface Enhanced Raman Spectroscopy (SERS). (Source: http://www.nidek-intl.com)

The Raman scattering includes the assimilation and discharge of photons which are about indistinguishable in vitality. The aggregate diffusing upgrade is normally relative to the fourth energy of the field improvement. Consequently, common improvement variables got are $\approx 10^6$, and it is conceivable to acquire considers as substantial as $\approx 10^{10} - 10^{12}$. Such upgrade empowers the identification of single atoms.

➢ Optical lithography: - The exceedingly localized near field of a nanoantenna likewise finds a characteristic application in optical lithography. Lithography is a procedure to make a resist on a given wafer. It is the vital piece of semiconductor assembling technology. Optical lithography comprises of an optical framework which exchanges the image from the cover to the resist layer. The plasmonic dimers for instance bowtie antenna kept the field as far as possible where it is proportional to a stronger light spot which will enhance the determination of optical lithography [76]. The procedure of optical lithography is appeared in figure 2.11 and the compelling source utilized is optical nanoantenna.

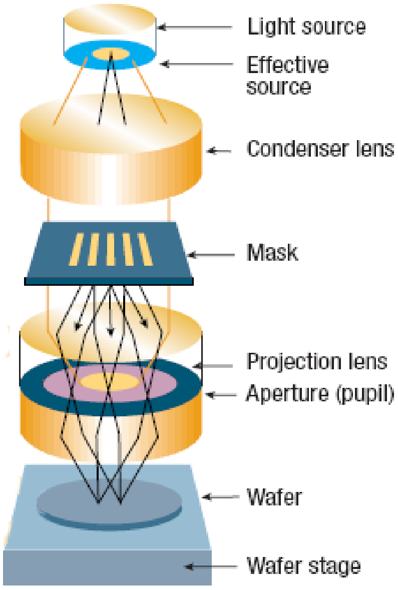


Fig. 2.11 The procedure of optical lithography [106].

- <u>Optical tweezing with nanoantennas</u>: - Optical tweezers are the tools that utilization light to control minuscule items as small as a solitary iota [107]. All the more as of late, it has been exhibited tentatively that the optical catching in very much controlled problem areas in the hole of nanoantennas. The expansive antenna field improvement permits catching with lower excitation power and higher proficiency and dependability [108, 109].

- <u>Antenna based photovoltaics: -</u> The issue with present day sunlight based power designing is the advancement of thin film sun powered cells which can effectively change over sun oriented radiation into electric current. The utilization of thin photosensitive films in sun based cells may diminish the cost of electric power with a noteworthy size. Plasmonic photovoltaics is a standout amongst the latest fields in nanophotonics which can kept episode radiation in subwavelength run [110]. Standard sunlight based cells are consolidated with metallic nanostructures, which think and guide light at the nanoscale, prompting a decrease of the semiconductor thickness required, and in addition improving the broadband ingestion of the occurrence light, which is one of the vital difficulties to present day sun based cell advances [111].

- <u>Optical antenna detectors: -</u> Plasmonic nanoantennas shows limited resonances that are unequivocally rely on upon dielectric properties of nature. These kind of nanoantennas are exceptionally encouraging contender to detecting application. The fundamental standard behind plasmonic detecting is that the refractive list change in the encompassing medium of the nanoantenna converts into a move of particles resonance frequency. Numerous plasmonic sensors were shown in past for instance, detecting in light of molecule clusters on a fiber aspect [82] or on a substrate [112] with sensitivities down to the single-molecule level [113, 114].

- <u>Lasing in nanoantennas: -</u> Surface Plasmon Amplification by Stimulated Emission of Radiation (SPASER), has been initially proposed by Bergman and Stockmann [115]. In this specific situation, metal nanoparticles going about as optical antennae can assume a part in light of their vast local field improvement and greatly lessened interaction volume. Recently, subwavelength plasmon lasers in light of the first SPASER proposition have been shown [116, 117]. Bigger improvement and repression, contrasted with single particles, can particularly be experienced in the crevice of two-wire or tie nanoantennas. Along this line, laser operation for bow-tie antenna coupled to semiconducting quantum dabs or different quantum wells has been hypothetically tended to [118].

- <u>Nanomedicine: -</u> The utilization of metal nanoparticles for biomedical applications has settled many difficulties in present day solution [119, 120]. Nanoparticles can be utilized as a part of treatment for harmful neoplasms. Metallic nanoparticle put at the influenced site is illuminated with the near field light, the warming of nanoparticle causes by radiation is exchanged to wipe out cells and in this manner, execute them. The imaging of organic examples and the location of maladies, for example, malignancy require biomarkers and difference operators. There is an enthusiasm for misusing the substantial dispersing cross areas related with LSPRs for bio-imaging and medication and quality conveyance [121]; application which depend on both their biostability and optical properties. Gold particles have likewise been proposed as differentiation specialists for magnetic resonance imaging [122]. The absorptive properties of metal NPs are likewise encouraging for restorative imaging.

2.6 Fabrication Techniques of Optical Nanoantenna

Since the resonances of optical antennas emphatically rely on upon the correct geometry and measurements, creation of nanoantennas requires solid and reproducible structuring methods with a run of the mill resolution underneath 10 nm with a specific end goal to precisely characterize basic measurements, for example, feed gap size or antenna arm length. This push cutting edge nanostructuring procedures as far as possible and can be viewed as one of the fundamental challenges in the acknowledgment of optical antennas.

Detailed discussion on the process of manufacturing is beyond the scope of the thesis as the work done is purely theoretical and based on numerical calculations. However, various methods used for creating nanostructures are listed below: -

- Electron-beam lithography
- Focused ion-beam milling
- Nano-imprint lithography
- Self- and atomic-force-microscopy-based assembly of nanoantennas
- Nanoantennas on tip

CHAPTER - 3

ALL-DIELECTIC OPTICAL NANOANTENNA

3.1 Introduction

As briefly explained in Chapter 2 dielectric nanoantennas are the devices made from materials which exhibit electric as well as magnetic resonances in the optical regime mainly the visible and near IR spectrum. This kind of response of the material minimizes the dissipative losses experienced in plasmonic nanoantennas. This enables the possibility of creation of the Huygens element using a single particle. This effect is of primary importance to optics. Due to the directional properties and low losses, Huygens-element particles can be utilized to construct compact dielectric nanoantennas with very high directivity, such as, for instance, Yagi Uda nanoantennas. Moreover, many light-trapping nanostructures comprise ordered combinations of dielectric and semiconducting nanoelements that can be classified as receiving dielectric nanoantennas.

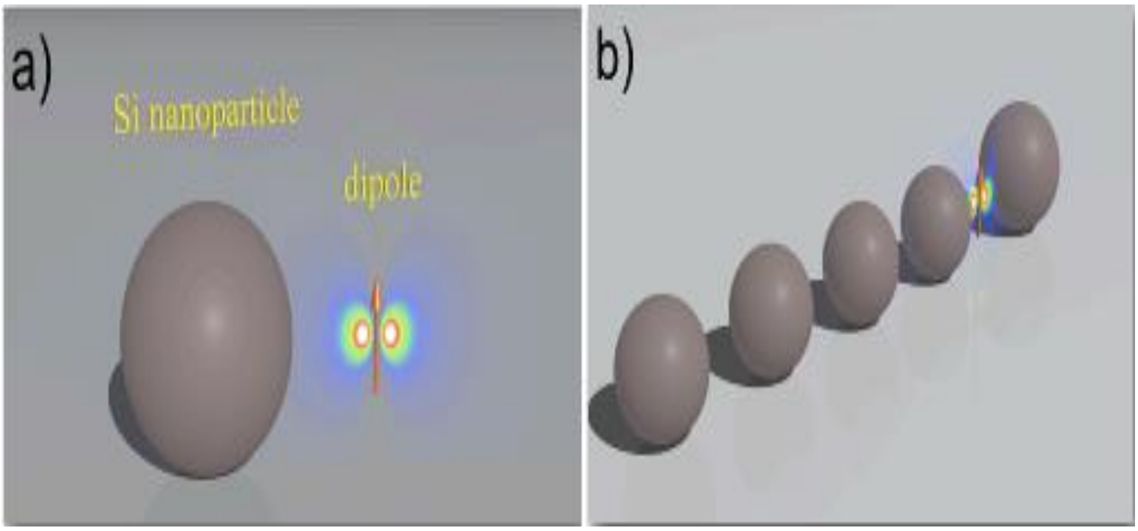


Fig 3.1 Schematic view of two types of all-dielectric nanoantennas. a) Huygens source b) Dielectric optical Yagi-Uda nanoantenna

3.2 Huygens component

The idea of Huygens component depends on the Huygens rule. As indicated by Huygens standard, "all points of a wave front of light in a vacuum or clear medium might be viewed as new wellsprings of wavelets that grow toward each path at a rate contingent upon their speeds". Christiaan Huygens, Dutch mathematician, physicist, and astronomer, in 1690 proposal had turned into an intense technique for concentrate different optical phenomenon. Huygens standard of wave examination comprehends the developments of waves around items [123].

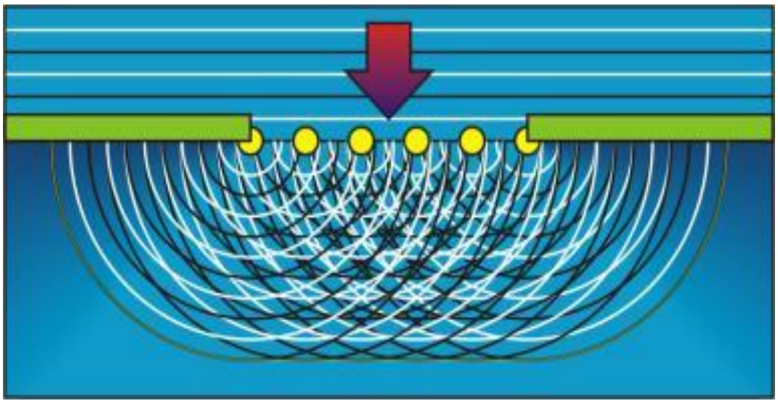


Fig 3.2 Illustration of Huygens guideline

As appeared in the figure 3.2 to one side, when light travels through an aperture (an opening inside a boundary) each point of the light wave inside the aperture can be seen as making a roundabout wave which proliferates outward from the gap. The opening, hence, is dealt with as making another wave source, which proliferates as a round wave front. A surface digression to the wavelets constitutes the new wave front and is known as the envelope of the wavelets. In the event that a medium is homogeneous and has similar properties all through (i.e., is isotropic), allowing light to go with a similar speed paying little respect to its heading of propagation, the three-dimensional envelope of a point source will be round.

Huygens component is a dielectric molecule of high permittivity material i.e. of the order 10-20. Because of high permittivity of dielectric material initial two Mie resonances, electric and magnetic, are seen in visible frequency go [56]. The electric and magnetic dipole moments are prompted when energized by a emitter. Huygens particles can be utilized to plan dielectric nanoantennas with high directivity. A Huygens component (of silicon material) is depicted in figure 3.3 (a). A round dielectric silicon nanoparticle is set in the near field of a rudimentary dipole. Figure 3.3 (b) delineates the wavelength reliance of the directivity calculate for Huygens component.

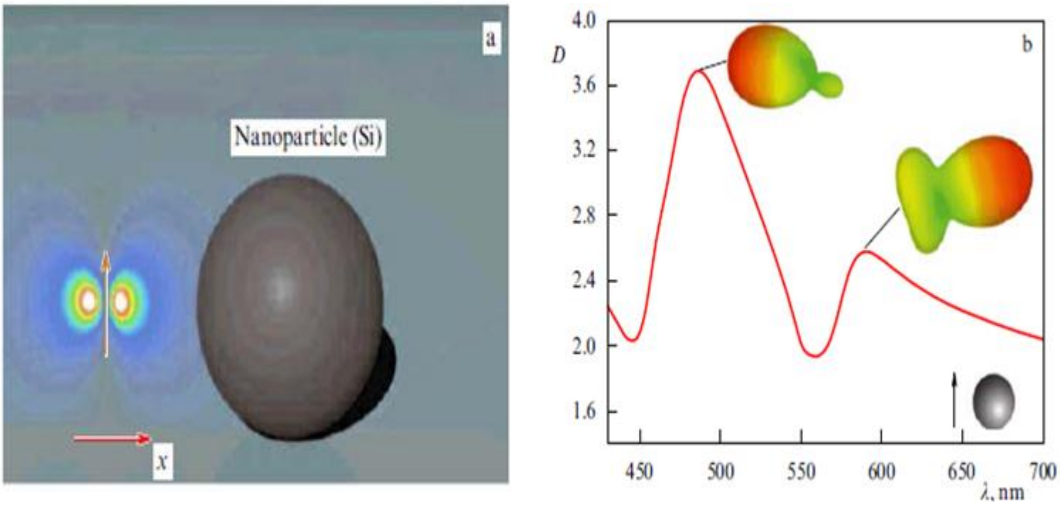


Fig. 3.3 Huygen Component (a) A case of Huygens component. (b) Wavelength reliance of directivity elements [9].

3.3 Optical magnetism in Dielectric Optical Nanoantennas

An oscillating dipole is alluded as a couple of swaying electric charges of inverse signs. The oscillating dipole produces electromagnetic (EM) radiation at the resonance. Single "magnetic charges" or monopoles are not found in nature. The normal foundation of magnetic field in nature are magnetic dipoles. Magnetic dipole field can be ascertained as the limit of a current ring that is contracting to a point. The regular case of a magnetic dipole radiation is an EM wave delivered by a split ring resonator (SRR) [124] as depicted in figure 3.4. The current inside the SRR which is energized by an outer EM radiation creates a transverse oscillating backward and forward magnetic field at the focal point of the resonator ring, which shapes a swaying dipole. The split ring resonator is the fundamental component for metamaterials. The purposes behind enthusiasm for such counterfeit frameworks are as per the following:

- They have capacity to react to a magnetic part of approaching EM radiation.
- They have magnetic permeability which is either non-solidarity or negative at optical regime.

- These sorts of frameworks with above properties are not found in nature

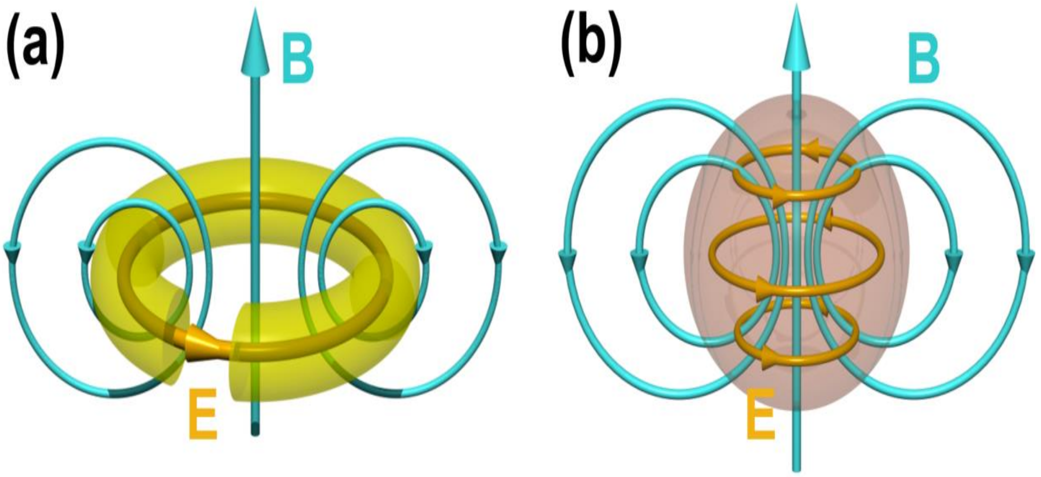


Fig. 3.4 Schematic of field lines in SRR (a) The schematic portrayal of EM field circulation inside a SRR and high refractive file dielectric nanoparticle. (b) EM appropriation at magnetic resonance [124].

The artificial framework has numerous applications in outline of material properties, for example, clocking [125, 126], superlensing [127], negative refraction [128] and so on. Nonetheless, the greatest impediments of metal manufactured framework are inborn losses at visible frequencies range. So, another option to maintain a strategic distance from such losses and accomplish magnetic reaction is to utilize high-refractive list dielectric nanoparticles [129]. The solid magnetic reaction by high-list dielectric particles is clarified utilizing a circular dielectric nanoparticle. The diffusing by a round dielectric nanoparticle takes after Mie arrangement of light dissipating. For this molecule a solid magnetic dipole resonance can be accomplished in a specific parameter run. The primary resonance of this molecule is an magnetic dipole resonance and it occur at wavelength of the light $\lambda/n_s \approx 2R_s$, where λ is wavelength in free space, R_s and n_s are the range and refractive list of the molecule. Magnetic field motions in the inside under this condition are as appeared in figure 3.4(b).

3.4 Unidirectional Scattering in Dielectric Nanoparticles

The unidirectional scattering in dielectric nanoparticles has been extensively studied by scholars due the advantages mentioned in preceding sections. The two basic theories which have been exploited are the Generalized Kerker's condition and Fano resonance. Although, the latter had been observed for plasmonic material way before its existence was noticed in dielectric material. In the subsequent sections both the theories have been briefly explained.

3.4.1 Generalized Kerker's Condition

To accomplish a directional example with zero backscattered field, Kerker proposed exploiting the interference of the electric and magnetic dipole modes of a scatterer. As of late, the supposed Kerker condition has pulled in impressive consideration, both in theoretic and experimental work, to acknowledge directional outflow from dielectric and metallic nanoantennas.

Thirty years prior, Kerker *et. al.*[130] demonstrated that the backscattered light from spherical scatterers can be totally muted if the dielectric and magnetic properties of the scatterers are the same ($\varepsilon = \mu$). A molecule such behaviour shows identical electric (a_n) and magnetic (b_n) multipole coefficients that destructively meddle in the regressive propagating direction (first Kerker condition). Up to this point, zero backscattering at visible range has been a hypothetical interest because of the absence of magnetic materials ($\mu_r = 1$) in the optical domain. Kerker's condition for zero backscattering can be summed up for round particles expecting that the scattered field is sufficiently portrayed by the electric (a_1) and magnetic (b_1) dipole terms of the Mie expansion.

In their paper, the dispersing from a sphere was viewed and two typical diffusing conditions were found. The first of them, known as the main Kerker condition, demonstrated that the back scattered radiation from a sphere can be lessened to zero when the relative electric permittivity and magnetic porousness are equivalent. Interestingly, the second Kerker condition, substantial for small size spheres typically ranging from 80nm to 200nm approximately, demonstrate backward scattering capability as well.

Therefore the two conditions were established first where the backward scattering was completely suppressed and second Kerker"s condition where there is maximum backward scattering.

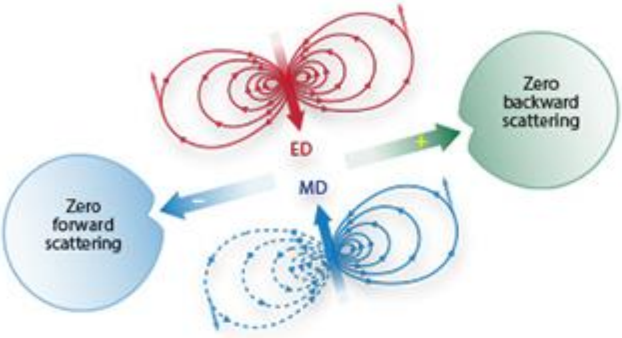


Fig. 3.5 Unidirectional scattering due the electric and magnetic dipole moments

3.4.2 Fano Resonance

In physics, a Fano resonance is a type of resonant scattering phenomenon that brings into the uneven line-shape. asymmetric line-shape is produced by interference of background and a resonant scattering caused by the nanoparticle. It is named after Italian-American physicist Ugo Fano, who gave a theoretical clarification for the scattering line-shape of inelastic scattering of electrons from helium.

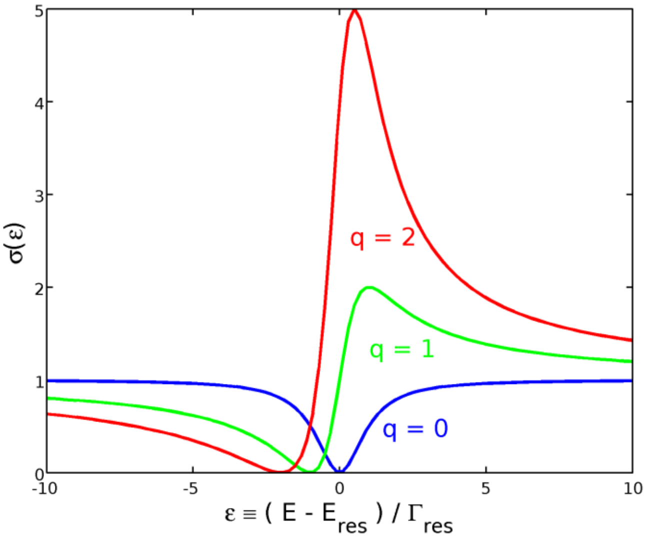


Fig 3.6 Plot of scattering cross-section versus normalized energy for various values of the parameter q illustrating the asymmetric Fano line-shape

The Fano resonance in nanoantenna can described as a narrow resonance dip caused by the destructive interference between overlapping broad resonance with a narrow resonance. Conventional Fano resonances in metallic molecule oligomers [41-43] or other plasmonic nanostructures [44-46] have been generally explored. Specifically, Fano resonances can be seen in heterodimers, for example, nanorod dimers with various perspective ratios [47,48] or, on the other hand nanoparticle dimers with various radii or diverse materials. [49,50]. This one of a kind line shape, which is delicate to geometry or neighborhood environment. Because of symmetry breaking, heterodimers show more complex coupling practices and give rise to Fano resonance. Lately, all-dielectric nanostructures showing low-loss scattering furthermore, solid magnetic response at visible wavelengths have drawn expanding response [35,131].

Fano resonance is easier to generate when the number of nanoparticle is more than one and are in close proximity. The magnetic response of all the nanoparticle couples and produces a narrow coupled magnetic response. However, electric dipoles couple to produce a broad electric response. In short, the broad "bright" mode interacts narrow "dark" mode to give Fano type line shape to the scattering intensity of the light

CHAPTER - 4

CALCULATIONAL METHOD AND SOFTWARE TOOLS

4.1 Finite Element Method

4.1.1 Introduction

In science and engineering submissions, Partial Difference Equations (PDEs) are used to descried the system. With complex geometries and problems, analytical methods fall short to give solutions to these PDEs. Instead of that, an estimate of the equations can be built, classically created upon diverse types of quantization. This quantization approximates the PDEs with numerical model equations, which can be resolved using numerical procedures and technique. This solution to the numerical model equations is an approximate solution of the real answer to the PDEs. The finite element method (FEM) is one of the numerical method used to solve those problems. FEM makes assembly of finite element. A physical and continuous problem is converted into a discrete finite element problem [132].

Two important aspects of the FEM are:

- ➢ Part-wise calculation of physical fields on finite elements which leads to sufficient precision even with modest approximating functions. By increasing the number of elements, the precision can be improved but the solution time and calculations increase.

- ➢ Locality of approximation leads to sparse equation systems for a quantised problem. This helps to solve problems with very large number of nodal unknowns.

4.1.2 The FEM technique

The finite element method is a systematic process (as shown in figure 4.1), which are explained below:

- Discretize the continuum: - In the stage one, the solution region of a problem is divided into finite elements. The mesh of finite element of the solution region is generated by a preprocessor program. Mesh generally consists of several arrays which further consist of element connectivities and nodal co-ordinates.

- Selection of interpolation functions: - The Interpolation functions are used to interject the field variables over the section. Interpolation functions selected are the polynomials which are derived equations to satisfy the nodal conditions. The degree of the polynomial required for interpolation functions depends on the number of nodes allocated to the element.

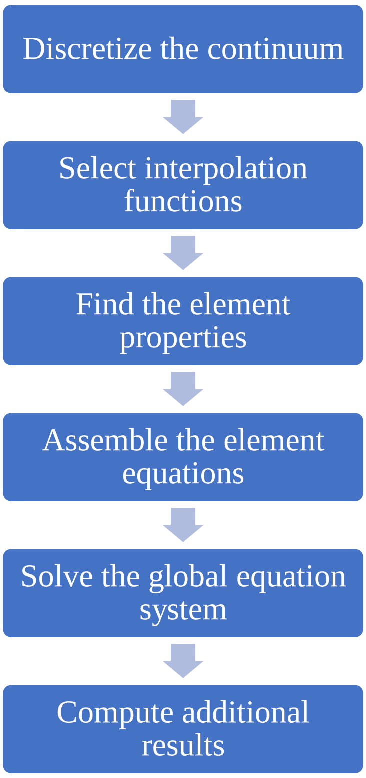


Fig. 4.1 Flow chart for FEM

- Find the element properties: - After interpolation function is selected the element properties are to be established. Here we must establish the matrix equations for the finite element which will relate the nodal values of the indefinite function to other parameters or limits. For this job, any suitable methods can be used; the befitting approaches used in finite element method are: the variational approach and the Galerkin method.

- To assemble the element equations: - The next step is to find the universal equation for the entire system. Hence, we must gather all the element equations to form a global equation system. The local element equations need to be combined for all elements that are used for quantization. For the assembly of the equations the Element connectivities are used. The boundary conditions should be imposed before the solution is obtained.

- Solve the global equation system: - The global equation system formed in is now solved using different methods. The equation system is scant, symmetric, and positive definite. To solve the global equation system direct and iterative methods can be used. The nodal values of the required function are produced because of the solution of global equation.

- Compute additional results: - In many instances, we need to evaluate additional parameters as depending on the type of problem. For instance, in mechanical problems strains and stresses require particular attention in addition to displacements or shifts, which are found after solution of the universal equation system.

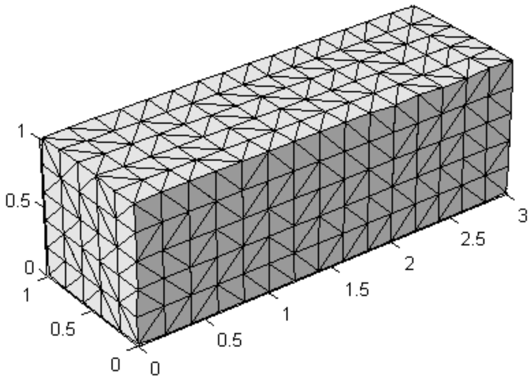


Fig. 4.2 Meshing done using FEM

4.2 Software Tools Used

The software tools used are COMSOL MultiPhysics and MATLAB. They have been briefly explained in subsequent sections

4.2.1 COMSOL MultiPhysics

COMSOL Multiphysics® is an influential interactive environment used to model and resolve all varieties of scientific and engineering problems. The software delivers a powerful unified desktop environment with a Model Builder that gives you a jam-packed summary of the model and access to all functionality. With COMSOL Multiphysics one can effortlessly encompass conventional models for one type of physics into Multiphysics models that crack down coupled physics phenomenon and do so concurrently. Accessing this power does not require a detailed acquaintance of mathematics or numerical analysis.

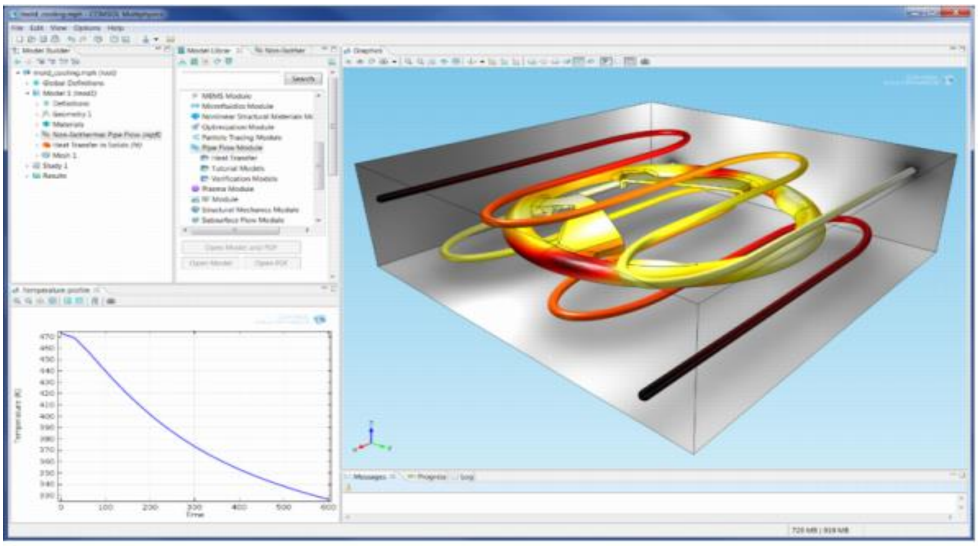


Fig. 4.3 COMSOL Dashboard

Using the integral physics user interfaces and the advanced support for material properties, it is possible to figure models by defining the pertinent physical quantities such as material properties, loads, constraints, sources, and fluxes rather than by defining the basic equations. One can constantly apply these variables, expressions, or numbers directly to solid and fluid domains, boundaries, edges, and points independently of the computational mesh. COMSOL then within compiles a usual set of equations representative of the entire model. One can access the power of COMSOL as a standalone merchandise through a flexible graphical user interface (GUI) or by script programming in Java® or the MATLAB® language (requires the LiveLink™ for MATLAB®). Using these physics boundaries, you can perform various types of studies including:

- Linear and nonlinear studies
- Stationary and time-dependent (transient) studies
- Eigen frequency, modal, and frequency response studies

While solving the models, COMSOL gathers and solves the problem using a set of unconventional numerical analysis tools. The software runs the examination along with adaptive meshing (if designated) and fault control by means of a variety of numerical solvers. The studies can make use of multiprocessor systems and group computing, and one can run batch jobs and parametric sweeps. COMSOL generates sequences to record all stages that generate the geometry, mesh, studies and solver settings, and visualization and results exhibition. It is therefore comfortable to parameterize any part of the model: Just change a node in the model tree and re-run the sequences. The program recalls and reapplies all other info and data in the model. Partial differential equations (PDEs) form the foundation for the laws of science and provide the basis for modelling a wide range of scientific and engineering phenomena. One can use COMSOL in many application areas, including:

- Electrochemistry
- Electromagnetics
- Fluid dynamics
- Acoustics
- Bioscience
- Chemical Reactions
- Corrosion and Corrosion protection
- Heat transfer
- Microelectromechanical systems (MEMS)
- Microfluidics
- Microwave Engineering
- Multibody dynamics

- Optics
- Diffusion
- Fuel cells and electrochemistry
- Geophysics and geomechanics
- Particle tracing
- Photonics
- Plasma physics
- Semiconductor devices
- Structural mechanics
- Porous media flow
- Quantum mechanics
- Radio-frequency components
- Transport phenomena

In its basic outline, COMSOL offers modelling and examination power for many application expanses. For more than a few of the important application expanses there are also optional modules. These application-specific modules use jargons and solution approaches specific to the specific discipline, which makes it simpler making and analyzing models. The components also comprise all-inclusive model libraries with sample models that display the use of the product within its application areas.

The Wave Optics Module is of particular interests to us as it resolves glitches in the field of EM waves at optical frequencies (corresponding to wavelengths in the nano- to micrometre range). The basic equations for electromagnetics are inevitably obtainable in all the physics interface—a feature exclusive to COMSOL Multiphysics. This also brands unusual modelling effortlessly available. With the Wave Optics Module, one can do time-harmonic simulations of domains 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

This segment is useful for simulations and modelling of optical applications in almost all areas where one can find electromagnetic waves, such as:

- Optical fibres
- Photonic waveguides
- Active devices in photonics
- Photonic crystals
- Nonlinear optics
- Laser resonator design

The physics interfaces include the succeeding types of EM field simulations and handle time-harmonic, time-dependent, and Eigen frequency/Eigen mode problems:

- In-plane, axisymmetric, and full 3D electromagnetic wave propagation

- Full vector mode analysis in 2D and 3D

Material properties contain inhomogeneous and completely anisotropic materials, medium with gains or losses, and complex-valued material properties. The module supports usual post processing features and direct computation of S-parameters and far-field patterns. One can enhance ports with a wave excitation with stated power level and mode type, and add PMLs (perfectly matched layers) to simulate EM waves that propagate into an unrestrained domain. For time-harmonic replications, one can use the scattered wave or the total wave.

With COMSOL Multiphysics one can combine simulations with heat transfer, structural mechanics, fluid flow formulations, and other physical phenomena. Autonomously of the structure size, the segment houses any case of nonlinear, inhomogeneous, or anisotropic media. It also encompasses materials whose behavior vary as a function of time as well as frequency-dispersive materials.

4.2.2 MATLAB

MATLAB is a high-performance language for technical computing. It assimilates computation, visualization, and programming in a simple environment where problems and solutions are expressed in familiar mathematical notation. Typical uses include: -

- Math and computation
- Algorithm development
- Modelling, simulation, and prototyping
- Data analysis, exploration, and visualization
- Scientific and engineering graphics
- Application development, including Graphical User Interface building

MATLAB is an intelligent framework whose fundamental information component is an array that does not necessitate dimensioning. This enables you to tackle numerous specialized processing issues, particularly those with matrix and vector problems, in a small amount of the time contrasted with what it would take to compose a program in a scalar noninteractive dialect, for example, C or Fortran.

The name MATLAB remains for MATrix LABoratory. MATLAB has advanced over a time of years with contribution from numerous clients. In college situations, it is the standard instructional apparatus for early on and propelled courses in arithmetic, building, and science. In industry, MATLAB is the apparatus of decision for high-efficiency research, advancement, and investigation. It includes a group of use particular arrangements called tool kits. Important to most clients of MATLAB, tool kits enable you to learn and apply specific innovation. Tool compartments are complete accumulations of MATLAB capacities (M-documents) that extend the MATLAB condition to take care of classes of issues. Hence, it has been utilized for counts of dissipating cross area of the field scattered by the nanoparticle.

CHAPTER - 5

DESIGN AND ANALYSIS OF DIELECTRIC NANOANTENNA

In this section, the proposal and simulations of the nanoantenna assembly have been discussed. Work on two designs has been done as part of this thesis. The first one is A dielectric cuboidal nanoantenna has been designed and studied for highly directional scattering properties. In the first section, the design of the dielectric nanoantenna and its scattering properties has been discussed in detail. The second design is of a linear Quadrumer array of Silicon Nanoparticle. Various parameters are changed to see the effect on the design. All the simulations are done in FEM by use of COMSOL MultiPhysics software

5.1 Cuboidal Dielectric Nanoantenna

5.1.1 Motivation

It is apparent from past work that the actual engineering of scattering radiation depends on the electric and magnetic responses of dielectric nanoparticles when EM wave is incident on it. The unfamiliar electromagnetic scattering properties on magnetodielectric particles were first theoretically proposed by Kerker et al [130]. According to Kerker, comprehensive forward or backward scattering is conceivable, due to the interfering of magnetic and electric dipolar resonances. According to Mie theory the primary and secondary lowermost resonances of dielectric sphere-shaped nanoparticles indicates the magnetic and electric dipole terms respectively [133]. For large permittivity materials, increase in quality factor of Mie resonances leads to high scattering efficiency. In, the theoretical and experimental works by scholars on the strong electric and magnetic dipolar resonances of high-dielectric sphere-shaped particles like Si or Ge in the visible and near infrared regions have been reported based on Mie theory

[134-137]. Desired resonant wavelength can be chosen for these semiconductor nanoparticles by changing their shape and size [138, 139].

5.1.2 Design and Approach

In this section, unidirectional light scattering is shown by use of a nanoparticle of shape of cuboid with the dimensions as w=100nm, d=150nm and h= 200nm. Incident radiation is linearly polarized in the z-direction and propagating in the x-direction.

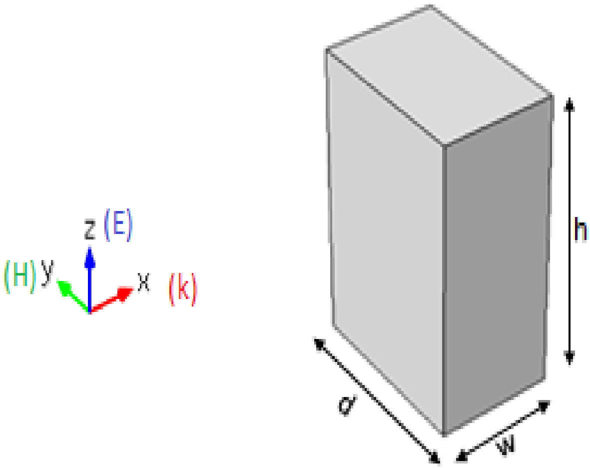


Fig. 5.1 Schematic diagram of Cuboidal Nanoparticle

A Perfectly matched layer was placed around the cuboid to study the scattering of the incident wave by the cuboid. The relative permittivity for all the calculations is ε = 16.

5.1.3 Scattering Analysis

The electric current density J and polarization P. portray the nonmagnetic particle. The electric current density and polarization brought in by external electromagnetic fields are associated by $J = -i\omega P$, where ω is the angular frequency [140, 141]. The magnetic permeability μ of the nanoparticle in non-absorbent medium is given by μ =1.The time average extinction power P_{ext} $(P_{ext} = P_{sca})$ for EM scattering in non-absorbing non-magnetic medium is given by

$$P_{ext} = \frac{\omega}{2} Im \int E_0^*(r).P(r)dV' \tag{5.1}$$

where, $E_0^*(r)$ represents the electric field of the incident EM waves, *r* symbolizes the position coordinate and volume of the scattering object is given by V'. *P(r)* is denotes the position coordinate. *P(r)* is defined as

$$P(r) = \varepsilon_0(\varepsilon_r - 1)E(r) \tag{5.2}$$

where ε_0,ε_r have their regular meanings and *E(r)* is the total electric field which is the summation of scattered and incident electric field. From multipole decomposition of scattering power, we get,

$$p_{sca} \approx \ p^p{}_{sca} + p^m{}_{sca} + p^Q{}_{sca} + p^M{}_{sca} \ + \cdots \tag{5.3}$$

where, $p^p{}_{sca}$is scattering power for electric dipole, $p^m{}_{sca}$ is scattering power for magnetic dipole and $p^Q{}_{sca}$, $p^M{}_{sca}$ are quadrupoles. Then the total scattering power is specified by

$$p_{sca} = \frac{c^2{k_0}^4 Z_0}{12\pi}|p|^2 + \frac{c^2{k_0}^4 Z_0}{12\pi}|m|^2 + \frac{c^2{k_0}^6 Z_0}{40\pi}\sum\left|Q_{\alpha'\beta'}\right|^2 + \frac{c^2{k_0}^6 Z_0}{160\pi}\sum\left|M_{\alpha'\beta'}\right|^2 + \ldots \tag{5.4}$$

where, *m* is the magnetic dipole moment, *p* is the electric dipole moment, *Q* is electric quadrupole tensor and *M* is the magnetic quadrupole tensor. Scattering powers at higher order modes are insignificant so we can disregard the higher order modes in calculations.

$$p = \varepsilon_0(1 - \varepsilon_r)\int_v E(r')dV' \tag{5.5}$$

$$m = \frac{i\omega\varepsilon_0(1-\varepsilon_r)}{2c}\int_v [r\times E(r')]dV' \tag{5.6}$$

where, all variables have their regular meaning,

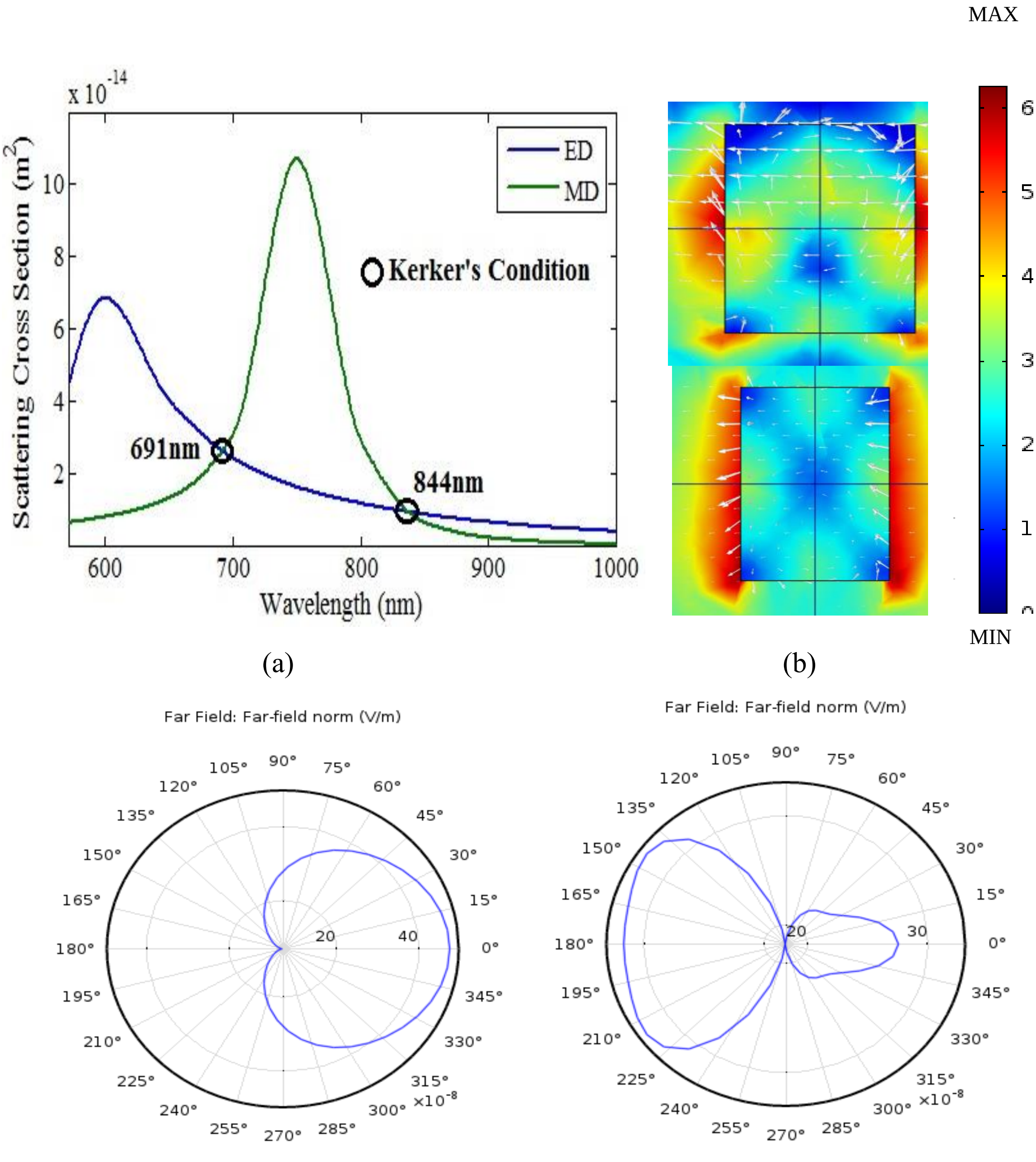
From the Eq. (4) - (6) the scattering cross section (σ_{sca}) associated to separate multipole can be calculated by merely normalizing every scatter power by the incident power density (I_0), given by

$$\sigma^p{}_{sca} = \langle p_{sca,ED}\rangle / I_0 \tag{5.7a}$$

$$\sigma^{m}{}_{sca} = \langle p_{sca,MD} \rangle / I_0 \tag{5.7b}$$

5.1.4 Simulation and Results

The scattering spectrum of Si cuboid nanoparticle has been obtained as shown in figure 5.2 (a, b, c & d). Complete forward scattering takes place at 844nm and backward scattering takes place at 691nm in case of Si nanoparticle

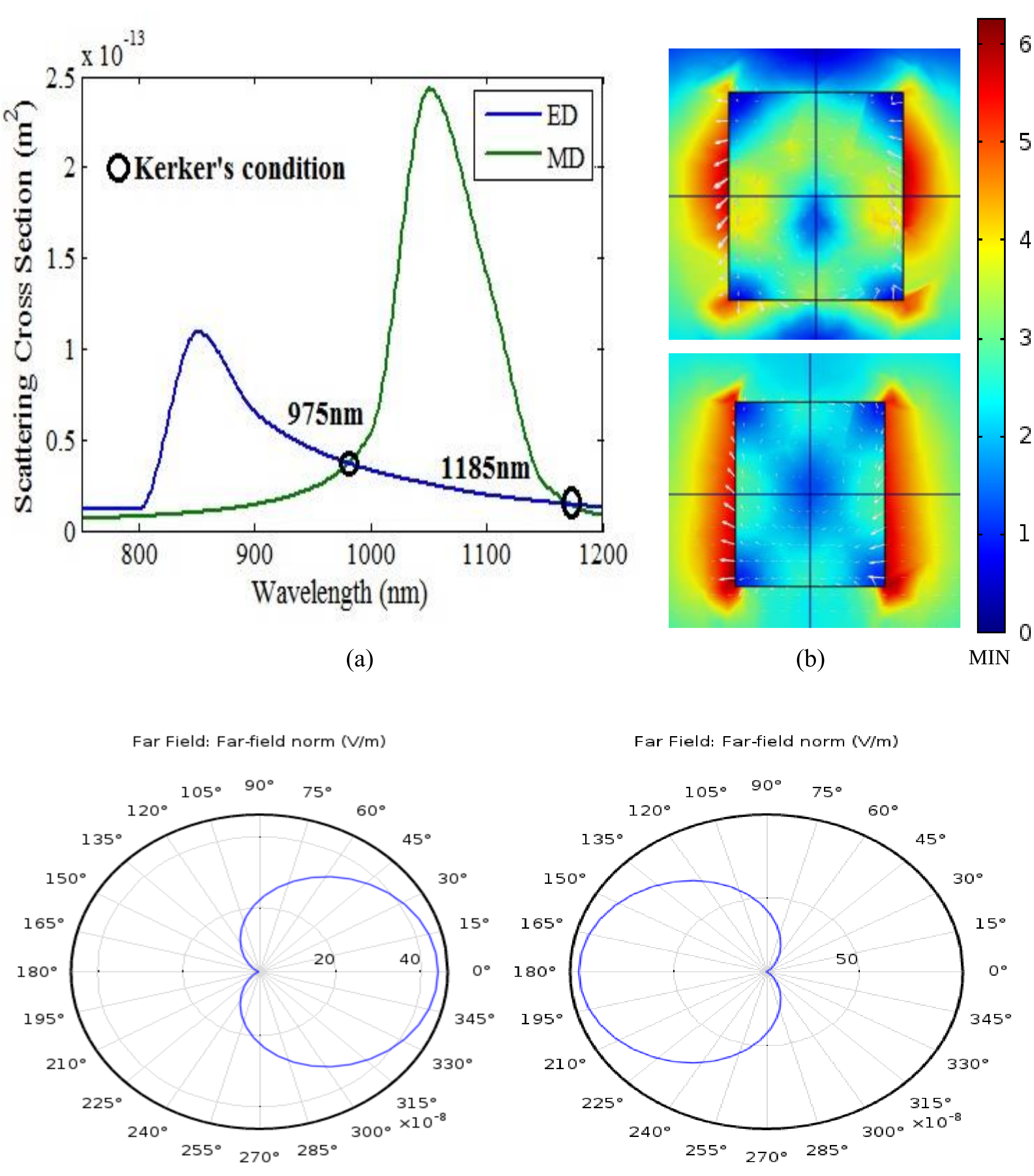


(a) (b)

(c) (d)

Fig 5.2 Si nanoparticle (a) Scattering Cross Section (b) Normalized 2D polarization distribution patterns for MD at λ=750 nm and ED at λ=600 nm (c) Forward scattering at 844nm (d) Backward Scattering at 691nm

The scattering spectrum of Ge cuboid nanoparticle has been obtained as shown in figure 5.3(a, b, c & d). Complete forward scattering takes place at 1185nm and backward scattering takes place at 975nm. These are the wavelengths where electric and magnetic dipole moments cross each other



(a) (b)

(c) (d)

Fig 5.3 Ge nanoparticle (a) Scattering Cross Section (b) Normalized 2D polarization distribution patterns for MD at λ=1050 nm and ED at λ=850 nm (c) Forward scattering at 1185nm (d) Backward Scattering at 975 nm

5.2 Linear Quadrumer Array Dielectric Nanoantenna

5.2.1 Motivation

Directional fano resonance existence in metallic symmetry breaking nanostructures has been an area of interest for scholars over the past few years. Different number of particles and of different shapes have been theoritically and experimentally used for generation of strong fano-resonance. At the resonant wavelength where the narrow dip occurs the nanoparticle exhibit directionality and hence can be utilised as nanoantenna.

It is only recently that the concept of Fano resonance has been extended to dielectric materials having both electric and magnetic responses. Experimentally it has been demonstrated that directional Fano resonance can be seen in Si homodimers and hetrodimers [40]. The sizes of these spheres varied from 80nm to 200nm as they exhibit strong magnetic response in the visible frequency range. The particles were kept close to each other so that the magnetic dipole contructively interacts and electric dipole destructively interacts to give a broad electric dipole moment.

These magnetic based Fano resonance have important usage in the unit cells of metamaterials. As the Fano resonance provides directional scattering it can also be used as optical switch in the field of nano-optics and nanotechnology. These advantages gives need to explore better and newer designs for directional Fano resonance based nanoantenna.

5.2.2 Design and Approach

The design uses four spherical Si nanoparticles (max size of 50nm) in different linear arrangement and sizes. The linear arrangment is varied by changing the distance *d* (= -10 nm, 0, +10 nm) between the four Si nanoparticles . The other variation is size is brought about by changing the size of the sphere. In the first variation the size of the nanoparticle is linearly reduced by a constant value of 5nm. The in the other the size of the sphere is kept same at 50 nm. This gives us six combinations for the Si sphere.

They are: -

- Si spheres with reducing size (50,45,40 ans 35 nm) and *d* = -10nm
- Si spheres with reducing size (50,45,40 ans 35 nm) and *d* = 0
- Si spheres with reducing size (50,45,40 ans 35 nm) and *d* = +10nm
- Si spheres with same size (50nm) and d = -10nm
- Si spheres with same size (50nm) and d = 0
- Si spheres with same size (50nm) and d = +10nm

In all the above cases, the Incident radiation is linearly polarized in the z-direction and propagating in the x-direction. The relative permittivity of Si for all calculation purposes is taken from Palik.

5.3.3 Simulation and Results

The forward and backward scattering for each of the cases were calculated. Also the scatterinf cross section was evaluated to verify the broad electric dipole moment and narrow coupled magnetic moment. The direction of incident field has been kept unchanged in all the cases. The Fano resonance for forward scattering for all the combinations occurs at λ = 500nm and backward scattering at λ = 450 nm. This is due to the same size of Si sphere used. To change the wavelength size of the sphere will have to be changed

- **Si spheres with reducing size (50,45,40 ans 35 nm) and d = -10nm.**

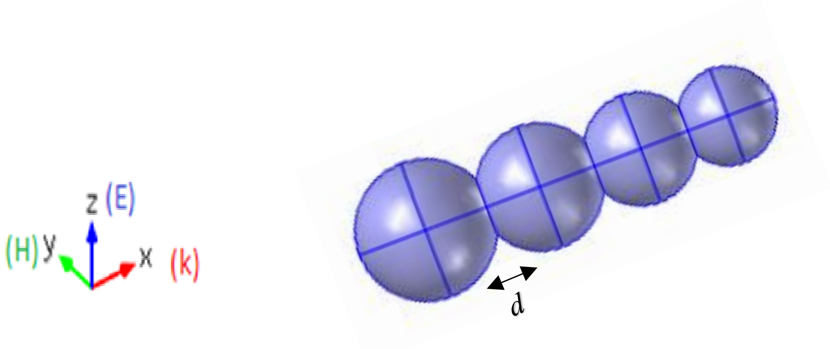


Fig 5.4 Schematic of Si reducing size quadrumer with d = -10nm

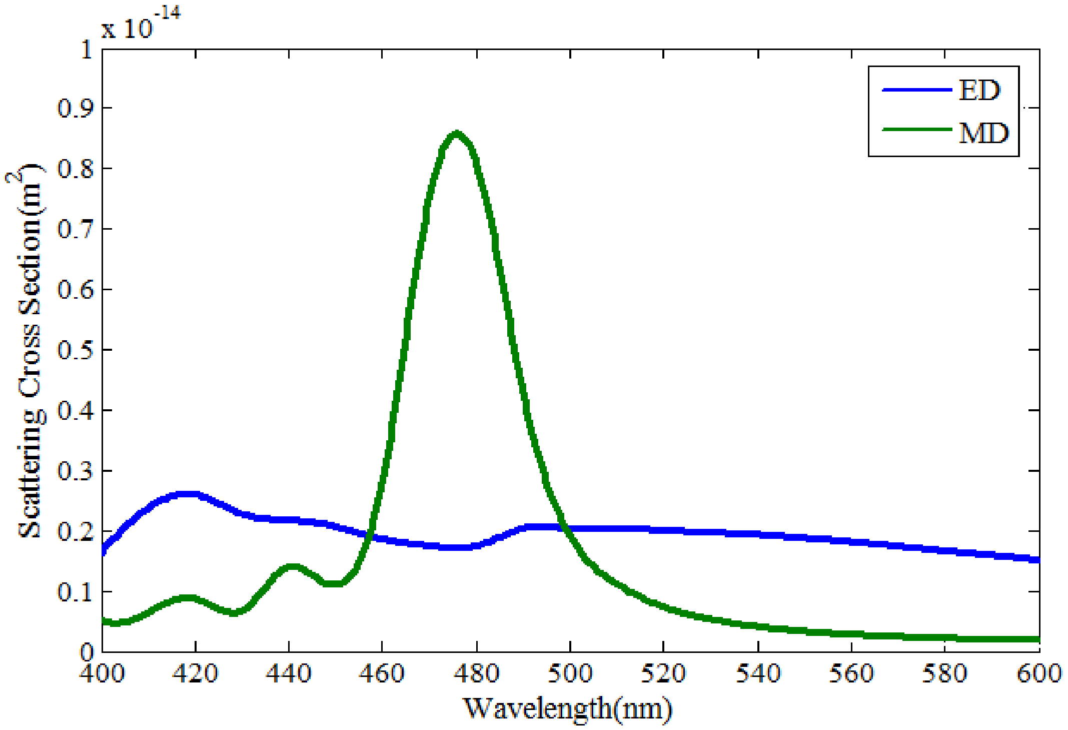


Fig 5.4(a) Narrow peak in the magentic response with broad electric response

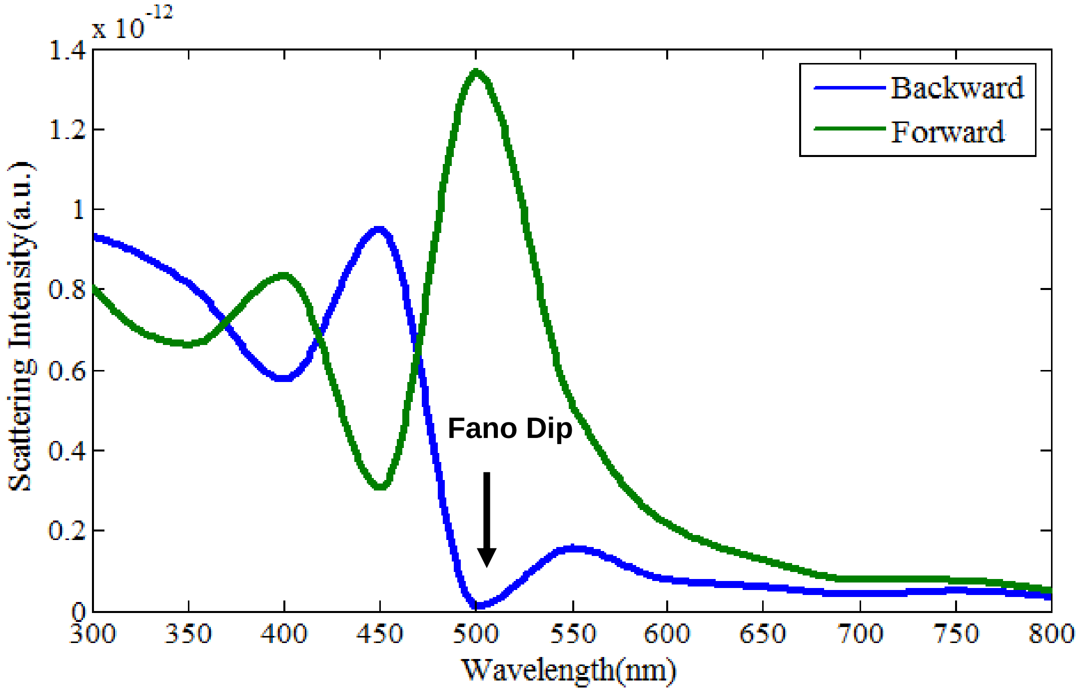
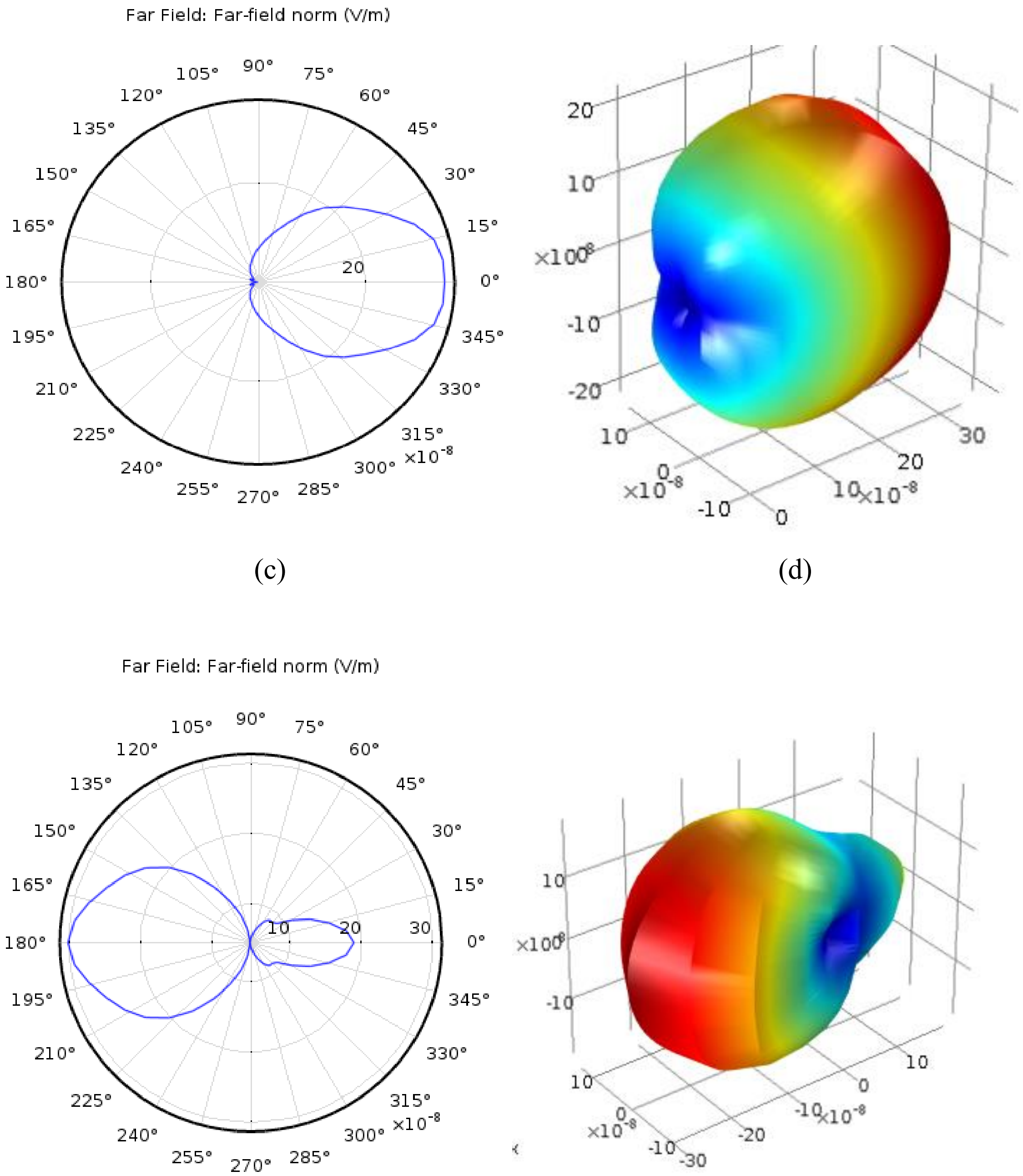


Fig 5.4(b) Fano dip seen at λ = 500nm



(c) (d)

(e) (f)

Fig 5.4 At λ = 500nm (c) Polar plot and (d) 3D polarisation; at λ = 450nm (e) Polar plot and (f) 3D polarisation

- **Si spheres with reducing size (50,45,40 ans 35 nm) and *d* = 0**

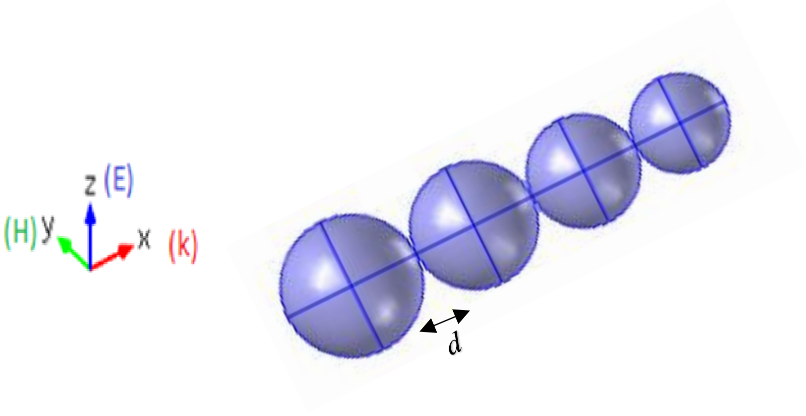


Fig 5.5 Schematic of Si reducing size quadrumer with d = 0

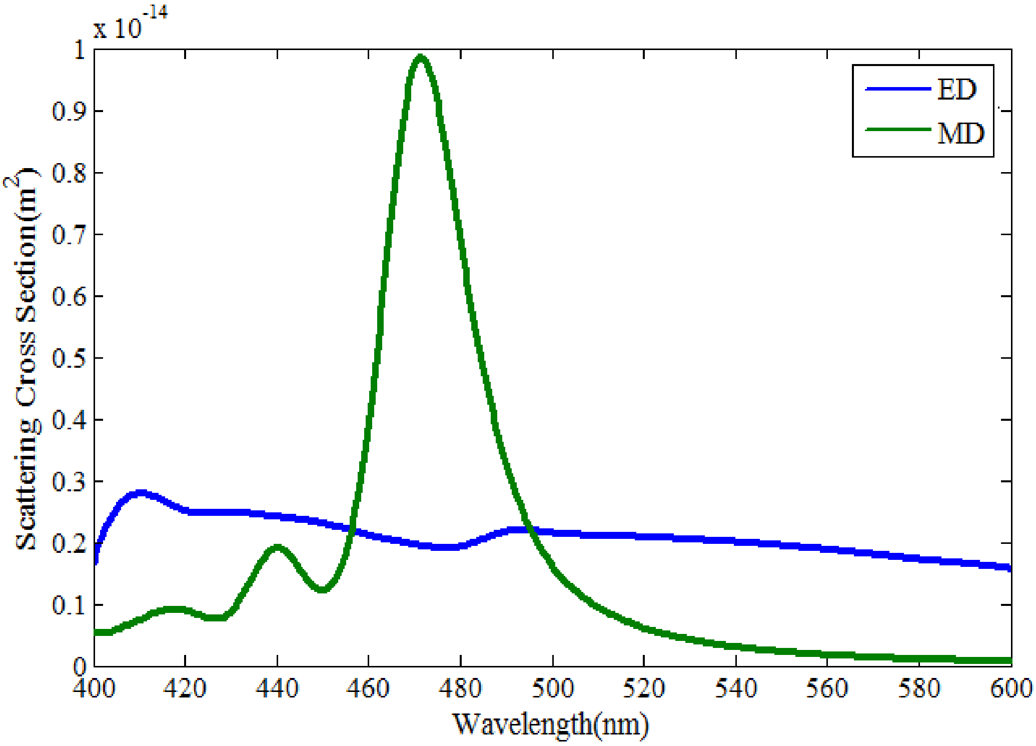


Fig 5.5(a) Narrow peak in the magentic response with broad electric response

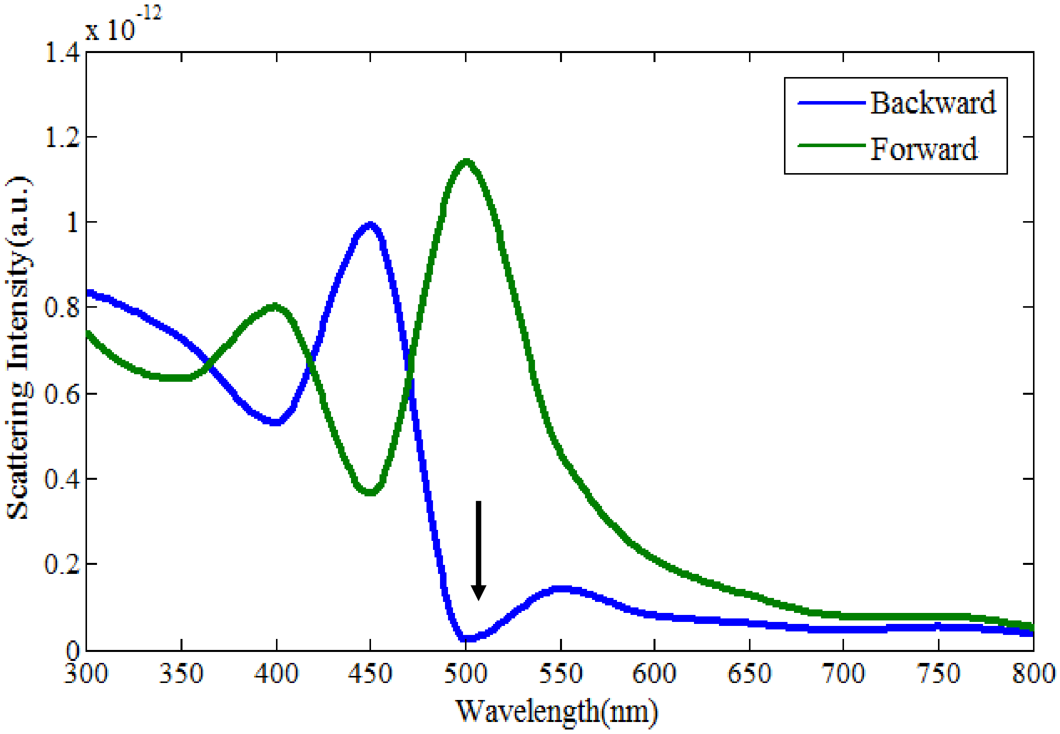
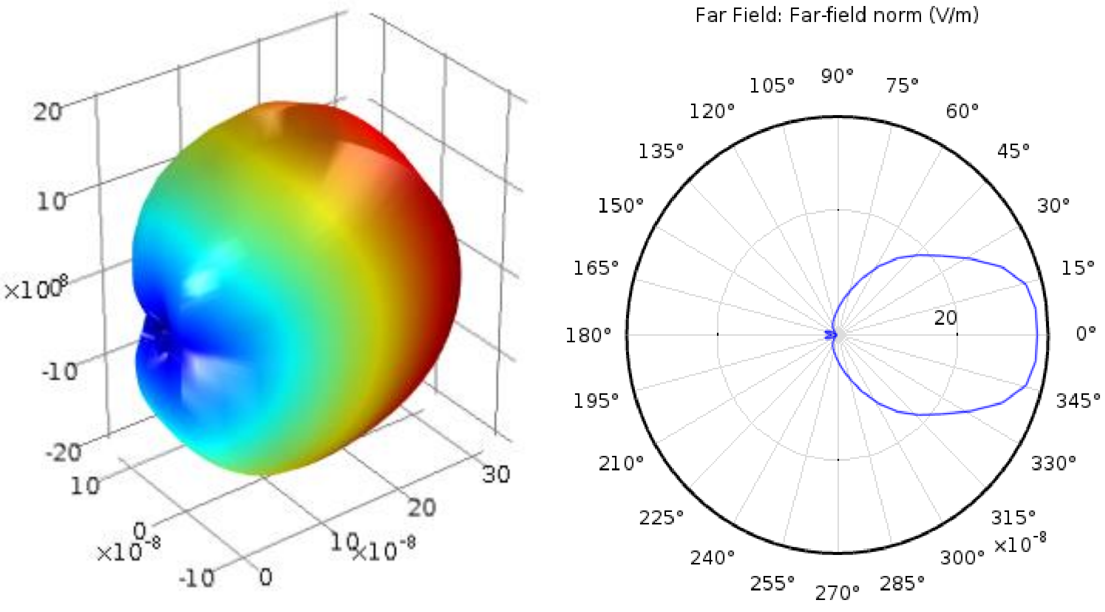
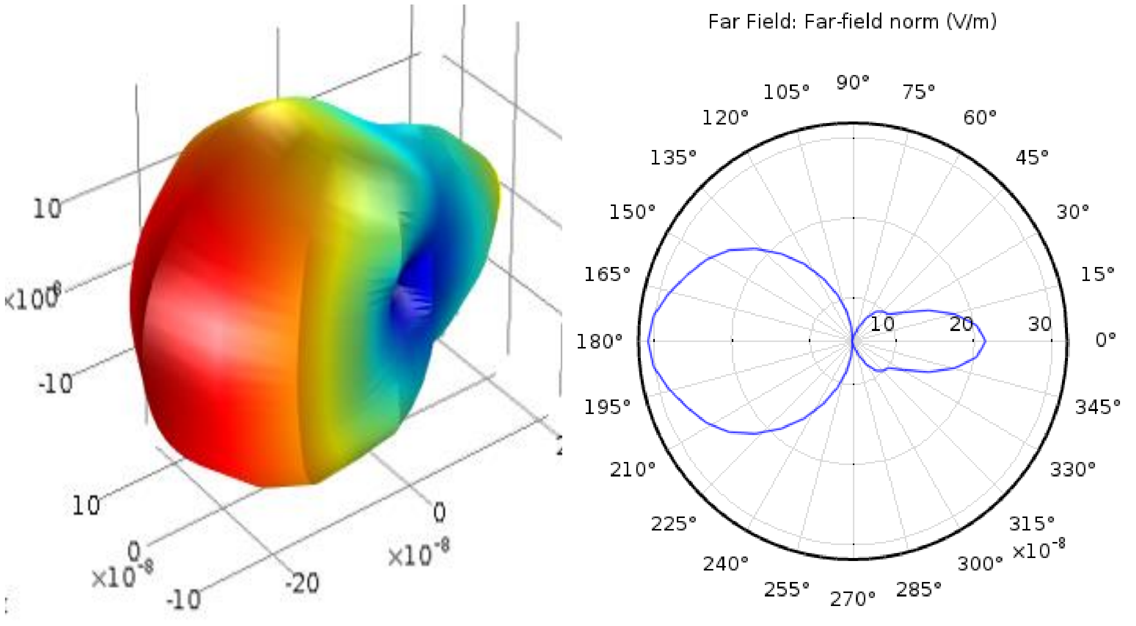


Fig 5.5(b) Fano dip seen at λ = 500nm



(c) (d)



(e) (f)

Fig 5.5 At λ = 500nm (c) Polar plot and (d) 3D polarisation; at λ = 450nm (e) Polar plot and (f) 3D polarisation

- **Si spheres with reducing size (50,45,40 ans 35 nm) and *d* = +10nm**

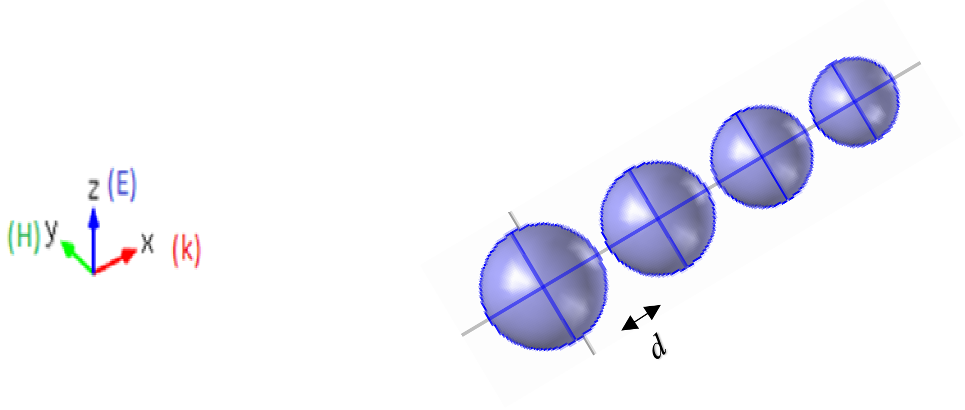


Fig 5.6 Schematic of Si reducing size quadrumer with d = +10nm

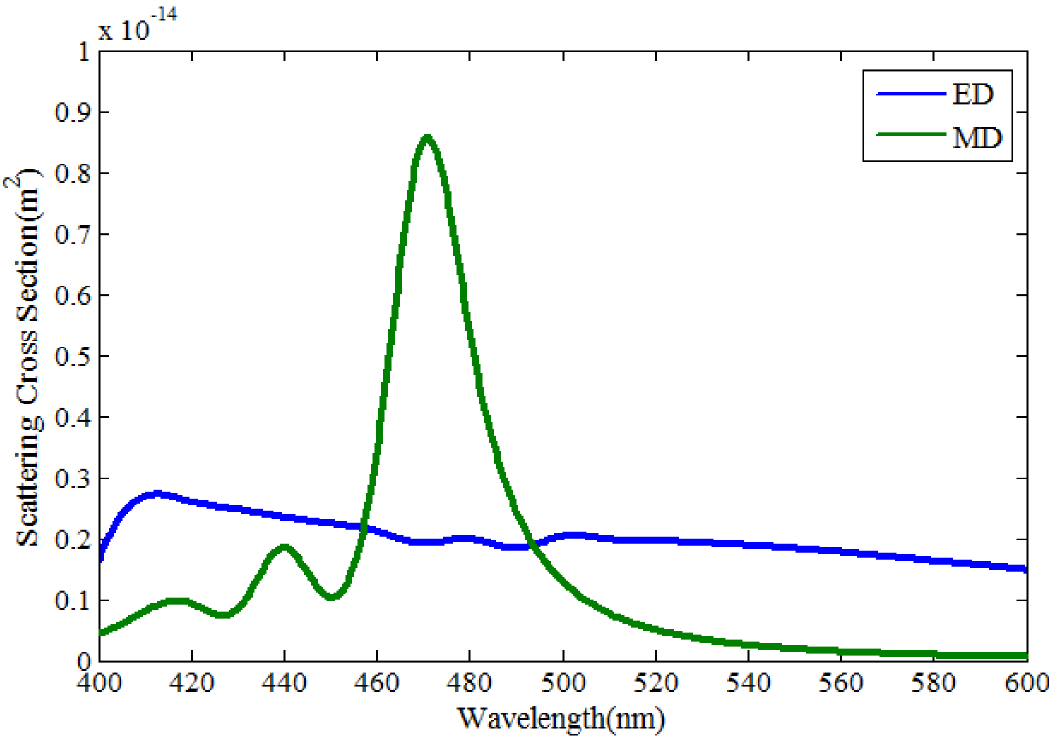


Fig 5.6(a) Narrow peak in the magentic response with broad electric response

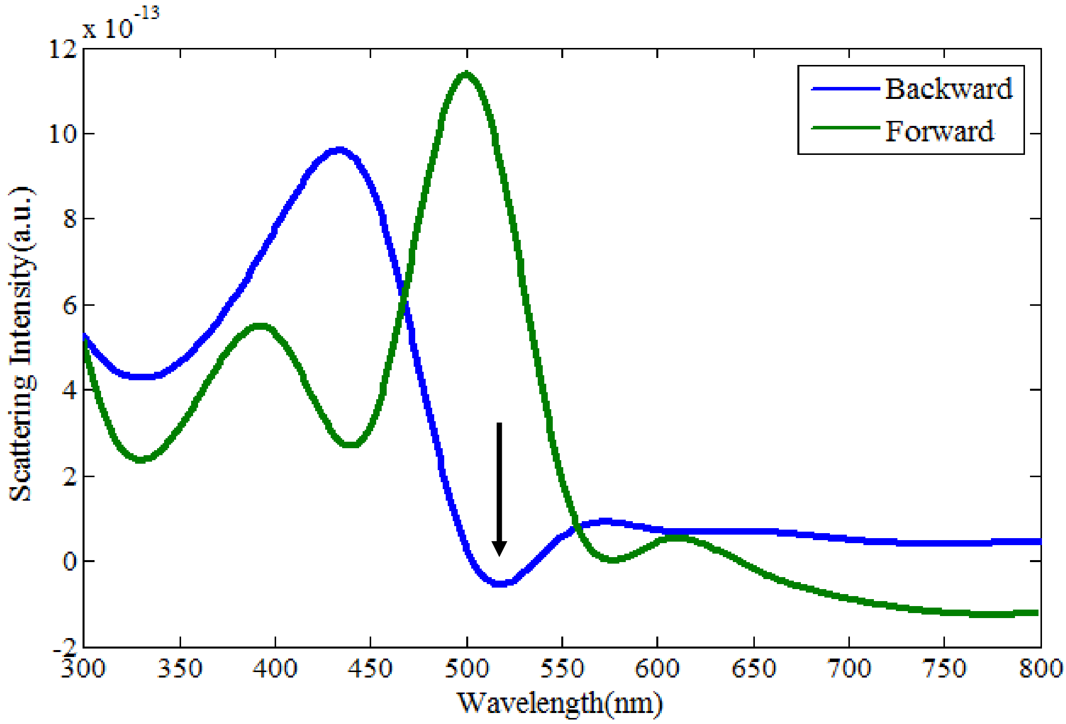
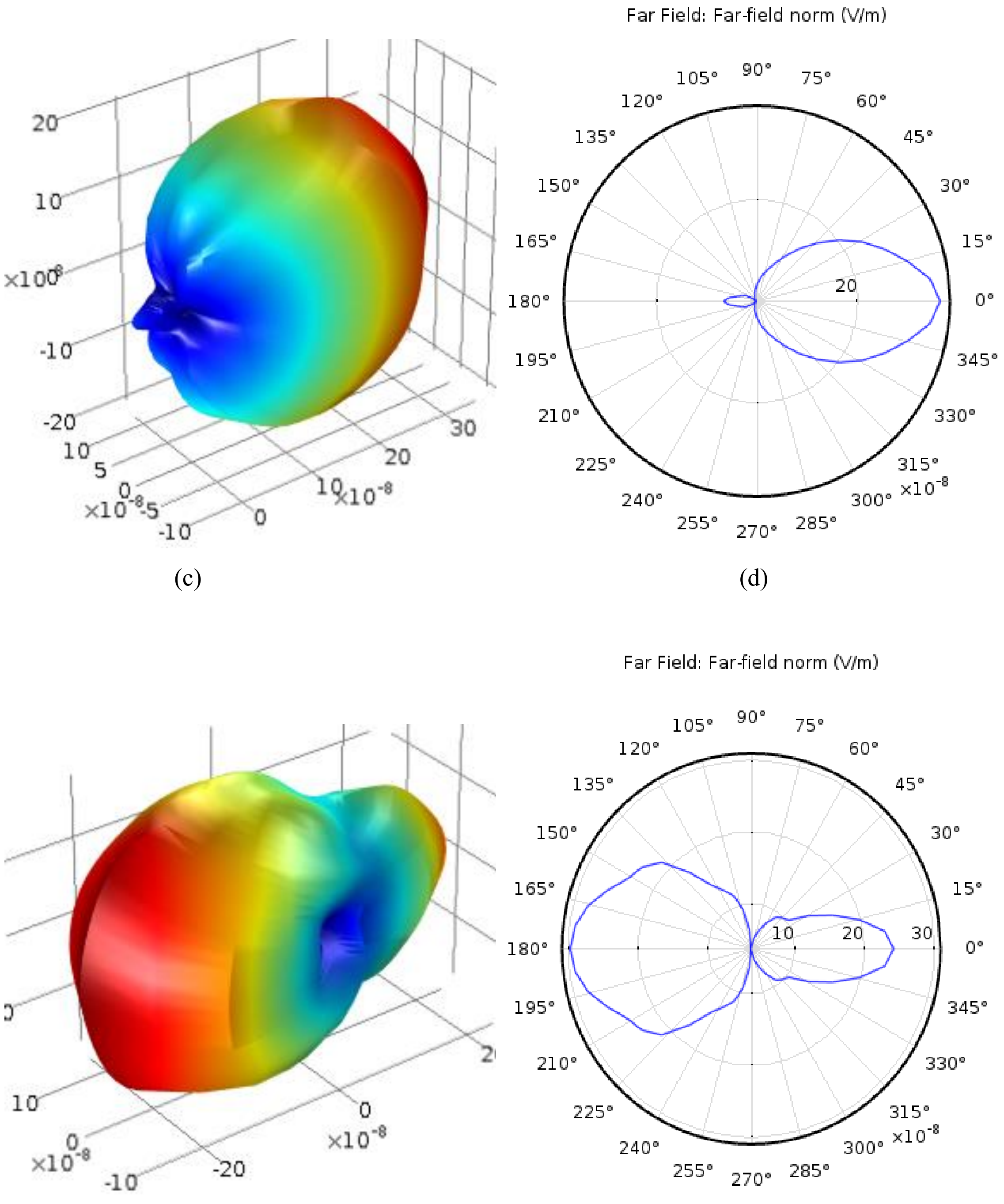


Fig 5.6(b) Fano dip seen at $\lambda = 500$nm


Far Field: Far-field norm (V/m)

Far Field: Far-field norm (V/m)

(c) (d)

(e) (f)

Fig 5.6 At λ = 500nm (c) Polar plot and (d) 3D polarisation; at λ = 450nm (e) Polar plot and (f) 3D polarisation

- **Si spheres with same size (50nm) and d = -10nm**

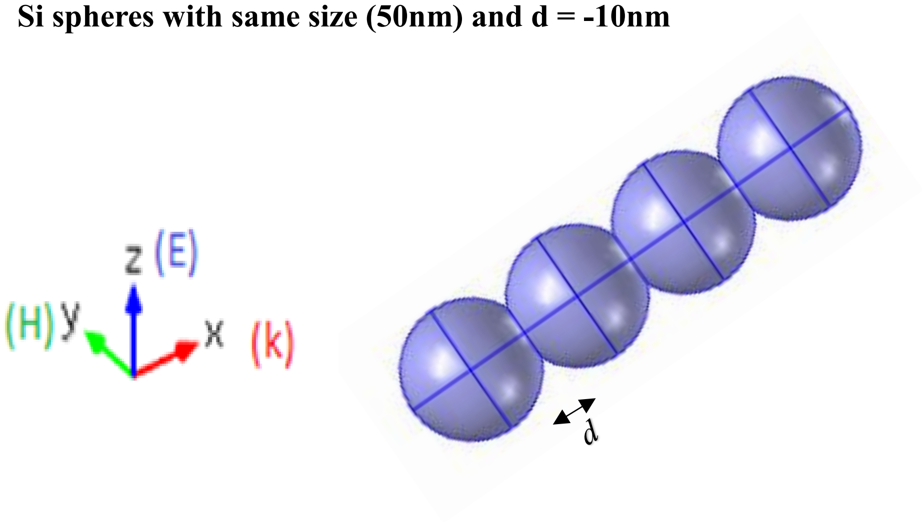


Fig 5.7 Schematic of Si same size quadrumer with d = -10nm

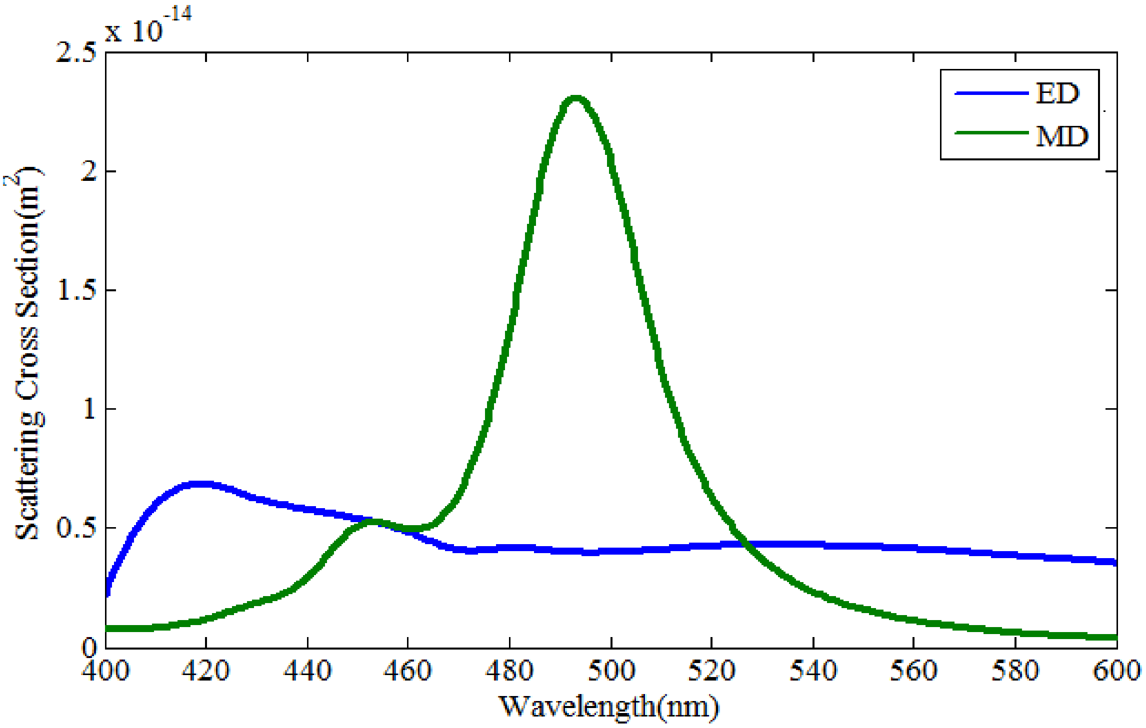


Fig 5.7(a) Narrow peak in the magentic response with broad electric respon

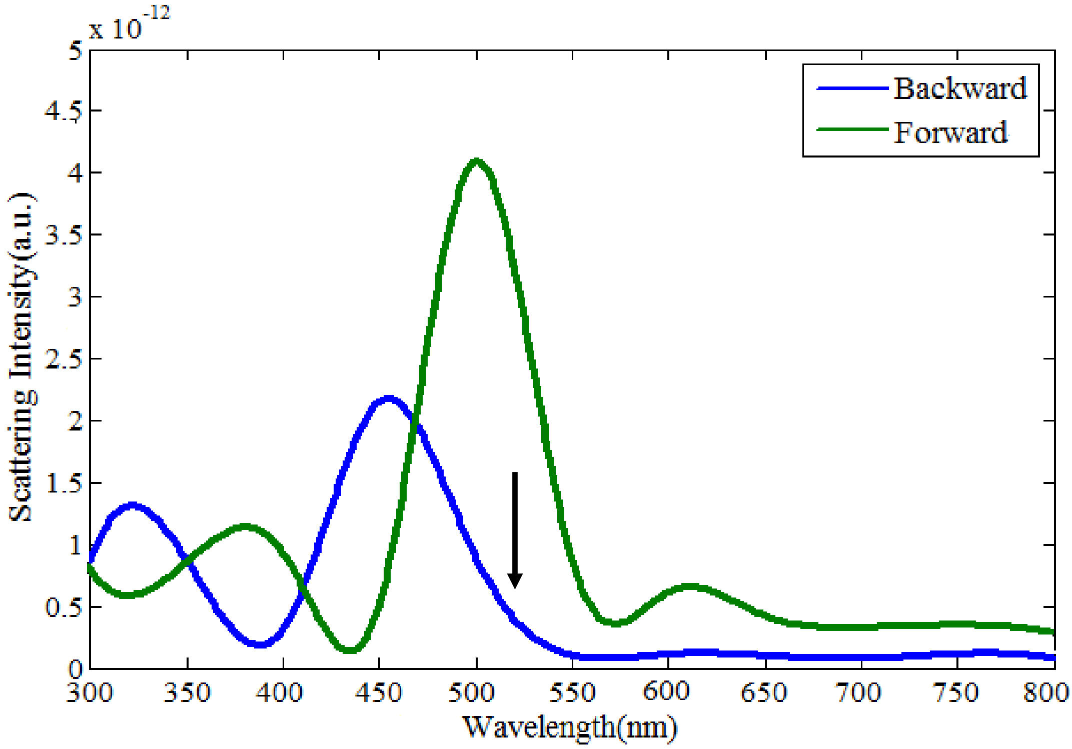
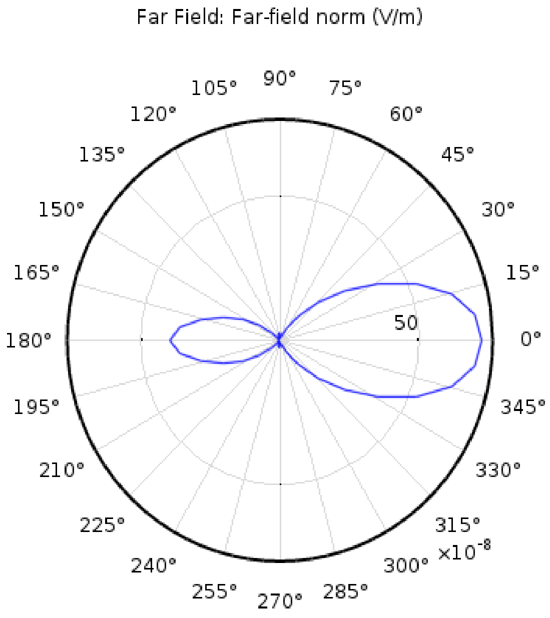
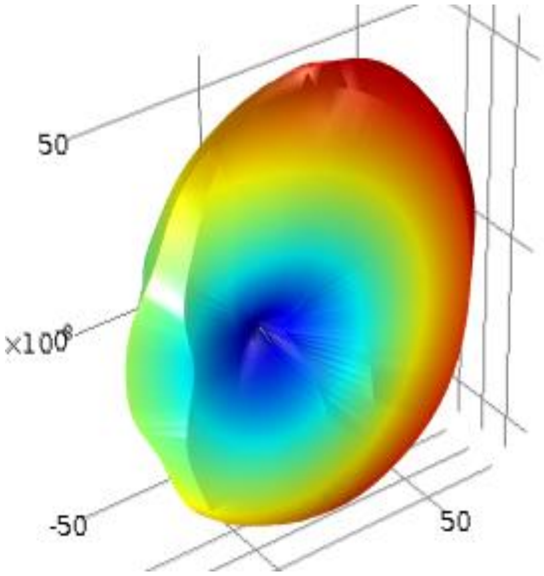
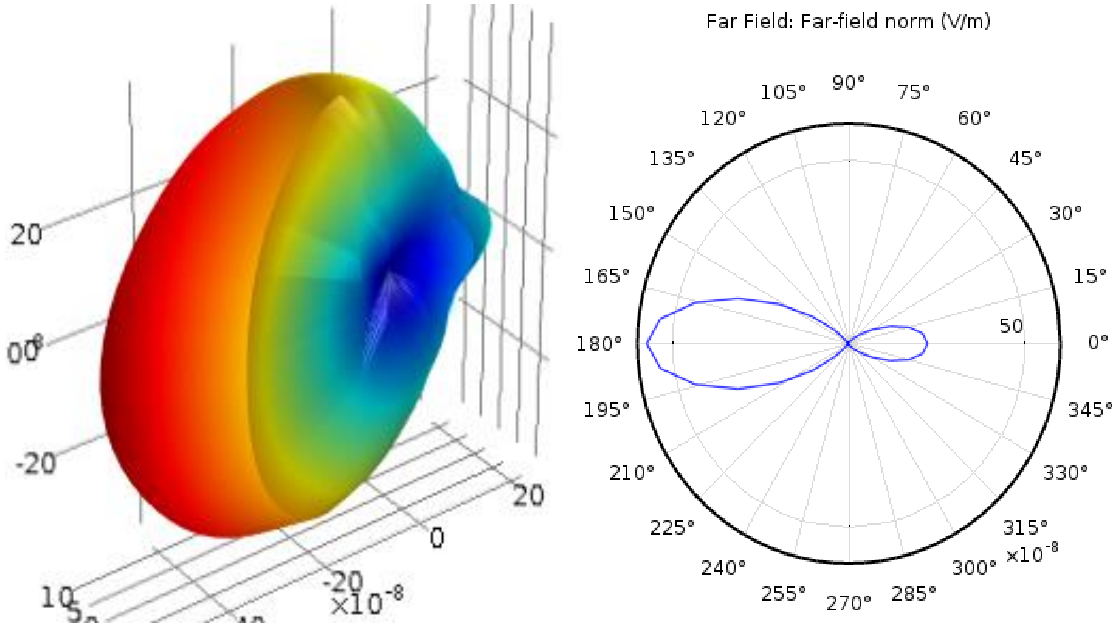


Fig 5.7(b) Fano dip seen at λ = 500nm





(c) (d)



(e) (f)

Fig 5.7 At λ = 500nm (c) Polar plot and (d) 3D polarisation; at λ = 450nm (e) Polar plot and (f) 3D polarisation

- **Si spheres with same size (50nm) and d = 0**

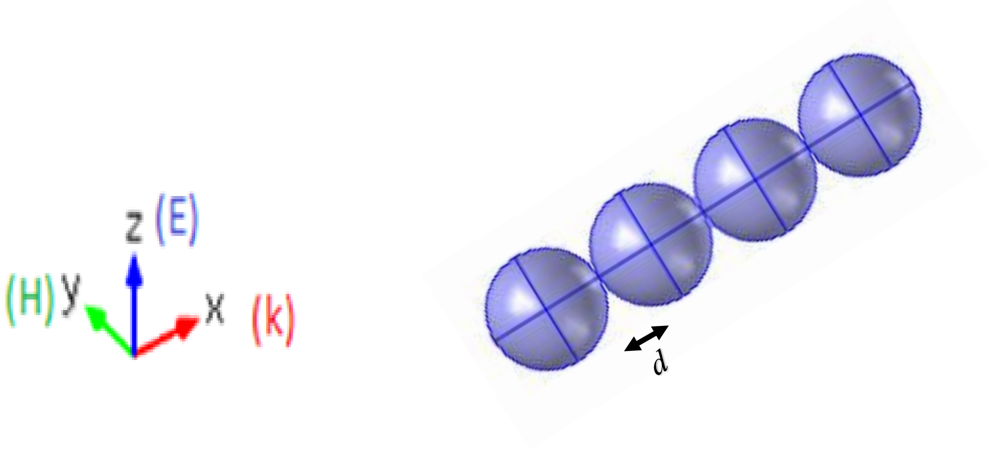


Fig 5.8 Schematic of Si same size quadrumer with d = 0

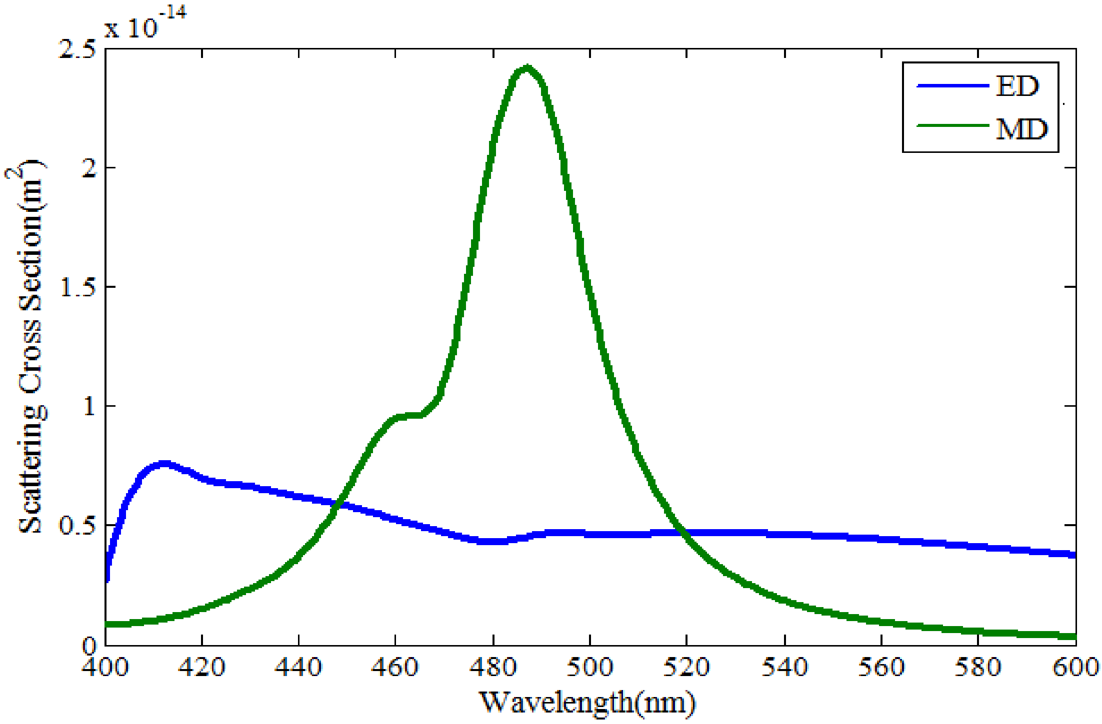


Fig 5.8(a) Narrow peak in the magentic response with broad electric respon

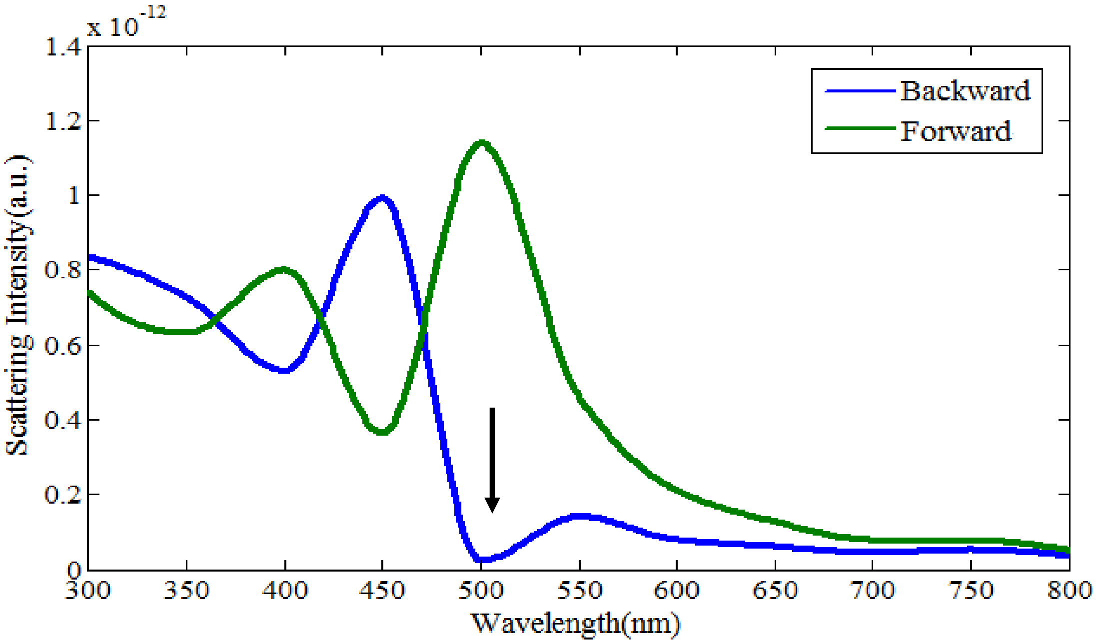
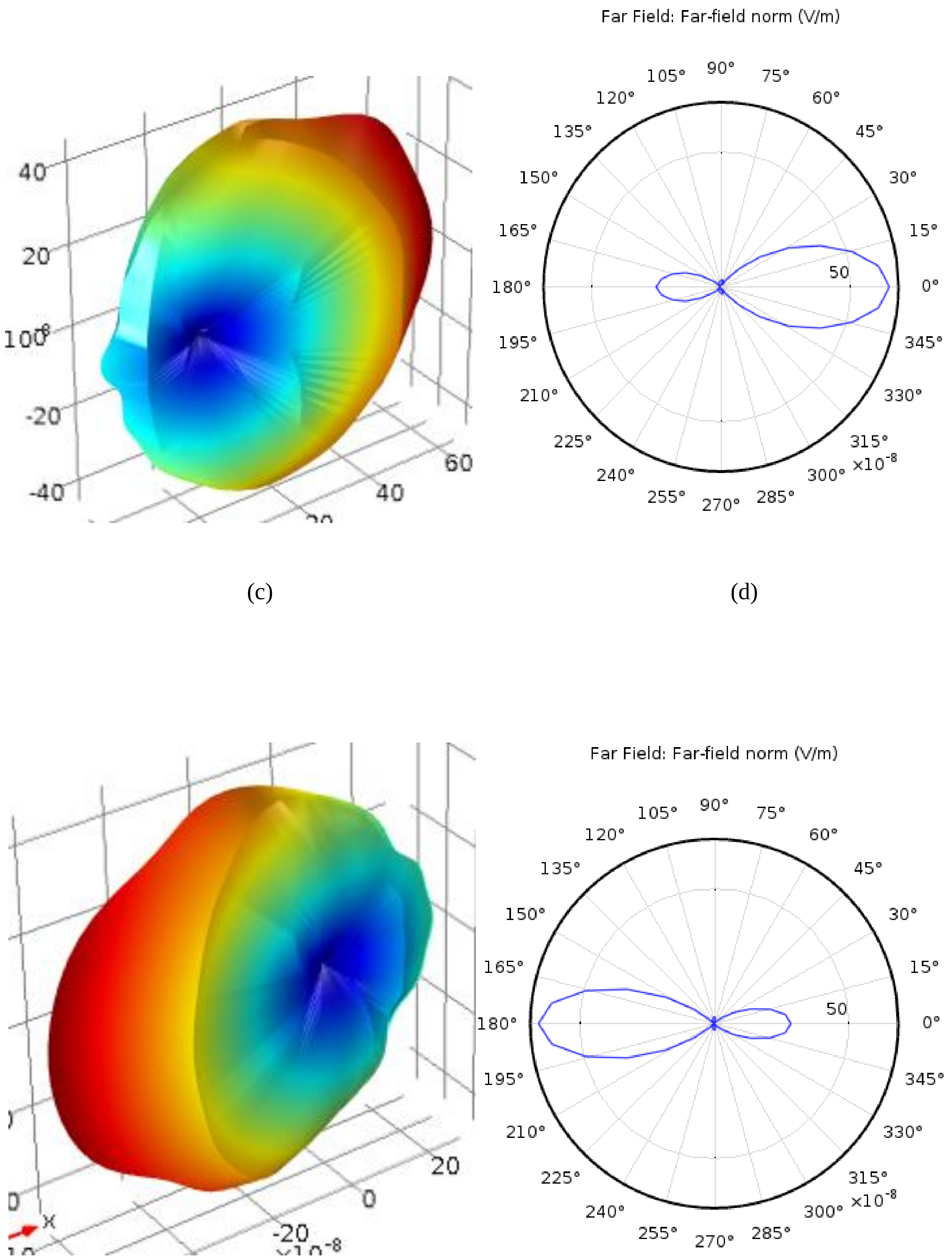


Fig 5.8(b) Fano dip seen at $\lambda = 500$nm



(c) (d)

(e) (f)

Fig 5.8 At λ = 500nm (c) Polar plot and (d) 3D polarisation; at λ = 450nm (e) Polar plot and (f) 3D polarisation

- **Si spheres with same size (50nm) and d = +10nm**

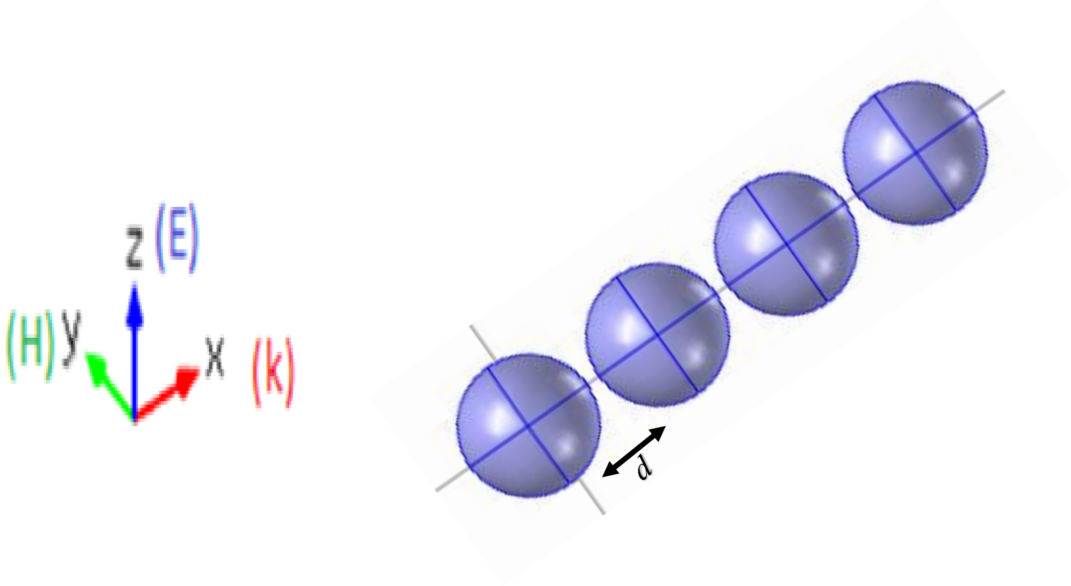


Fig 5.9 Schematic of Si same size quadrumer with d = +10nm

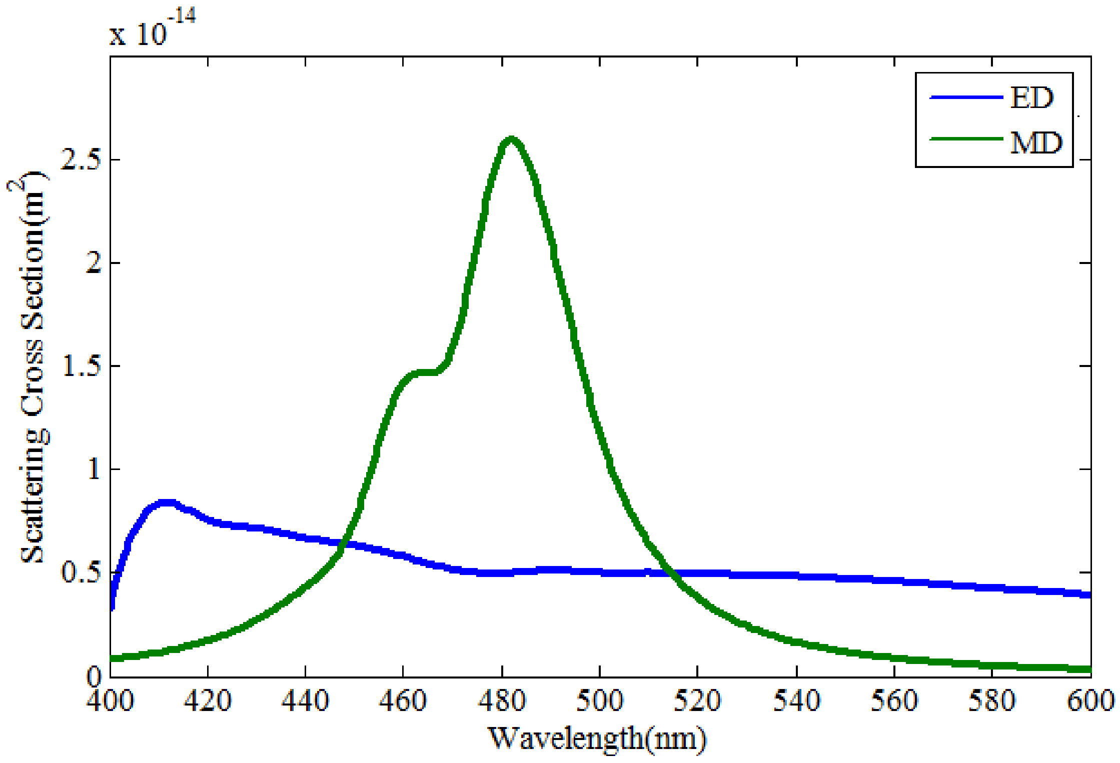


Fig 5.9(a) Narrow peak in the magentic response with broad electric respon

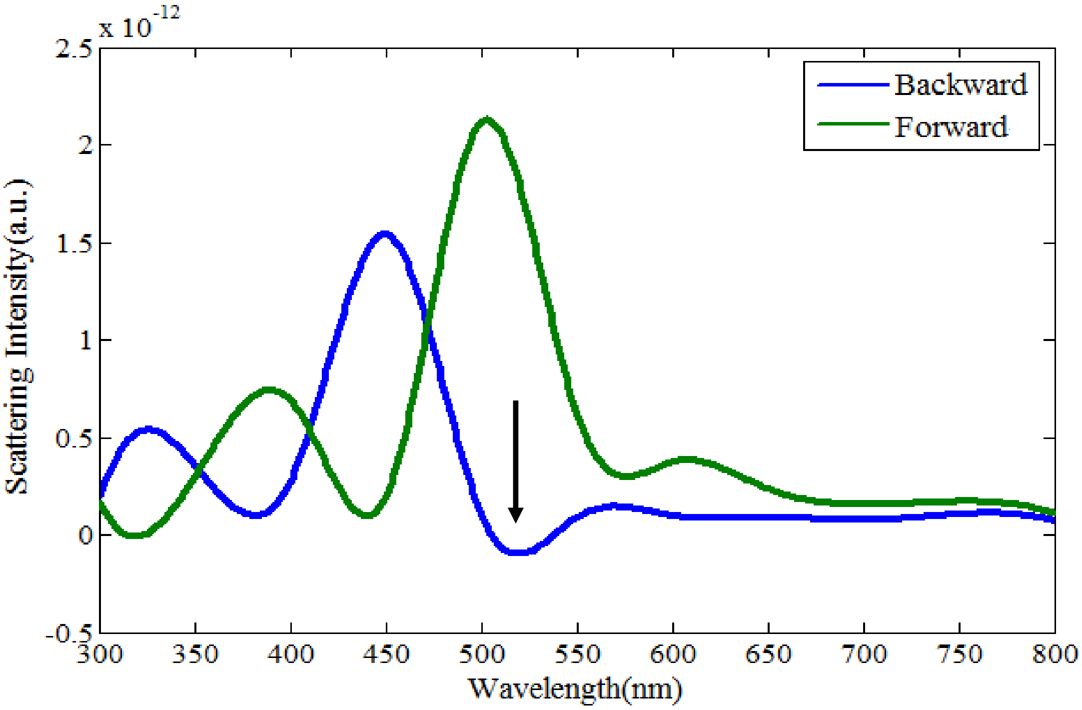
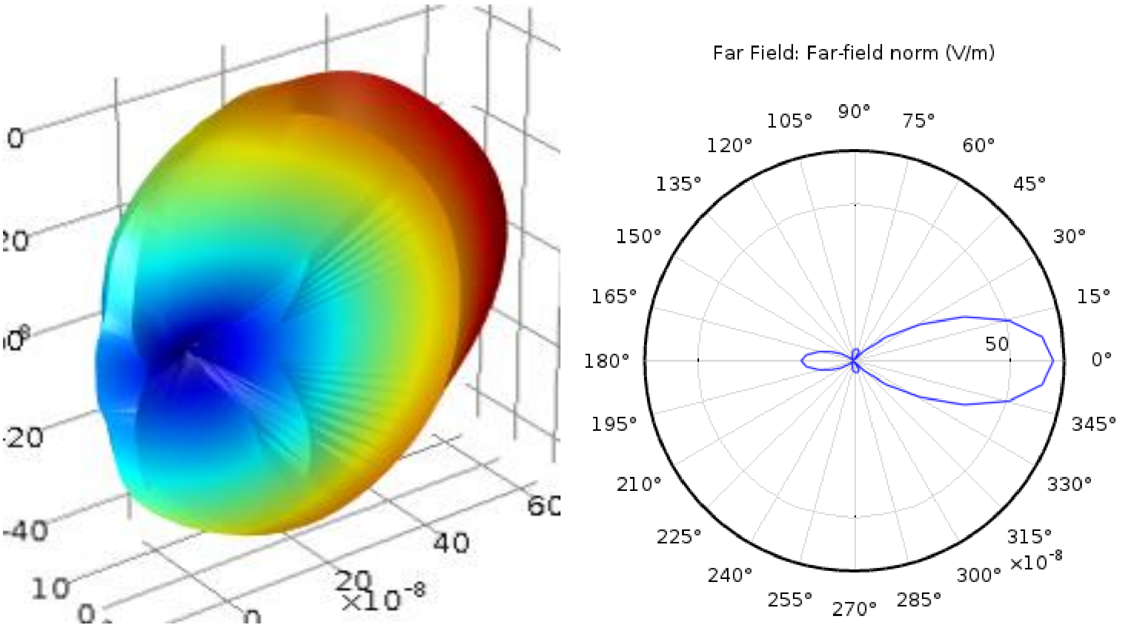
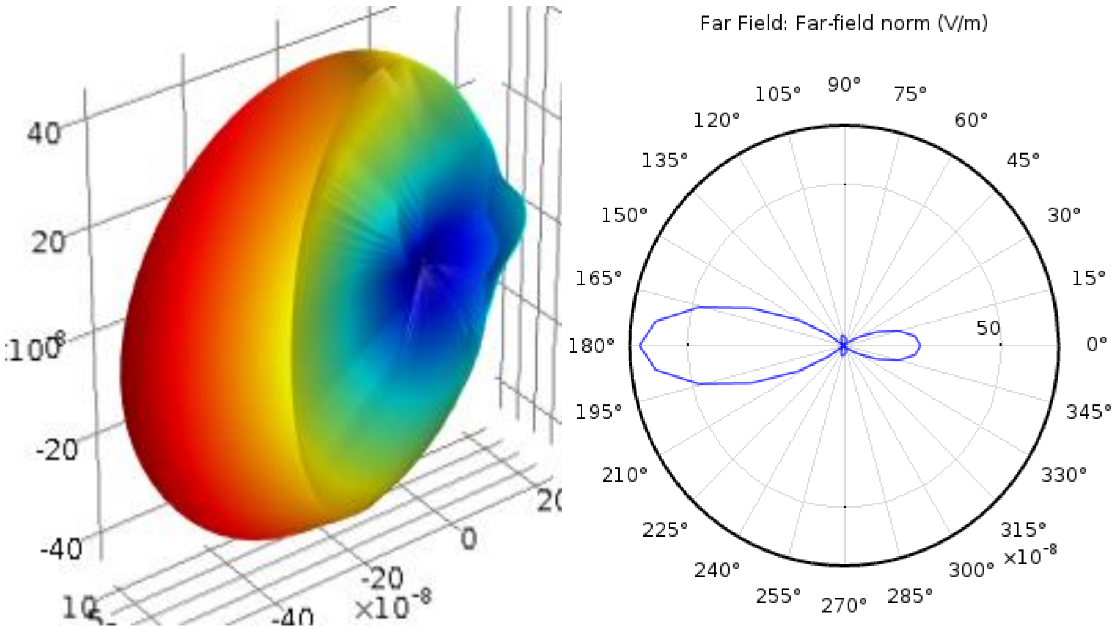


Fig 5.9(b) Fano dip seen at λ = 500nm



(c) (d)



(e) (f)

Fig 5.9 At λ = 500nm (c) Polar plot and (d) 3D polarisation; at λ = 450nm (e) Polar plot and (f) 3D polarisation

The directivity for designs in preceding paragraphs was also calculated and listed below:-

Name of design	Paramter	Forward Sattering (nm)	Diretivity	Backward Scatterng (nm)	Directiity
Cuboid	**Si**	844	2	691	1.36
	Ge	1185	2.133	975	1.85
Si reducing size quadrumer	***d* = -10nm**	500	2.5	450	1.99
	***d* = 0**	500	2.64	450	1.88
	***d* = +10nm**	500	3	450	1.84
Si same size quadrumer	***d* = -10nm**	500	2.7	450	3.92
	***d* = 0**	500	3.42	450	3.94
	***d* = +10nm**	500	3.87	450	4.35

Table 5.1 Table for directivity of various designs

5.3 Inferences

From above designs and results following can be inferred: -

- The scattering properties of dielectric nanoparticle is highly dependent on material and its shape.
- The orientation of the electric field changes the scattering properties of the nanoparticle.
- The resonant wavelength so desired can be tuned by changing the above parameters.
- The magnetic resonance and electric resonance wavelengths do not change until and unless the size or material is varied. This property makes it highly stable for operations like switching in nano circuits
- The interaction between different size nanoparticles is better as the 3D polarization of linear quadrumer gives almost complete forward scattering with azimuth width also being satisfactory.
- Though the directivity in homoparticles has increased the azimuth width of the polarization has reduced.

CHAPTER - 6

CONCLUSION AND FUTURE SCOPE

6.1 Conclusion

In this thesis, presents theoretical study and numerical evaluation of dielectric nanoantenna comprising of single and multiple nanoparticles. Both the approaches are completely different from each other. The first one, scattering by a dielectric nanocuboid has been confirmed for nanoantenna applications in visible and NIR based on the Generalized Kerker's Condition. A single nanoparticle exhibits properties to behave like a nanoantenna. It was seen in various works the antenna can be made highly directive by adding similar size particle in an array. This highly directive nanoantenna can be used as a tool to manipulate light at subwavelength sizes.

The second one comprises of linear arrangement of four nanoparticles and is based on Fano resonance. It is only recently that the concept of Fano resonance has been extended to dielectric material. The interaction between two or more spheres leads to a broad electric resonance and narrow magnetic resonance and hence the Fano dip is generated at a particular wavelength. This wavelength is size, material, and gap dependent. One can see forward scattering at the wavelength where Fano dip occurs.

6.2 Future scope

The research in field of all-dielectric nanoantennas has great scope in the field of nanophotonics, nano-optics, remote sensing and so on. The advantage of use of dielectric material which gives low dissipative losses gives a cutting-edge breakthrough in the field of nanoantenna.

Earlier designs and fabrication included developing optical nanoantenna which analogous to RF regime. However, as the design in this thesis arbitrary designs can also be thought in the visible and NIR.

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