NANOPHOTONICS FOR 21st CENTURY: FROM FABRICATION TO APPLICATION

By

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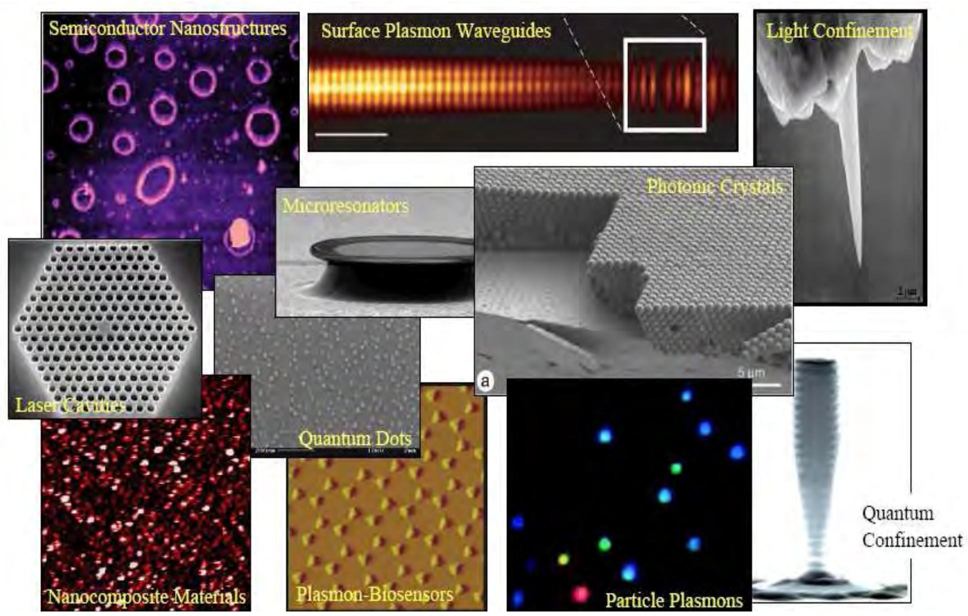
Nanophotonics and Nanoplasmonics Today Particle



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Abstract

This project work gives a panoramic view of the past activities, present development and future directions with multi-facets application possibilities of nanophotonics. Nanophotonics is a new paradigm of nanoscience for 21st century, which deals with optical processes at the much smaller length scale than the wavelength of optical radiation. The nanoscale matter-radiation interaction includes nanoscale confinement of radiation, nanoscale confinement of matter, and nanoscale photo-physical or photochemical transformation, offer numerous opportunities for both fundamental research and technological applications. Two main broad areas of Nanophotonics are Surface Plasmonics and Photonic Crystal. Surface Plasmonics are collective charge oscillations that occur at the interface between conductors and dielectrics. Plasmonic devices have already shown to be excellent candidates for a number of different optical applications. Photonic Crystals are artificial periodic structures whose dielectric constant is periodically modulated in the order of light wave length, which can create arrange of forbidden frequencies called a Photonic band gap (PBG). In Photonic Crystal structures, the band structures ideas of solid state physics are applied to electromagnetic wave. Here we present mainly the physics of nanophotonics, challenges in fabrications and many applications. This paper concludes with the future of nanophotonics, seems bright and close to reality. This field is expected to revolutionize many aspects of modern life. We start with a brief introduction and then elaborate the physics behind it. The application areas are, however, wide spread and in every field of Science and Technology.

Objectives

General objectives

- To understand the confinement of light at nanodimeansions and to determine interaction between light and matter on a nanoscale much smaller than the wave length of light.

Specific objectives

- To describe the principle of Nanophotonics.
- To identify Nanophotonics devices.
- To explain how nanophotonics materials are synthesized and fabricated.
- To describe the theory of surface plasmons in nanophotonics.
- To define photonic crystals and its interaction with light.
- To explain the applications of nanophotonics in varies field.

Acknowledgements

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Chapter 1

Nanophotonics

In this chapter we are going to see what nanophotonics are, and the two type of synthesis techniques and the fabrication techniques and also we will discuss what are the challenges of nanophotonics and silicon nanophotonics. Finally we will see also what are the application and perspective of nanophotonics.

1.1 Introduction

Since nanotechnology is considered a key to the 21st century, its promises have been assessed by various scientific communities. By meeting at the nanoscale, various disciplines, from physics via chemistry to biology, from engineering to medicine contribute synergetically to the newly created knowledge base and the resulting technological advances [1].Nanotechnology and in particular, the burgeoning field of nanophotonics holds the promise of enabling a whole host of a new application capabilities in the world of spectral analysis and chemical imaging [2].

1.2 Nanophotonics

Nanophotonics is an emerging technology that involves the interaction of light with structures smaller than about 100nm. Thanks to recent fabrication advances, nanophotonic applications have been growing in number and diversity. The anticipated attainment of 16nm lithography resolution by 2020 would further advance the field by improving system integration. The increased resolution would lead to fabrication methods that are reliable, scalable, power-efficient, and cost-effective. Nanoscale component integration would be feasible, both from the top down (e.g., fabrication on wafers), and from the bottom up (e.g. building the system starting at the scale of atoms and molecules) [3].

Nanophotonics is all about the manipulation and emission of light (both far-field and near-field) using nano-scale materials. It is the study of the behavior of light on the nanometer scale and their interactions in different material media. The ability to fabricate devices in nanoscale that has been developed in recent years called nanotechnology is the purpose of this study. Nanotechnology is defined as a novel and multidisciplinary use of materials or processes at the nanometer scale (below 100 nm). So, the use of carbon nanotubes is clearly nanotechnology, but carbon black nanoparticles are not, because they have been used in products for more than 100 years. Nanotechnology involves mixing elements from the core fields of physics, chemistry, and biology to address other fields, and nanotechnology is also constantly finding new applications. Nanophotonics is the use of nanotechnology in photonics or the use of photonics in nanotechnology. Particularly promising market opportunities for nanophotonics include improving the light output of high brightness LEDs, reducing the manufacturing cost of solar cells, identifying better fluidic sensor solutions, and commercializing novel display [4].

Nanophotonics is the field of Nanotechnology concerned with discovering and developing nanomaterials that can control the flow of light and in some cases localize or confine it within a volume. Intuitively, we view light as rays, which propagate in a single direction, either being absorbed or reflected to some extent by any object on which it impinges. However, the propagation of light through a material is itself a quantum effect, involving the excitation and relaxation of electrons in the material. Creating a material with structural and compositional features on a length scale comparable to the wavelength of light (i.e. 300-900nm for visible light) enables us to guide light in any direction that we choose.

The area nanophotonics deals with a number of interesting topics in nanophotonics and nanostructures and their applications in general. Interactions of waves in semiconductors are main focus and different approaches to confine these waves and devices employing such confinement are the key issue in nanophotonics. Localization of light and applications to metallic mirrors, photonic crystals, optical waveguides, microresonators, plasmonics are gaining tremendous applied interest. Localization of quantum mechanical waves in quantum wells, wires and dots has been demonstrated. Devices incorporating localization of both electromagnetic and quantum mechanical waves, such as resonant cavity quantum well lasers and microcavity-based single photon sources are on the way of commercialization. System-level applications of the introduced concepts, such as optical communications, biochemical sensing, and quantum cryptography are targeted for future [5, 6].

1.3 Nanophotanics at a Glance

Nanophotonics are classified into three branches as illustrated in the block diagram (fig 1.1) depicting various process and techniques in Nanophotonics. One way to induce interactions between light and matter on a nanometer size scale is to confine light to nanoscale dimensions that are much smaller than the wavelength of light. The second approach is to confine matter to nanoscale dimensions, there by limiting interactions between light and matter to nanoscopic dimensions. This defines the field of nanomaterials. The last way is nanoscale confinement of a photoprocess where we induce photochemistry or a light-induced phase change. This approach provides methods for nanofabrication of photonic structures and functional units [7].

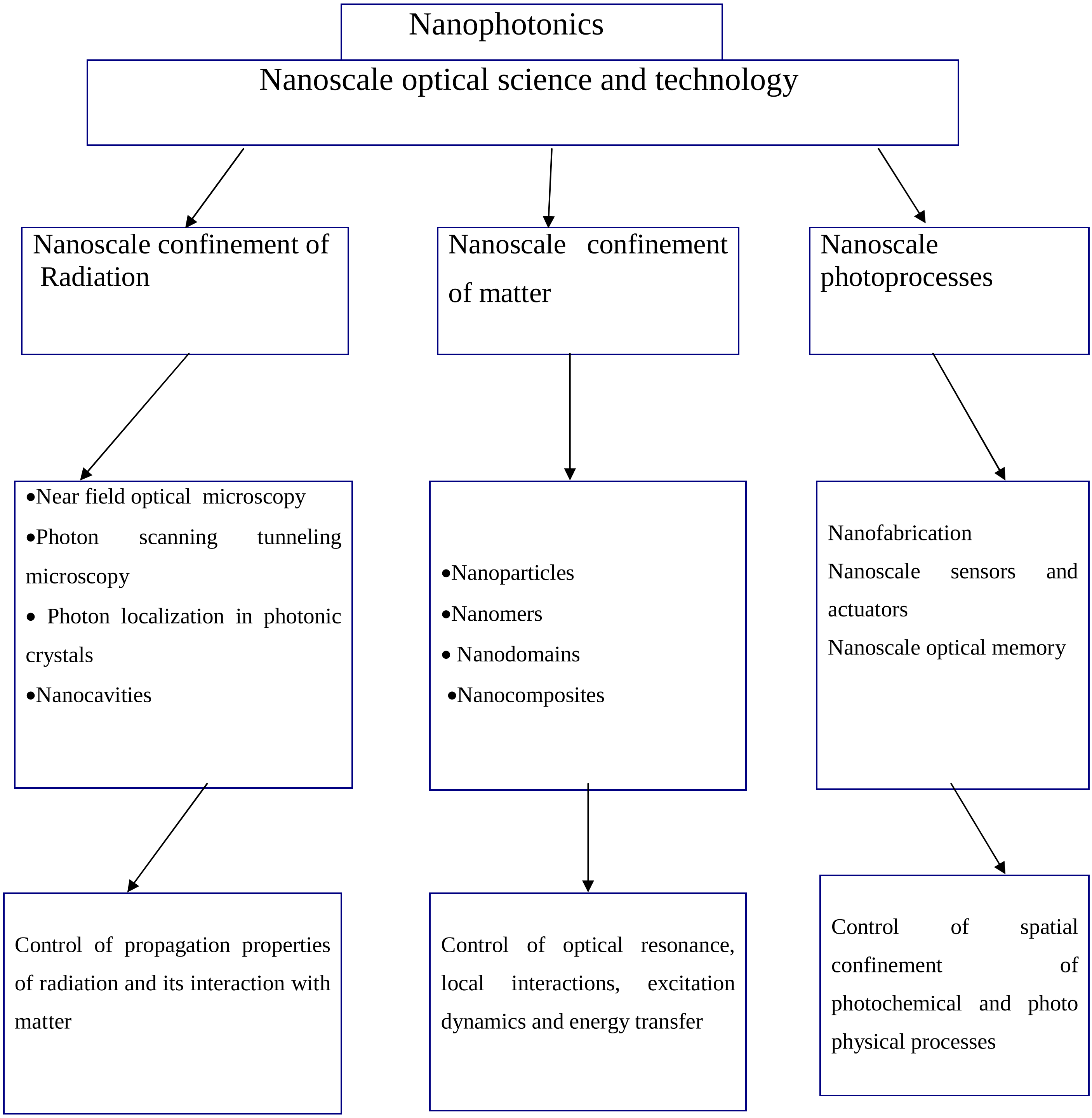


Figure 1.1: Block diagram depicting various processes and techniques in Nanophotonics.

1.3.1 Nanoscale Confinement of Radiation

Conventional optical studies have been conducted in the far-field. Due to the diffraction limit of the probe light, the information obtained is the average response over a macroscopic region. The Near field Scanning Optical Microscopy (NSOM) and the Photon Scanning Tunneling Microscopy (PSTM) overcome this diffraction limit and make it possible to probe localized optical interactions in nanoscopic regions. The principle of NSOM is to scan a nanoscopic light source in the near field above a sample with the resulting field intensity being detected. With PSTM, a nanoscopic probe senses the evanescent field above a sample that is illuminated under total internal reflection. The optical process detected by NSOM and PSTM involve both a propagating field(also called allowed light which has its wave vector real) and an evanescent field (also called forbidden light where the wave vector is imaginary).However, most efforts related to NSOM and PSTM have concentrated on linear optical effects. The area of non linear optical interaction of nanometer scale is still virtually unexplored [8].

1.3.2 Nanoscale Confinement of Matter

The nanoscale confinement of matter to make nanomaterials for photonics involves various ways of confining the dimensions of matter to produce nanostructures. For example, one can utilize nanoparticles that exhibit unique electronic and photonic properties. It is gratifying to find that these nanoparticles are already being used for various applications of nanophotonics such as UV absorbers in sunscreen lotions. Nanoparticles can be made of either inorganic or organic materials. Nanomers, which are nanometer size oligomers (a small number of repeat units) of monomeric organic structures, are organic analogues of nanoparticles. In contrast, polymers are long chain structures involving a large number of repeat units. These nanomers exhibit size-dependent optical properties. Metallic nanoparticles exhibit unique optical response and enhanced electromagnetic field and constitute the area of “plasmonics.” Then there are nanoparticles which up-convert two absorbed IR photons into a photon in the visible UV range; conversely, there are nanoparticles, called quantum cutters, that down-convert an absorbed vacuum UV photon to two photons in the visible range. A hot area of nanomaterials is a photonic crystal that represents a periodic dielectric structure with a repeat unit of the order of wavelength of light. Nanocomposites comprise nanodomains of two or more dissimilar materials that are phase-separated on a nanometer size scale. Each nanodomain in the nanocomposite can impart a particular optical property to the bulk media. Flow of optical energy by energy transfer (optical communications) between different domains can also be controlled [7].

1.3.3 Nanoscale Confinement of Photo-Processes

Nanoscale photo-processes can be used for nanolithography to fabricate nanostructures. These nanostructures can be used to form nanoscale sensors and actuators. A nanoscale optical memory is one of exciting concepts of nanofabrication. An important feature of nanofabrication is that the photoprocesses can be confined to well-defined nanoregions so that structures can be fabricated in a precise geometry and arrangement [8].

1.4 Top-Down and Bottom-Up Synthesis Techniques

The terms top-down and bottom-up have gained significant meaning via nanotechnology. The terms are self-explanatory and understanding that, we could technically be done with this study guide and stop here. Top-down fabrication is a subtractive process from bulk starting materials to make nanomaterials and bottom-up fabrication is an additive process that starts with precursor atoms or molecules to make nanomaterials.

1.4. 1 Top- Down Synthesis Techniques

Mechanicanosynthetic Methods Mechanical methods offer the least expensive ways to produce nanomaterials in bulk. Ball milling is perhaps the simplest of them all. Ball milling produces nanomaterials by mechanical attrition in which kinetic energy from a grinding medium is transferred to a material undergoing reduction. Compaction and consolidation is an industrial scale process where in nanomaterials are "put back together" to form materials with enhanced properties. Metallic alloys can be made this way. Many top-down mechanical methods are utilized by industry. Thermal methods form a nebulous category and we try and focus on those that provide heat to a fabrication process. Of these, electro spinning is a means to form nanothread materials. High energy methods are those that require an excessive input of energy– whether in the form of heat, electricity or solar energy. Arc discharge was the first controlled means of making carbon nanotubes. Laser ablation and solar flux also work well. The problem is control of quality and potential upscale. We include plasma methods in this category. Plasmas are created in high-energy situations (high potential bias, etc.). The problem with this and other high-energy methods is upscale potential– with the possible exception of solar flux methods as sunlight is easily available

Top-down chemical fabrication methods are always easy to upscale and many, such as anodizing, are widespread industrial processes. Lithographic methods, as we all know quite well, although energy intensive and requiring expensive equipment and facilities are top-down methods capable of producing for the most part micron-sized features. Lithography is the means of making printed circuits and computer boards for several decades now. The push to miniaturize in the future is a costly venture as more powerful sources (high energy electron beams and shorter wavelength sources), support equipment and facilities are required.

1.4 .2 Bottom-Up Synthesis Techniques

Bottom-up methods start with atoms or molecules to form nanomaterials. Chemical vapor deposition is a gas-phase process by which reactive constituents react over a catalyst or pre-templated surface to form nanostructured materials. The economical synthesis of carbon nanotubes is by Chemical Vapor Deposition (CVD). Precursors in the form of methane or acetylene or other carbon source gases are passed over Co, Fe or Ni catalyst. Once decomposed into carbon, nanotubes are formed by the catalyst particle. Atomic layer deposition is an industrial process that is capable of coating any material, regardless of size, with a monolayer or more of a thin film. A relatively pure bottom-up process starting with gas-phase constituents. Molecular beam epitaxy and MOCVD are other industrialized processes that are considered to be bottom-up. Liquid phase methods are also numerous. It is within the liquid phase that all of biology self-assembly and synthesis occurs. Liquid phase methods are up scalable and low cost. Electrodeposition and electroless deposition are very simple ways to make nanomaterials such as dots, clusters, colloids, rods, wires, and thin films. Anodizing aluminum to make a porous oxide structure is a simple way to make nanomaterials. The porous structure is a nanomaterial as well as any material synthesized within. Porous membranes are in many ways the ultimate template.

A new generation of nano bottom-up methods has made the scene. Many of the new methods are both inexpensive and offer high throughput. Disadvantages include establishment of long-range order. The new methods include nanolithography (dip pen method), nanosphere lithography [9].

1.5 Fabrication Techniques

Novel optical nanofabrication techniques beyond the diffraction limit are required for producing a variety of conventional electronic/photonic devices and nanophotonic devices. To fabricate nanophotonic devices, several capabilities are required. For example, a variety of materials must be deposited on a substrate, and the inaccuracy of their sizes and positions must be as low as 1nm for efficient reproducible optical near-field energy transfer. However, conventional fabrication technologies using electron beams, ion beams, and propagating light cannot meet these requirements due to their low resolution, contamination of and damage to the substrate, and low throughput. To meet the requirements, novel technologies had to be developed, and these have been realized by utilizing optical near-field energy transfer. As representative examples of such nanophotonic fabrication techniques are photochemical vapor deposition and photolithography.

Photochemical vapor deposition is a way to deposit materials on a substrate using a photochemical reaction with ultraviolet light that predissociates metalorganic molecules by irradiating gaseous molecules or molecules adsorbed on the substrate.

Photolithography is a technology used to carve a substrate material. After coating the substrate with a thin film of a photoresist, light is irradiated through a photomask to induce a photochemical reaction in the photoresist. When the aperture on the photomask is smaller than the wavelength of the light, the transmission of the propagating light is sufficiently low, while an optical near-field is generated at the aperture. Using the photochemical reaction between the optical near-field and photoresist, a nanometric pattern beyond the diffraction limit is formed on the photoresist, and a chemical etching process is subsequently used to carve the substrate. Several preliminary experiments have used a fiber probe to generate optical near-fields. Alternatively, a photomask is used to improve the throughput of fabrication dramatically. Practical technologies, such as using a two-layered photoresist, have been developed to form deep patterns, thus realizing a quantitative innovation [10].

1.6 Challenges of Nanophotonics

Nanophotonics has the potential to improve optoelectronic products in a wide array of new applications. However the technologies and applications are diverse and multidisciplinary, in early stages of development, and the opportunities are spread throughout the value chain. There are different challenges for nanophotonics [11].Some of them is

- Market strategy
- Single –molecule addressing (pre-requisite for architectures work)
- Optical nanoscopic of molecules
- Assessment of nanowires in nanophotonics
- Hierarchy of interactions with other quasi particles
- Energetically sound
- Amplification and gain
- Integration, costs, standards, etc

1.7 Silicon Nanophotonics

Silicon nanophotonics is a very rapidly growing research domain. The basic idea is to use the tools and materials employed for processing the most advanced electronic circuits also for the fabrication of photonic circuit. These tools are typically much more advanced than those used for the fabrication of classical optoelectronic devices and therefore allow for a much higher performance, much denser integration, mass manufacturing and integration with electronics. In addition, silicon is a very attractive material for the fabrication of ultra compact photonic devices. It has very low losses in the telecom range (1.3micrometer, 1.55micrometer) and the high refractive index contrast with air or with SiO2, which is typically used as a cladding material permits strong light confinement [12].

1.8. Applications of Nanophotonics

Nanophotonics is a unique field because it combines scientific challenges with large variety of near-term applications [13-16]. Fundamental research on nanophotonics leads to applications in:

♦ Communications technology.
Data networking over long distances typically employs fiber optic networks to carry data. This data then needs to be modulated from optical to electronic signals. Nanophotonics enables devices which are capable of interacting more easily with electronic networks.

♦ Optical computers the vision of an all-optical computer is still decades away, but nanophotonics is enabling more data transfer to take place over optical networks. An application which could have very high impact is the use of photonic connections between multiple processor cores on an integrated circuit.

♦Lasers (Light amplification by stimulated emission of radiation) is a mechanism for emitting electromagnetic radiation, typically light or visible light, via the process of stimulated emission.
The emitted laser light is (usually) a spatially coherent, narrow low-divergence beam that can be manipulated with lenses

Figure 1.2: Laser beams in fog and on a car windshield

♦ Solar cells are a device that converts the energy of sunlight directly into electricity by the photovoltaic effect.

Figuer1.3: A solar cell made from a monocrystalline silicon wafers

♦ Solid-state lighting(SSL) refers to a type of lighting that uses semiconductor light- emitting diodes (LEDs), organic light –emitting diodes (OLED), or polymer light-emitting diodes (PLED) as sources of illumination rather than electrical filaments,plasma (used in arc lamps such as fluorescent lamps), or gas

Figure 1.4: LED lamp with E27 Edison screw

- Data storage
- Lithography
- (Bio-) Sensors
- Light-activated medical therapies
- Displays

Chapter 2

Surface Plasmon Nanophotonics

In this chapter we are going to see what surface plasmons are, and also we will discusses what surface plasmon resonance and its dependence, optical properties of metal, surface plasmons ploraitons and optical waveguides are . Finally we will see the applications of surface plasmons.

2.1 Introduction

Surface Plasmons are collective charge oscillations that occur at the interface between conductors and dielectrics. They can take various forms, ranging from freely propagating electron density waves along metal surfaces to localized electron oscillations on metal nanoparticles. Their unique properties enable a wide range of practical applications, including light guiding and manipulation at the nanoscale, biodetection at the single molecule level, enhanced optical transmission through sub-wavelength apertures, and high resolution optical imaging below the diffraction limit . By definition, Surface Plasmons are the quanta of surface-charge-density oscillations, but the same terminology is commonly used for collective oscillations in the electron density at the surface of a metal. Because the surface charge oscillations are intimately coupled to electromagnetic fields, surface plasmons are polaritons. In the past, surface plasmons have attracted considerable attention due to their application in optical sensor devices. Because of their localized nature, surface plasmons have recently also been explored in integrated optical circuits and optical waveguides [17].

2.2. Surface Plasmons-Present and Future

Since the early days of surface plasmon optics there has been a gradual transition from fundamental studies to more application driven research. The present surge in plasmon based research is happening at a time where crucial technological areas such as optical lithography, optical data storage, and high density electronics manufacturing are approaching fundamental physical limits. Several current technological challenges may be overcome by utilizing the unique properties of surface plasmons. Thanks to many recent studies, a wide range of plasmon-based optical elements and techniques have now been developed, including a variety of passive waveguides, active switches, biosensors, lithography masks, and more. These developments have led to the notion of plasmonics, the science and technology of metal-based optics and nanophotonics.

The growth of the field of plasmonics is clearly reflected in the scientific literature. Figure 2.1 shows the annual number of publications containing the words “surfaceplasmon” in the title or the abstract. Since 1990 the annual number of papers on surface plasmons has doubled every five years. This rapid growth is stimulated by the development and commercialization of powerful electromagnetic simulation codes, nanofabrication techniques, and physical analysis techniques, providing researchers and engineers with the necessary tools for designing, fabricating, and analyzing the optical properties of metallic nanostructures. A major boost to the field was given by the development of a commercial surface plasmon resonance based sensor in 1991. At present an estimated fifty percent of all publications on surface plasmons involve the use of plasmons for biodetection.

Most recently, metal nanostructures have received considerable attention for their ability to guide and manipulate “light” (SPPs) at the nanoscale, and the pace of new inventions in the area has accelerated even further. In 1997 Junichi Takahara and co-workers suggest that metallic nanowires enable the guiding of optical beams with a nanometer scale diameter in 1998 Thomas

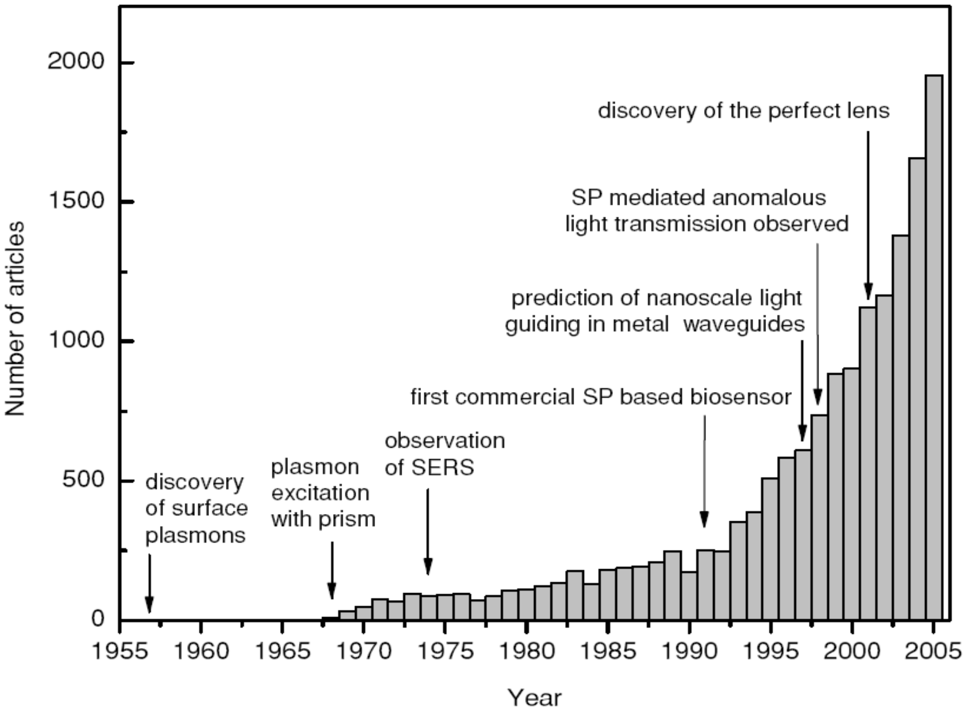


Figure 2.1: The growth of the field of metal nanophotonics is illustrated by the number of scientific articles published annually containing the phrase "surface plasmon" in either the title or abstract (based on data provided on www.sciencedirect.com).

Ebbesen and coworkers report on the extraordinary optical transmission through subwavelength metal apertures, and in 2001 John Pendry suggests that a thin metallic film may act as a "perfect lens". All these findings have motivated a tremendous amount of new research, captured in a number of exciting review articles [17].

2.3 Surface Plasmon Resonance (SPR)

The surface plasmon resonance phenomena observed on noble metal surfaces or nanoparticles has been a great interest in several fields of research such as nanoscale photonics and biological sensing. Surface Plasmon Resonance can simply be defined as collective oscillations of free electrons coupled to the metal-dielectric interfaces [18].

Plasmon Resonance is an optical phenomenon arising from the collective oscillation of conduction electrons in a metal when the electrons are disturbed from their equilibrium positions. Such a disturbance can be induced by an electromagnetic wave (light), in which the free electrons of a metal are driven by the alternating electric field to coherently oscillate at a resonant frequency relative to the lattice of positive ions. For a bulk metal of infinite size, the frequency of oscillation ω_P can be described by $\omega_p = \left(Ne^2 / \varepsilon_0 m_e\right)^{1/2}$, where N is the number density of conduction electrons, ε_0 is the dielectric constant of vacuum, e is the charge of an electron, and m_e is the effective mass of an electron. Thus, the bulk plasmon frequency of a particular metal depends only on its free electron density. The plasmon frequencies for most metals occur in the ultraviolet (UV) region, with alkali metals and some transition metals such as Cu, Ag, and Au exhibiting plasmon frequencies in the visible region. Because the penetration depth of an electromagnetic wave on a metal surface is limited (<50nm for Ag and Au), only plasmons caused by surface electrons are significant and are commonly referred to as surface plasmons. If a surface plasmon is associated with an extended metal surface, it is called a propagating surface plasmon. The frequency of a propagating surface plasmon is lower than the bulk frequency, with the theoretical propagating-surface-plasmon frequency corresponding to $\omega_P / \sqrt{2}$ when the boundary conditions of a metal-vacuum interface are applied. Figure 2.2a illustrates such a plasmon, which causes alternating positive and negative charges along a metal surface with the propagation of the electron density waves. If the collective oscillation of free electrons is confined to a finite volume as with a metal nanoparticle, the corresponding plasmon is called a localized surface plasmon. The theoretical frequency of a localized surface plasmon is $\omega_P / \sqrt{3}$ for a metal sphere placed in vacuum.

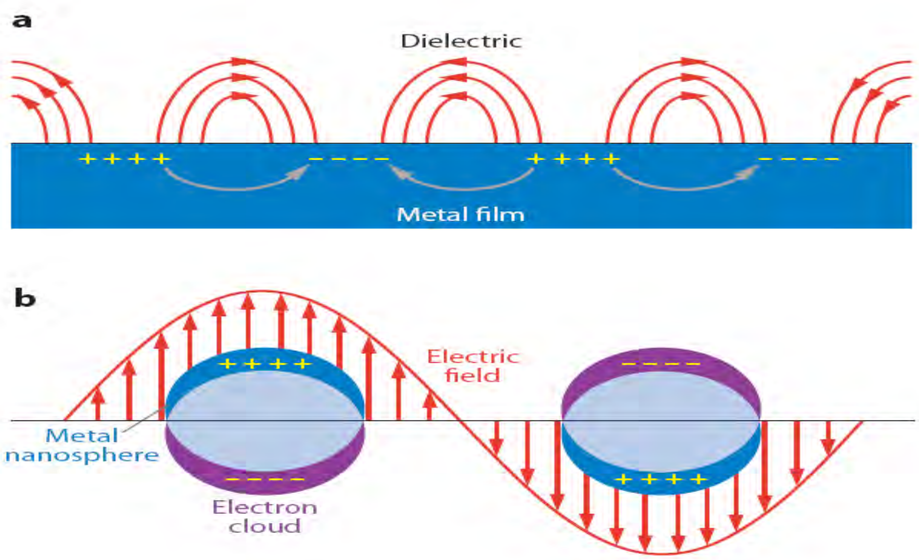


Figure 2.2: Depiction of (a) propagating surface plasmons of a metal surface and (b) localized surface plasmons (LSPs) of a metal nanosphere.

Figure 2.2b shows the interaction between the electric field of incident light and the free electrons of a metal sphere whose size is smaller than the wavelength of light. The electric field can cause free electrons to move away from the metal particle in one direction, creating a dipole that can switch direction with the change in electric field. When the frequency of the dipole plasmon is approximately the same as the incident light, a resonance condition is reached, leading to constructive interference and the strongest signal for the plasmon. Such a condition is referred to as surface plasmon resonance, or localized surface plasmon resonance (LSPR) for the case of a metal nanoparticle. For spherical nanoparticles of Au and Ag with diameters less than 30 nm, mainly dipole plasmon resonance is involved; however, for larger particles, quadrupole plasmon resonance from two negatively charged poles and two positively charged poles may be observed [19].

Gold nanostructures have been a subject of intensive research for their fascinating surface plasmon resonance properties. Surface Plasmon Resonance is an optical phenomenon arising from the interaction between an electromagnetic wave and the conduction electrons in a metal. Under the irradiation of light, the conduction electrons in a gold nanostructure are driven by the electric field to collectively oscillate at a resonant frequency relative to the lattice of positive ions. At this resonant frequency, the incident light is absorbed by the nanostructure. Some of these photons will be released with the same frequency in all directions and this process is known as scattering. At the same time, some of these photons will be converted into phonons or vibrations of the lattice and this process is referred to as absorption. In general, the SPR peak of a gold nanostructure should include both scattering and absorption components. The cross-sections of these two components can be substantially different depending on the size and shape of the nanostructure. For gold nanospheres about 50 nm in diameter, the SPR peak is positioned at 520 nm and this peak is responsible for the ruby red colour displayed by conventional gold colloids. Michael Faraday was the first person to observe this spectacular phenomenon. In 1857, he prepared the first stable suspension of gold colloids by reducing gold chloride with phosphorus in water [20]. Noble metal nanoparticles and their brilliant colors due to surface plasmon resonance absorption constitute a large ongoing research field. The color of the nanoparticle is found to depend on the shape and size of the nanoparticle and dielectric constant of the surrounding medium, leading to many studies on their synthesis and applications [21].

2.3.1 Dependence of SPR on the Size and Shape of Nanoparticle

Metallic nanostructures have been a subject of considerable interest in recent years. The field of metallic nanostructures is now more popularly called plasmonics, since the major manifestation produced by optical excitations is the collective oscillation of electrons, which are localized along the interface. Hence, this wave is also called a surface plasmon wave .The light absorption by metallic nanoparticles is described by coherent oscillation of the electrons, which is induced by interaction with the electromagnetic field. These oscillations produce surface plasmon waves. It should be noted that the term “surface plasmons” is used to describe the excitations at the metal–dielectric interface in the case of flat surfaces, where the plasmons can only be excited by using special geometries of the Kretschmann geometry required for matching of the wave vector, k_{SP}, of the surface plasmon wave with that of light producing it. The Kretschmann configuration of ATR is widely used to excite surface Plasmons. This configuration is shown in Figure 2.3. A microscopic slide is coated with a thin film of metal (usually a 40- to 50-nm-thick gold or silver film by vacuum deposition). The microscopic slide is now coupled to a prism through an index matching fluid or a polymer layer. A p-polarized laser beam (or light from a light-emitting diode) is incident at the prism. The reflection of the laser beam is monitored. At a certain θ_{SP}, the electromagnetic wave couples to the interface as a surface plasmon.

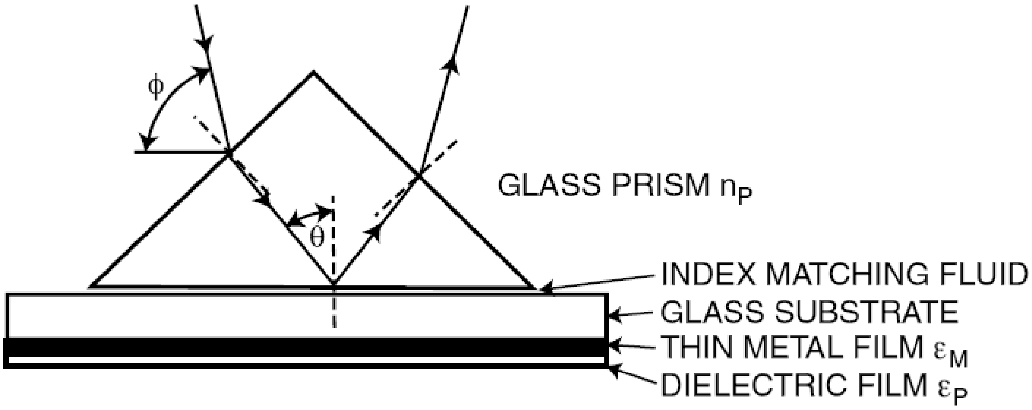


Figure 2.3: Kretschmann (ATR) geometry used to excite surface plasmons

The angle is determined by the relationship

$$k_{SP} = kn_P \sin\theta_{SP} \tag{2.3.1}$$

Where k_{SP} is the wavevector of the surface plasmon, k is the wavevector of the bulk electromagnetic wave, and n_P is the refractive index of the prism. The surface plasmon wavevector k_{SP} is given by

$$K_{SP} = (\omega / c)[(\varepsilon_m \varepsilon_d)/(\varepsilon_m + \varepsilon_d)]^{1/2} \tag{2.3.2}$$

Where ω is the optical frequency, c the speed of light, and ε_m and ε_d are the relative dielectric constants of the metal and the dielectric, respectively, which are of opposite signs. In the case of metal nanostructures (e.g., nanoparticles), plasmon oscillations are localized and thus not characterized by a wavevector k_{SP}. To make a distinction, the plasmon modes in metallic nanoparticles are also sometimes referred to as localized surface plasmons. These localized plasmons are excited by light absorption in the nanoparticles, with the specific absorption bands being referred to as plasmon bands. To excite these localized plasmons in metallic nanostructures, no special geometry, such as those required for plasmon excitation along a planar metal–dielectric interface, is required. The specific wavelengths of light absorption producing plasmon oscillations are called surface plasmon bands or simply plasmon bands.

A systematic study of the optical properties of metallic nanoparticles reveals the following features:

♦ For metallic nanoparticles significantly smaller than the wavelength of light, light absorption is within a narrow wavelength range. The wavelength of the absorption peak maximum due to the surface plasmon absorption band is dependent on the size and the shape of the nanocrystals, as well as on the dielectric environment surrounding the particles.

♦ For extremely small particles (<25 nm for gold), the shift of the surface plasmon band peak position is rather small. However, a broadening of the peak is observed.

♦ For larger nanoparticles (>25 nm for gold), the surface plasmon peak shows a red shift. Figure 2.4.illustrates these features for a series of gold nanoparticles of different sizes.

♦ For a nanorod-shaped metallic nanoparticle, the plasmon band splits into two bands corresponding to oscillation of the free electrons along (longitudinal) and perpendicular (transverse) to the long axis of the rod. Figure 2.5 shows this splitting for a gold nanorod.

♦ The transverse mode resonance is close to that observed for spherical particles, but the longitudinal mode is considerably red-shifted, depending strongly on the aspect ratio, which is the length divided by the width of the rod.

The origin of these shifts is not due to quantum confinement. The quantum confinement does affect the energy spacing of the various levels in the conduction band. However, the quantization, derived from the confinement, affects the conductive properties of the metal and is often used to describe the metal-to-insulator transition occurring as the particle size is reduced from microscopic to nanoscopic size. When the dimensions of the metallic nanoparticles are large, the spacing of levels within the conduction band is significantly less than the thermal energy, kT (k is Boltzmann’s constant and T is the temperature in kelvin), and the particle exhibits a metallic behavior.

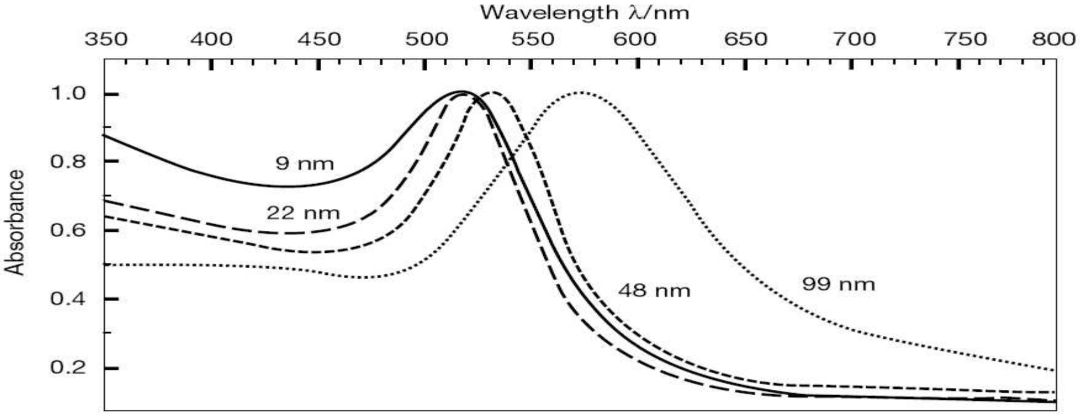


Figure 2.4: Optical absorption spectra of gold nanoparticles of different sizes.

When the nanoparticles approach a size at which the increased energy separation due to the quantum confinement effect (smaller length of the box for the free electron) is more than the thermal energy, an insulating behavior results because of the presence of these discrete levels. However, the energy level separations are still too small to affect the optical properties of metals in the UV to the IR rang.

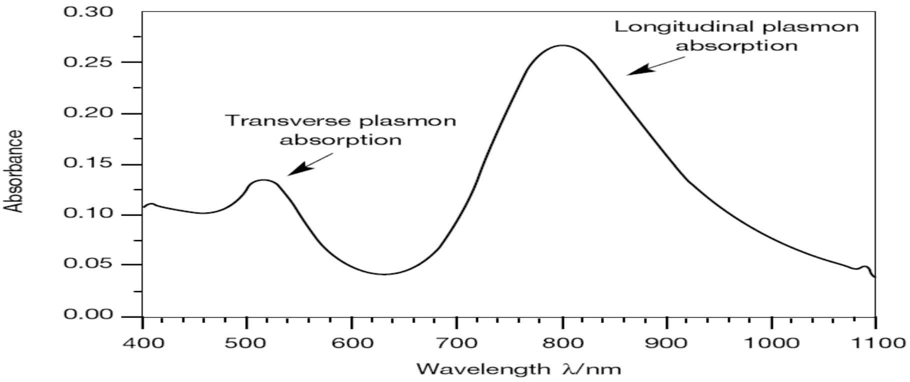


Figure 2.5: Absorbance of gold nanorods.

Although a number of theoretical models have been proposed the original classical model of Mie is often used to describe the optical properties of the metal nanoparticles. Often one utilizes a dipole approximation in which the oscillation of conduction electrons (plasmon oscillations), driven by the electromagnetic field of light, produces oscillating dipoles along the field direction where the electrons are driven to the surface of the nanoparticles as shown in Figure 2.2b. A more rigorous theory shows that this dipolar-type displacement is applicable to smaller-size particles and gives rise to an extinction coefficient k_{ex} (measure of absorption and scattering strengths collectively) by the following equation:

$$k_{ex} = \frac{18\pi NV\varepsilon_h^{3/2}}{\lambda} \frac{\varepsilon_2}{[\varepsilon_2 + 2\varepsilon_h]^2 + \varepsilon_2^2} \tag{2.3.3}$$

Where λ is the wavelength of light, and ε_h is the dielectric constant of the surrounding medium. The terms ε_1 and ε_2 represent the real and the imaginary parts of the dielectric constant, ε_m, of the metal (ε_m = ε_1 + iε_2) and are dependent on the frequency ω of light. If ε_2 is small or weakly dependent on ω, the absorption maximum corresponding to the resonance condition is produced when $\varepsilon_1 = -2\varepsilon_h$, leading to a vanishing denominator. Hence, a surface plasmon resonance absorption is produced at optical frequency ω at which the resonance condition ε_1 = –2 ε_h is fulfilled. The size dependence of the surface plasmon resonance comes from the size dependence of the dielectric constant ε of the metal. This is often described as the intrinsic size effect. In the case of noble metals such as gold, there are two types of contributions to the dielectric constant of the metal: One is from the inner d electrons, which describes interband transition (from inner d orbital to the conduction band), and the other is from the free conduction electrons. The latter contribution, described by the Drude model is given as

$$\varepsilon_D(\omega) = 1 - \frac{\omega_p^2}{\omega^2 + i\gamma\omega} \tag{2.3.4}$$

Where ω_p is the plasmon frequency of the bulk metal and γ is the damping constant relating to the width of the plasmon resonance band. It relates to the lifetime associated with the electron scattering from various processes. In the bulk metal, γ has main contributions from electron–electron scattering and electron–phonon scattering, but in small nanoparticles, scattering of electrons from the particle's boundaries (surfaces) becomes important. This scattering produces a damping term γ that is inversely proportional to the particle radius r. This dependence of γ on the particle size introduces the size dependence in $\varepsilon_D(\omega)$ [thus ε_1 in Eq. (2.3.3)] and, consequently, in the surface plasmon resonance condition.

For larger-size nanoparticles (>25 nm for gold particles), higher-order (such as quadrupolar) charge cloud distortion of conduction electrons becomes important, as shown in Figure 2.6. These contributions induce an even more pronounced shift of the plasmon resonance condition as the particle size increases. This effect for the larger size particle is referred to as the extrinsic size effect. The position and the shape of the plasmon absorption band also depends on the dielectric constant ε_h of the surrounding medium as the resonance condition is described by $\varepsilon_1 = -2\varepsilon_h$ Hence, an increase in ε_h leads to an increase in the plasmon band intensity and band width, as well as produces a red shift of the plasmon band maximum. This effect of enhancing the plasmon absorption by using a higher dielectric constant surrounding medium forms the basis of what is known as immersion spectroscopy [17].

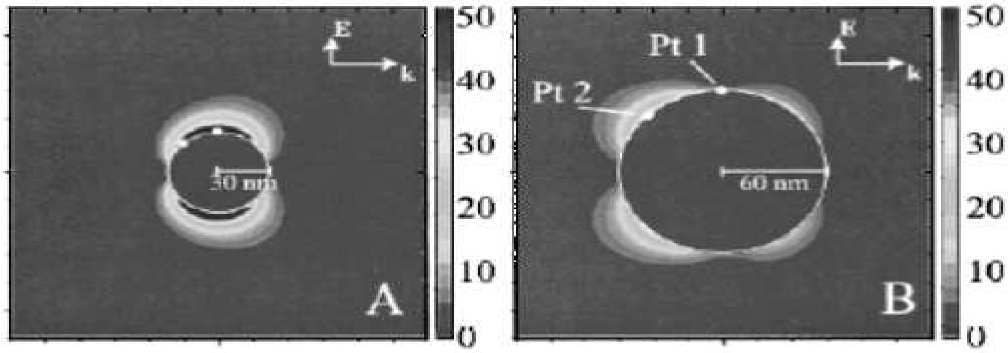


Figure 2.6: Calculated higher-order charge cloud distorsion around gold nanoparticles of sizes > 25 nm.

2.4 Optical Properties of Metal

Metals are defined by their quasi-free electrons in the ground state, which are not bound to single atoms but to the metal bulk. These free electrons are responsible for the well-known properties of high electric conductivity and high optical reflectivity. Qualitatively, the free electrons of the metal behave like a gas of free charge carriers (a plasma) and can be excited to sustain propagating plasma waves. Plasma waves are longitudinal electromagnetic charge density waves and their quanta are referred to as plasmons. They exist in two forms: bulk plasmons in the volume of a plasma and surface plasmons, which are bound to the interface of a plasma and a dielectric. Both modes cannot directly couple to propagating electromagnetic modes (light) in adjacent dielectrics. Surface Plasmons exist for metals like Au, Ag, Al, and Cu from. DC up to optical and near UV frequencies, depending on the dielectric function of both, the metal and the neighboring dielectric [17].

2.5 Surface Plasmon Polaritons (SPP)

Surface Plasmon Polaritons are quasi-two-dimensional electromagnetic excitations, propagating along a dielectric-metal interface and having the field components decaying exponentially into both neighboring media. The field of a plane SPP comprises a magnetic field component, which is parallel to the interface plane and perpendicular to the SPP propagation direction, and two electric field components, of which the main one is perpendicular to the interface (Fig. 2.7). Surface Plasmon Polaritons can be tightly bound to the metal surface, penetrating on the order of 100 nm into the dielectric and ~10 nm into the metal. This feature implies the possibility of using SPPs for miniature photonic circuits and optical interconnects and has attracted a great deal of attention to SPPs. It has been shown using numerical simulations that nanometer sized metal rods can support extremely confined SPP modes, though only propagating over hundreds of nanometers. Similar properties were expected and indeed found for the electromagnetic excitations supported by chains of metal nano-spheres. Metal stripes of finite width can also be employed to laterally confine the SPP propagation along the stripes.

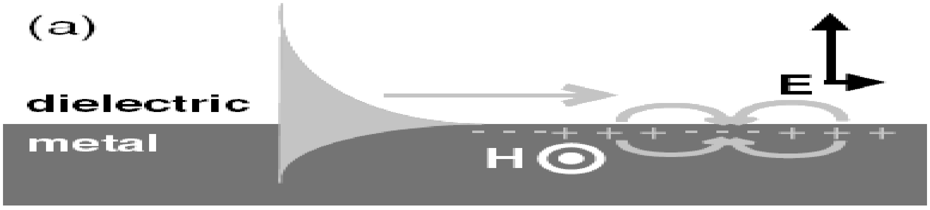


Figure 2.7: Schematic representation of a SPP propagating along a metal-dielectric interface and orientations of electric and magnetic field components).

A polariton is an electromagnetic mode related to the oscillation of polarization charge density. At the interface between two media with frequency dependent complex dielectric functions ε_1 and ε_2 ,surface polaritons with electromagnetic field exponentially decaying into both media may occur according to the well-known dispersion relation: $k_{SP} = (\omega / c)\sqrt{(\varepsilon_1\varepsilon_2)/(\varepsilon_1 + \varepsilon_2)}$ (where k_{SP} ω and c are respectively the in-plane wave-vector of the surface polariton, the angular frequency and the speed of light) provided the real part of the dielectric functions in the two media are of opposite sign. If the material with the negative real part dielectric function is a metal, the polarization charge density oscillation corresponds to the oscillation of the electron gas, and then the surface polariton is called a surface plasmon polariton. Unlike surface plasmon polariton excited on extended metal thin films, which have been studied for decades, surface plasmon polariton sustained by thin metal films of finite width (metal strips) have been considered only recently. These metal strips that can be viewed as surface plasmon polariton waveguides could play an important role in the development of surface wave based optical devices [17].

2.6 Optical Waveguides

An optical waveguide is a physical structure that guides electromagnetic waves in the optical spectrum. Common types of optical waveguides include optical fiber and rectangular waveguides. Optical Waveguides are used as components in integrated optical circuits or as the transmission medium in local and long haul optical communication systems. Optical Waveguides can be classified according to their geometry (planar, strip, or fiber waveguides), mode structure (single-mode, multi-mode), refractive index distribution (step or gradient index) and material (glass, polymer, and semiconductor).

Practical rectangular-geometry optical waveguides are most easily understood as variants of the simple dielectric slab waveguide, also called planar waveguide. The slab waveguide consists of three layers of materials with different dielectric constants, extending infinitely in the directions parallel to their interfaces.

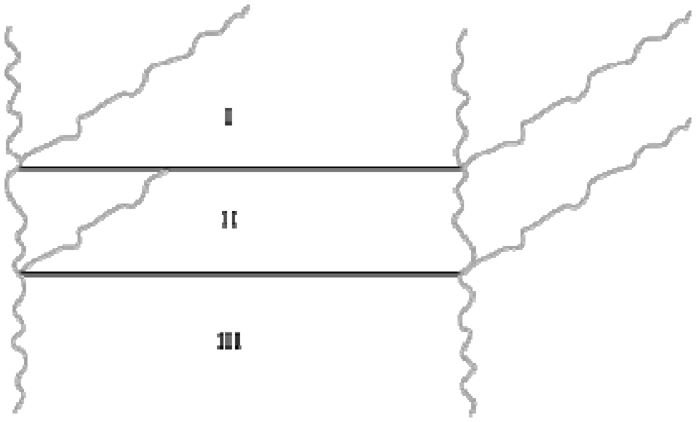
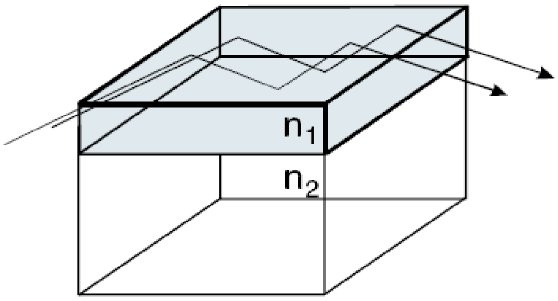


Figure 2.8: A dielectric slab waveguide consists of three dielectric layers with different refractive indices.

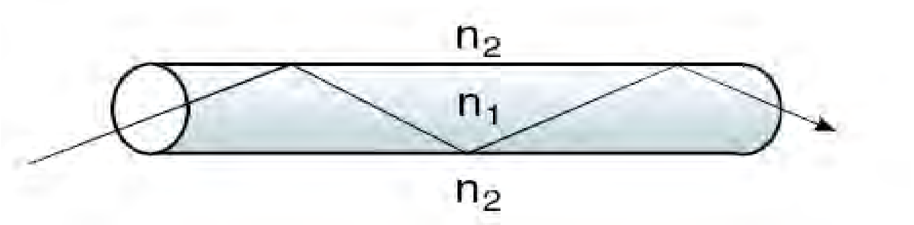
A strip waveguide is basically a strip of the guiding layer confined between cladding layers. The simplest case is a rectangular waveguide, which is formed when the guiding layer of the slab waveguide is restricted in both transverse directions rather than just one. Rectangular waveguides are used in integrated optical circuits, and in laser diodes. They are commonly used as the basis of such optical components as Mach-Zehnder interferometers and wavelength division multiplexers. The cavities of laser diodes are frequently constructed as rectangular optical waveguides. Optical waveguides with rectangular geometry are produced by a variety of means, usually by a planar process.

Optical fiber is typically a circular cross-section dielectric waveguide consisting of a dielectric material surrounded by another dielectric material with a lower refractive index. Optical fibers are most commonly made from silica glass, however other glass materials are used for certain applications and plastic optical fiber can be used for short-distance applications [22].

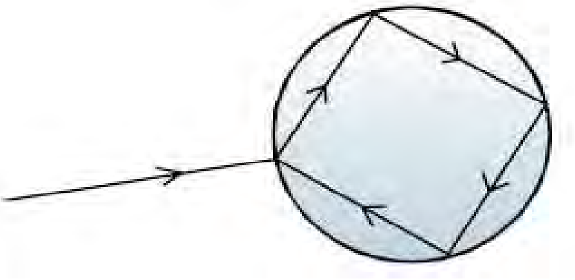
The photon confinement can be introduced by trapping light in a region of high refractive index or with high surface reflectivity. This confining region can be a waveguide or a cavity resonator. The examples of various confinements are shown in Figure 2.9. The confinements can be produced in one dimension such as in a plane, as in the case of a planar optical waveguide. Here, the light propagation is confined in a layer (such as a thin film) of high refractive index, with the condition that the refractive index n_1 of the light-guiding layer is higher than the refractive index n_2 of the surrounding medium, as shown in Figure 2.9. The figure shows the classical optics picture using a ray path to describe light guiding (trapping) due to total internal reflection. In the case of a planar waveguide, the confinement is only in the vertical (x direction). The propagation direction is z. In the case of a fiber or a channel waveguide, the confinement is in the x and y directions. A microsphere is an example of an optical medium confining the light in all dimensions. The light is confined by the refractive index contrast between the guiding medium and the surrounding medium. Thus the contrast n_1 / n_2 acts as a scattering potential creating barrier to light propagation. Such a waveguide is a dielectric medium whose dimensions are controlled by the refractive index contrast required to obtain single mode guiding, but are also limited by the diffraction limit of light. Thus, the minimum size of light confinement (transverse dimension of a waveguide) is of the order of $\lambda / 2n$ where λ the wavelength of the light is guided and n is the effective refractive index of the guiding medium at this wavelength [7].



Optical planar waveguide



Optical fiber



Microsphere optical cavity

Figure 2.9: Confinements of photons in various dimensions and the configurations used for them. The propagation direction is z.

2. 7 Applications of Surface Plasmons

Surface Plasmons have been used to enhance the surface sensitivity of several spectroscopic measurements including fluorescence, Raman scattering, and second harmonic generation. However, in their simplest form, SPR reflectivity measurements can be used to detect DNA or proteins by the changes in the local index of refraction upon adsorption of the target molecule to the metal surface. If the surface is patterned with different biopolymers, the technique is called Surface Plasmon Resonance Imaging (SPRI).

For nanoparticles, localized surface plasmon oscillations can give rise to the intense colors of solutions of plasmon resonance nanoparticles and/or very intense scattering. Nanoparticles of noble metals exhibit strong ultraviolet-Visible absorption bands that are not present in the bulk metal. Shifts in this resonance due to changes in the local index of refraction upon adsorption of biopolymers to the nanoparticles can also be used to detect biopolymers such as DNA or proteins. Related complimentary techniques include Plasmon Waveguide Resonance, QCM and Dual Polarisation Interferometry [23].

Chapter 3

Photonic Crystal

In this chapter we are going to see what photonic crystals are, and we will discusses how photonic bandgap are formed and also we will see the propagation of light in photonic crystals and the fabrication method and fabrication challenges. Finally we will see the applications of photonic crystal.

3.1 Introduction

Photonic Crystals represent a class of nanomaterials in which alternating domains of higher and lower refracting indices produce an ordered structure with periodicity on the order of wavelength of light. Photonic Crystals have emerged as a major thrust area of nanophotonics and have witnessed a remarkable growth of research activities worldwide. This growth has been fueled both by a quest for fundamental understanding of optical processes in photonic crystals and by their promise for many technological applications [7].

Photonic Crystals are artificial periodic structures whose dielectric constant is periodically modulated in the order of light wavelength, which can create a range of ‘forbidden frequencies’ called a Photonic Bandgap (PBG). Photons with energies lying in the bandgap cannot propagate through the medium. This provides the opportunity to shape and mould the flow of light for photonic information technology. In Photonic Crystals Structure, the band structure ideas of solid-state physics are applied to electromagnetic waves. Light cannot propagate in a Photonic Bandgap, in much the same way that electrons are forbidden within the electronic band gap of semiconductor. By exploiting PBG confinement, a well-defined wavelength of light can be trapped and guided through a waveguide carved in a photonic crystal structure by removing a row of holes, which forms a line defect that localizes light and sustains propagation modes [24].

3.2 Photonic Crystal

Photonic Crystals are optical materials that allow for controlling and manipulating the flow of light. Photonic Crystals are composed of a regular arrangement of a dielectric material that shows strong interaction with light; any material exhibiting spatial periodicity in refractive index is a photonic crystal. Photonic Crystals are materials with repeating patterns spaced very close to one another, with separations between the patterns comparable to the wavelengths of light. When light falls on such a patterned material, the photons of light interact with it, and with proper design of the patterns, it is possible to control and manipulate the propagation of light within the material. Because the physical phenomenon in photonic crystals is based on diffraction, the periodicity of the photonic crystal structure needs to be in the same dimensional scale as the wavelength of the electromagnetic waves of interest. The more the contrast in refractive index, the better the optical properties of the photonic crystal, photonic crystals are considered to be micro photonics structures, but they are generally discussed in the context of nanophotonics.

Photonic Crystals are artificially created, multidimensionally periodic structures. Photonic crystals are 2D or 3D ordered structures composed from submicrometersized objects. An example of a photonic crystal is opal, the gemstone: The opalescence is a photonic crystal phenomenon based on Bragg diffraction of light on the crystal's lattice planes. In general, photonic crystals are periodic dielectric structures that control the propagation of light. The dielectric structures have lattice parameters on the order of the wavelength of light. When these structures are periodic, that is, when the refractive index exhibits 2D or 3D modulation effects, the structures are“crystallinelike” and demonstrate “Bragg” diffraction. This is associated with the opening of a “bandgap” in the photonic Brillouin zone, namely, there is a range of frequencies at which the propagation of electromagnetic waves is forbidden. Photonic Bandgaps give rise to new possibilities for the design of optical switches, wavelength-selective mirrors (Bragg mirrors), lossless reflectors, and lasers.

The basic form of a photonic crystal is a 1D periodic structure such as a multilayer film. Electromagnetic wave propagation in such systems was first studied by Rayleigh in the late nineteenth century, when he demonstrated that any such 1D system has a bandgap. The 1D periodic systems eventually appeared in applications ranging from DFB lasers to reflective coatings. The 2D periodic optical structures, without bandgaps, received initial study in the 1970s and 1980s. The possibility of 2D and 3D periodic crystals with 2D and 3D bandgaps was suggested a century after Rayleigh: In 1987 Eli Yablonovitch and Sajeev John independently published articles describing these constructs.

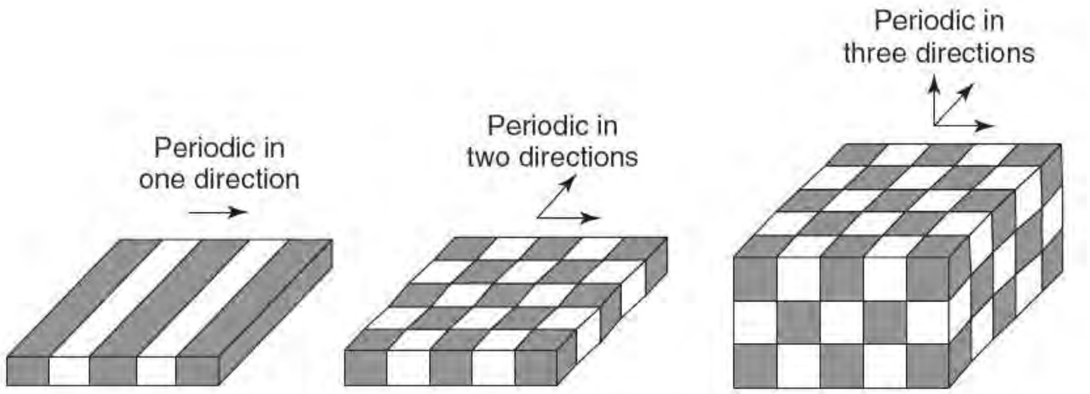
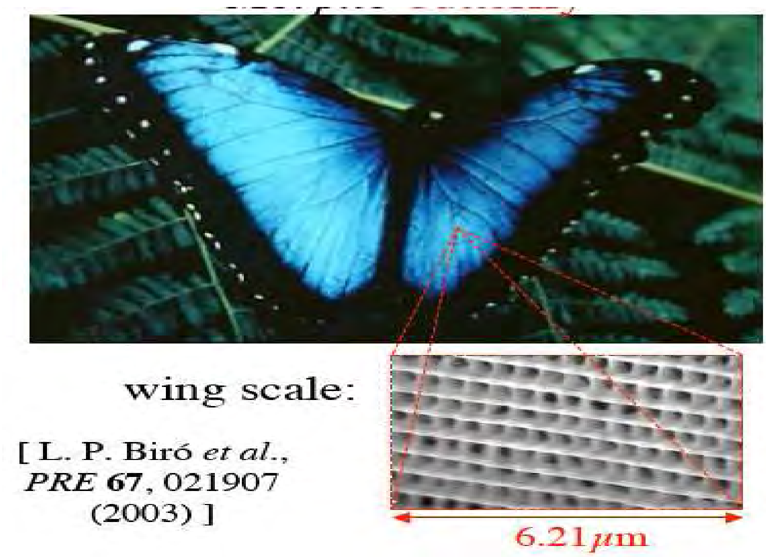


FIGURE 3.1: 1D, 2D, and 3D PCs. Different shades represent materials of different values of refractive index.

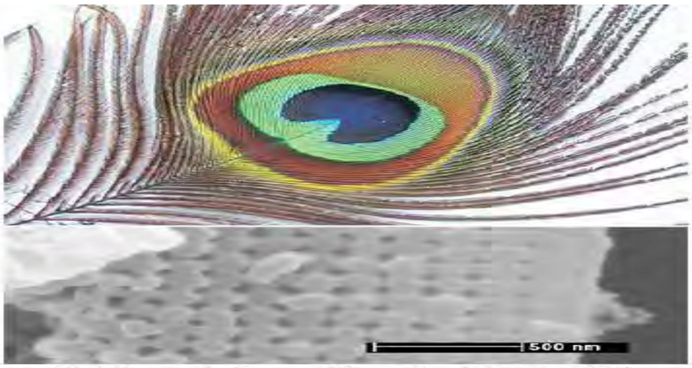
Figure 3.1 depicts how the periodicity defines dimensionality of photonic crystals. When the index of refraction changes periodically along one direction only, then the material is a 1D photonic crystal. 2D Photonic Crystal has refractive index varying periodically along two directions. In dielectric structures with a 3D periodicity, there are no propagation modes in any direction for a range of frequencies, giving rise to a complete photonic bandgap [25].

Light with a particular color that enters the structure is scattered in all directions by the photonic crystal. Effectively, the crystal acts as a mirror maze for photons. Due to interference effects, certain colors of light can be completely forbidden from propagating through the crystal. This notably leads to the peculiar phenomenon that an embedded light source is forbidden from emitting photons. In Nature, parts of several living organisms have Photonic Crystals in them. For example, Figure 3.2 shows iridescent colors of butterfly wings are due to Photonic Crystals. And also sea mouth and figure 3.3 shows peacock feathers have different colors because of Photonic Crystals [4].



[L. P. Biró *et al.*, *PRE* **67**, 021907 (2003)]

Figure 3.2: Iridescent colors of butterfly wings [26]



[J. Zi *et al*, *Proc. Nat. Acad. Sci. USA*, **100**, 12576 (2003)]

Figure 3.3: Natural photonic crystals in Peacock feathers [27]

3.2.1 Photonic Bandgap

Photonic Crystals describe a class of semiconductor structures with a periodic variation of refractive index in 1, 2, or 3 dimensions. As a result, photonic crystals possess a photonic band gap – a range of frequencies in which the propagation of light is forbidden. This unique characteristic of photonic crystals enables them to be used to manipulate light [28]. In recent years several dielectric structures were found to possess a photonic band gap, a range of frequencies for which no propagating states exist. The existence of a photonic band gap gives rise to a number of interesting and useful properties, including the localization of light at defects and at surfaces and the inhibition of radiation. These properties become more pronounced as the photonic band gap is made larger. Therefore, to permit us to take maximal advantage of the ability of photonic crystals to control electromagnetic radiation, development of photonic crystals with large band gaps is important [29].

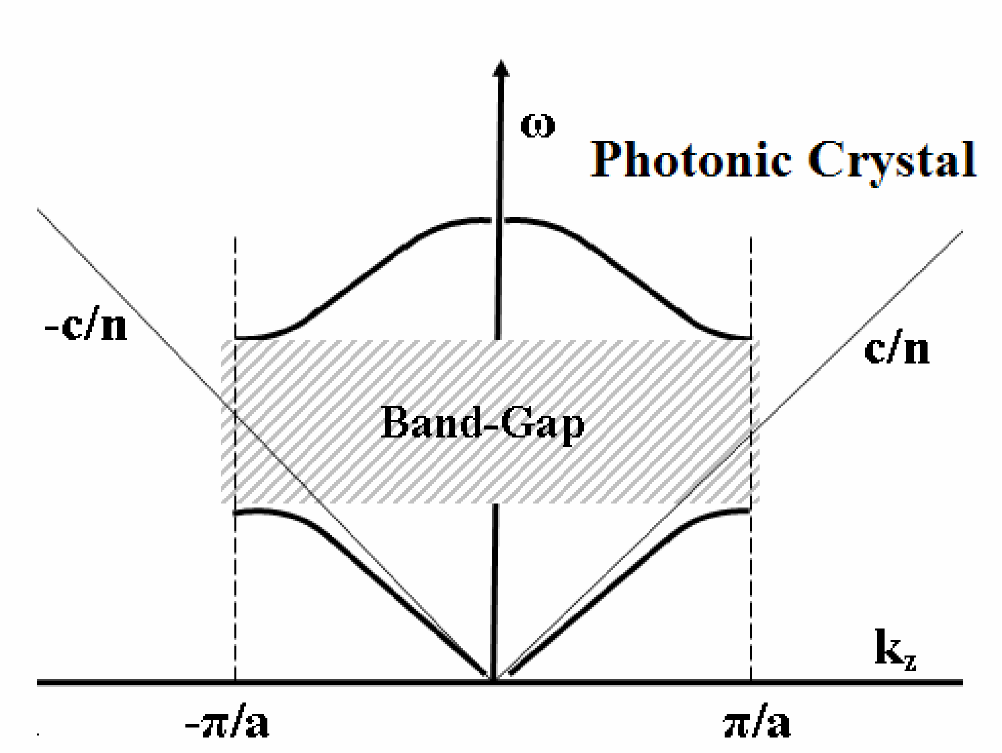


Figure 3.4: Typical band structures of photonic crystals [30].

3.3 Propagation of Light

The propagation of light in photonic crystal can be studied by using Maxwell equations. All of macroscopic electromagnetism, including the propagation of light in a photonic crystal, is governed by the four macroscopic Maxwell equations. These are

$$\begin{aligned} &\nabla . B = 0 \\ &\nabla X E + \frac{dB}{dt} = 0 \\ &\nabla . D = \rho \\ &\nabla X H - \frac{dD}{dt} = J \end{aligned} \qquad (3.3.1)$$

Where E and H are the macroscopic electric and magnetic fields respectively, D and B are the displacement and the magnetic induction fields, ρ and J is the free charge and current densities. We will see the propagation with a mixed dielectric medium, a composite of regions of homogeneous dielectric material as a function of (Cartesian) the position vector r, in which the structure does not vary with time and there are no free charges or currents. This composite need not be periodic in which light propagates but there are no sources of light, we can set ρ = 0 and J= 0.we can relate D to E and B to H with the constitutive relations. The components D_i of the displacement field D are related to the components E_i of the electric field E via power series.

$$\frac{D_i}{\varepsilon_0} = \sum_j \varepsilon_{ij} E_j + \sum_{j,k} X_{ijk} E_j E_k + O\left(E^3\right) \qquad (3.3.2)$$

Where $\varepsilon_0 \approx$ 8.854 x 10^{-12} farad/m is the vacuum permittivity. However, for many dielectric materials, it is reasonable to use the following approximations. First, we assume the field strengths are small enough so that we are in the linear regime, so that X_{ijk} (and higher-order terms) can be neglected. Second we assume the material is macroscopic and isotropic, so that E(r, ω) and D(r, ω) are related by ε_0 multiplied by a scalar dielectric function $\varepsilon(r,\omega)$ also called the relative permittivity. Third we ignore any exploit frequency dependence of the dielectric constant. Instead, we simply choose the value of dielectric constant appropriate to the frequency range of the physical system we are considering. Fourth, we focus primarily on transparent materials, which mean we can treat $\varepsilon(r)$ as purely real and positive. By assuming these four approximations to be valid, we have D(r) = $\varepsilon_0\varepsilon(r)E(r)$.A similar equation relates $B(r) = \mu_0\mu(r)H(r)$ (where $\mu_0 = 4\pi x 10^{-7}$ Henry/m is vacuum permittivity), but for most dielectric materials of interest the relative magnetic permittivity μ(r) is very close to unity and we may set $B = \mu_0 H$ for simplicity. In that case, ε is the square of the refractive index n that may be familiar from Snell's law and other formulas of classical optics. (That is $n = \sqrt{\varepsilon\mu}$) With all of these assumptions in place, the Maxwell equations (3.3.1) become

$$\nabla . H(r,t) = 0$$

$$\nabla .[\varepsilon(r)E(r,t)] = 0$$

$$\nabla X E(r,t) + \mu o \frac{dH(r,t)}{dt} = 0$$

$$\nabla X H(r,t) - \varepsilon o \varepsilon(r) \frac{dE(r,t)}{dt} = 0 \qquad (3.3.\ 3)$$

Both E and H are complicated functions of both time and space. Because the Maxwell equations are linear; however, we can separate the time dependence from the special dependence by expanding the fields in to a set of harmonic modes. We can write Maxwell equations that vary sinusoidally with time. This is no great limitation, since we know by Fourier analysis that we can build any solution with an appropriate combination of these harmonic modes. Often we will refer to them simply as modes or states of the system. For mathematical convenience, we employ the standard trick of using a complex –valued field and remembering to take the real part to obtain the physical fields. This allows us to write a harmonic mode as spatial pattern (or "mode profile times a complex ") exponential:

$$H(r,t) = H(r) \exp - iwt$$

$$E(r,t) = E(r) \exp - iwt \qquad (3.3.4)$$

To find the equations governing the mode profile for a given frequency, we insert the above equations in to equation (3.3.3). The two divergence equations give the conditions

$$\nabla . H(r) = 0$$

$$\nabla . [\varepsilon(r) E(r)] = 0 \qquad (3.3.5)$$

Which have a simple a physical interpretation: there are no point sources or sinks of displacement and magnetic fields in the medium. Equivalently, the field configurations are built up of electromagnetic waves that are transverse. That is, if we have a plane wave $H(r) = a \exp(ik.r)$, for some wave vector k, equation (3.3.5) requires that $a.k = o$. We can know focus our at tension only on the other two of Maxwell equations as long as we are always careful to enforce this transversality requirement. The two curl equations relate E(r) to H(r):

$$\nabla X E(r) - i\omega\mu oH(r) = 0$$

$$\nabla X H(r) + i\omega\varepsilon(r) E(r) = 0 \qquad (3.3.6)$$

We can decouple these equations in the following way. Divided the bottom equation of (3.3.6) by $\varepsilon(r)$, and then take the curl. Then use the first equation to eliminate E(r). Moreover, the constants

ε_0 and μ_0 can be combined to yield the vacuum speed of light; $c = \frac{1}{\sqrt{\varepsilon_0 \mu_0}}$ the result is an equation entirely in H(r):

$$\nabla X \left(\frac{1}{\varepsilon(r)} \nabla XH\ (r)\right) = \left(\frac{\omega}{c}\right)^2 H\ (r) \qquad (3.3.7)$$

This is the master equation. Together with the divergence equation (3.3.5), it tells us every thing we need to know about H(r). So for a given $\varepsilon(r)$, solve the master equation to find the modes H(r) and the corresponding frequencies, subject to transversality requirement. Then use the second equation of (3.3.6) to recover E(r):

$$E(r) = \frac{i}{\omega \varepsilon o \, \varepsilon(r)} \nabla XH\ (r) \qquad (3.3.8)$$

Using this procedure guarantees that E satisfies the transversality requirement $\nabla.\varepsilon E = 0$, because the divergence of curl is always zero. Thus, we need only impose one transversality constraint, rather than two. The reason why we choose to formulate the problem in terms of H(r) and not E(r) is merely one of mathematical convenience. We can also find H from E via the first equation of (3.3.6) [31]:

$$H\ (r) = \frac{i}{\omega \mu\ o} \nabla XE\ (r) \qquad (3.3.9)$$

3.4 Methods of Fabrication

A wide variety of methods have been used to fabricate photonic crystals. Some of them are more suitable for the fabrication of 1D and 2D photonic crystals, whereas others are useful when one needs to localize photons in three dimensions. Some of these methods are discussed here.

Self-Assembly Methods. Colloidal self-assembly seems to be the most efficient method for fabrication of 3D photonic crystals. In this method, predesigned building blocks (usually monodispersed silica or polystyrene nanospheres) spontaneously organize themselves into a stable structure. Although the currently available colloidal assemblies do not have a full photonic bandgap in the optical wavelengths because of their low index contrast, they do provide a template that can be infiltrated with material of higher refractive index.

A number of techniques are available for colloidal assembly fabrication. A widely used technique for creating colloidal crystals is gravity sedimentation. Sedimentation is a process where by particles, suspended in a solution, settles to the bottom of the container, as the solvent evaporates. The critical point here is finding the proper conditions for liquid evaporation so that the particles form a periodic lattice. Sedimentation under gravity is a slow process, taking as long as four weeks to get good crystals. If the process is accelerated to a few days, then crystallization produces a polycrystalline structure with many defects, as shown by the AFM image in Figure 3.5. The size of crystallites varies and depends on the quality of building blocks, time of crystallization, temperature, humidity, and so on.

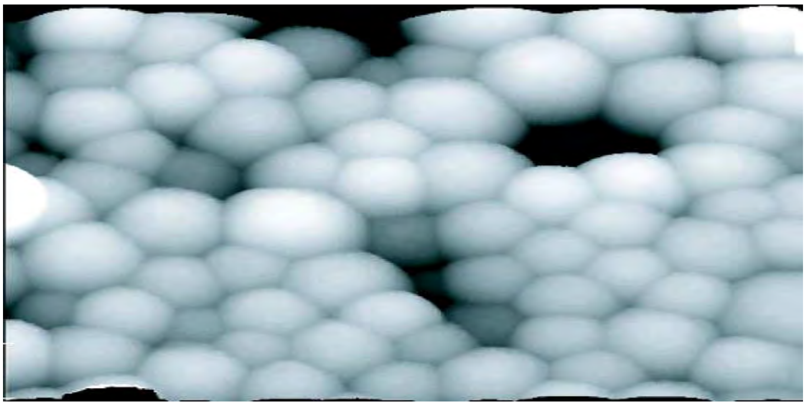


Figure 3.5: The AFM image of 450-nm silica beads produced by sedimentation method, using crystal growth for 5 days.

Two-Photon Lithography. Two-photon lithography has been used for 3D photonic crystal fabrication. This technique utilizes the fact that certain materials, such as polymers, are sensitive enough to two-photon excitation to trigger chemical or physical changes in the material structure, with nanoscale resolution in three dimensions.

E-Beam Lithography. Electron beam lithography is a method that enables one to create various photonic crystals with extremely high resolution. It is a relatively complicated method, because it includes many variables. Its main disadvantage is its high cost. In this method, the sample (wafer) is covered with an electron-sensitive material called resist. The material, used as resist, undergoes a substantial change in its chemical or physical properties, when it is exposed to an electron beam. The beam position and intensity is computer controlled, and electrons are delivered only to certain areas to get the desired pattern. After exposition, a part of the resist is dissolved away and the sample can be further processed with etching procedures to get the final crystalline structure. Electron beam lithography is mostly used for fabrication of 2D photonic crystals. An example of a 2D photonic crystal fabricated by this technique is shown in Figure 3.6.

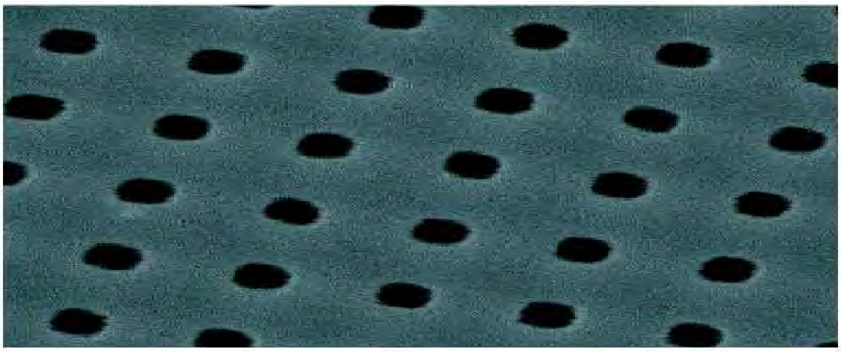


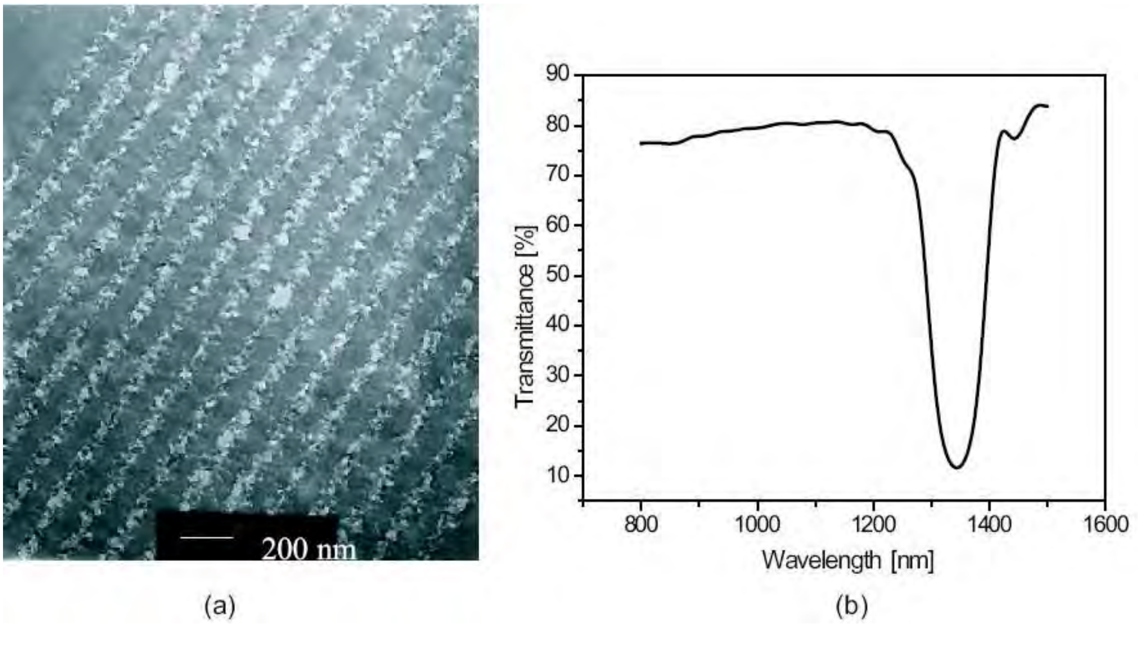
Figure 3.6: SEM image of a photonic crystal fabricated by E-beam lithography.

Etching Methods. These methods are more suitable for the fabrication of two dimensional photonic crystals and have been used for semiconductors. These methods utilize marking of a planar pattern of unwanted areas on the surface of a semiconductor, using a lithographic technique such as E-beam lithography. These marked areas are then etched to create holes. The two methods used are:

♦Dry Etching. An example is reactive-ion etching (RIE), which utilizes reactive ions generated by plasma discharge in a chlorine-based ($SiCl_4$ and Cl_2) or fluorine- based (CHF_3, CF_4, C_2F_6, and SF_6) reactive gas. These ions are accelerated toward the sample surface under an electric field. This dry etching provides a good control over the hole size, but has a limited maximum etching depth. The method has been used for many semiconductors, such as GaAs, AlGaAs, and Si.

♦Wet Etching. An example is electrochemical etching that has also been used for many semiconductors. Electrochemical etching of Si to produce microporous silicon photonic crystal is an example. In this case, a pre-pattern with etch pits was first created on the front face of a silicon wafer by using lithographic patterning and subsequent alkaline chemical etching using KOH solution. The wafer was then mounted in an electrochemical cell and electrochemically etched using an HF solution. The pre-etched pits form nucleation centers for electrochemical etching. The advantage provided by an electrochemical etching method is that deep holes can easily be produced.

Holographic Methods. Holographic methods, which utilize interference between two or more coherent light waves to produce a periodic intensity pattern, have been used to produce a periodic photoproduced photonic structure in a resin (photoresist). Here, the initial laser beam is split into several beams and allowed to overlap in the resin at angles predetermined by the desired periodicity. The simplest is the fabrication of a one-dimensional periodic structure (a 1D photonic crystal or a Bragg grating) produced by overlap of two beams, where the angle between the two beams determines the periodicity. This method has been in practice for a long time. Recent developments are the use of photopolymerizable (or photocrosslinkable) medium containing inorganic nanoparticles (as TiO2, metallic nanoparticles) or liquid crystal nanodroplets in which the nanoparticles prefer domains that are not photomodified. In this case, the bright spot in the intensity pattern not only produces a photomodified region, but also aligns the nanoparticles in the non-photomodified region to enhance the refractive index contrast. To produce 1D photonic crystals as shown in Figure 3.7. Interference of more than two beams has been utilized to produce 2D and 3D photonic crystals [7].



(a)

(b)

Figure 3.7: Holographic method used to produce one-dimensional photonic crystal using polymer-dispersed liquid crystal (a) TEM picture, (b) transmission spectrum.

3.5 Fabrication Challenges

The major challenge for higher dimensional photonic crystals is in fabrication of these structures, with sufficient precision to prevent scattering losses blurring the crystal properties and with processes that can be robustly mass produced. One promising method of fabrication for two-dimensionally periodic photonic crystals is a photonic crystal fiber, such as a "holey fiber". Using fiber draw techniques developed for communications fiber it meets these two requirements, and photonic crystal fibres are commercially available. Another promising method for developing two-dimensional photonic crystals is the so-called photonic crystal slab. These structures consist of a slab of material (such as silicon) which can be patterned using techniques borrowed from the semiconductor industry. Such chips offer the potential to combine photonic processing with electronic processing on a single chip. For three dimensional photonic crystals various techniques have been used including photolithography and etching techniques similar to those used for integrated circuits. Some of these techniques are already commercially available like Nanoscribe's Direct Laser Writing system. To circumvent nanotechnological methods with their complex machinery, alternate approaches have been followed to grow photonic crystals as self-assembled structures from colloidal crystals [31].

3.6 Applications of Photonic Crystals

Photonic Crystals are attractive optical materials for controlling and manipulating the flow of light. One dimensional photonic crystal are already in widespread use in the form of thin-film optics with applications ranging from low and high reflection coatings on lenses and mirrors to colour changing paints and inks. Higher dimensional photonic crystals are of great interest for both fundamental and applied research, and the two dimensional ones are beginning to find commercial applications. The first commercial products involving two-dimensionally periodic photonic crystals are already available in the form of photonic-crystal fibers, which use a microscale structure to confine light with radically different characteristics compared to conventional optical fiber for applications in nonlinear devices and guiding exotic wavelengths. The three-dimensional counterparts are still far from commercialization but offer additional features possibly leading to new device concepts (e.g. optical computers), when some technological aspects such as manufacturability and principal difficulties such as disorder are under control [32].

Chapter 4

Summary and Future Outlook

4.1 Summary

This paper reviews Nanophotonics; a sub-field of Nanotechnology that concerned with discovering and developing nanomaterials that can control the flow of light and in some cases localize or confine it within a volume. Intuitively, we view light as rays, which propagate in a single direction, either being absorbed or reflected to some extent by any object on which it impinges. However, the propagation of light through a material is itself a quantum effect, involving the excitation and relaxation of electrons in the material. Creating a material with structural and compositional features on a length scale comparable to the wavelength of light (i.e. 300-700) nm for visible light) enables us to guide light in any direction that we choose. Our aim is to present the recent exciting developments of nanophotonics and applications.

The area nanophotonics deals with a number of interesting topics in nanophotonics and nanostructures and their applications in general. Interactions of waves in semiconductors are main focus and different approaches to confine these waves and devices employing such confinement are the key issue in nanophotonics. Localization of light and applications to metallic mirrors, photonic crystals, optical waveguides, microresonators, plasmonics are gaining tremendous applied interest. Localization of quantum mechanical waves in quantum wells, wires and dots has been demonstrated. Devices incorporating localization of both electromagnetic and quantum mechanical waves, such as resonant cavity quantum well lasers and microcavity-based single photon sources are on the way of commercialization. System-level applications of the introduced concepts, such as optical communications, biochemical sensing, and quantum cryptography are targeted for future.

Surface Plasmon is an emerging field in nanophotonics in recent time. Surface Plasmons are collective charge oscillations that occur at the interface between conductors and dielectrics. They can take various forms, ranging from freely propagating electron density waves along metal surfaces to localized electron oscillations on metal nanoparticles. Their unique properties enable a wide range of practical applications, including light guiding and manipulation at the nanoscale, biodetection at the single molecule level, enhanced optical transmission through subwavelength apertures, and high resolution optical imaging below the diffraction limit. The Surface Plasmon Resonance (SPR) phenomena observed on noble metal surfaces or nanoparticles has been a great interest in several fields of research such as nanoscale photonics and biological sensing. Surface Plasmon Resonance can simply be defined as collective oscillations of free electrons coupled to the metal-dielectric interfaces. If the collective oscillation of free electrons is confined to a finite volume as with a metal nanoparticle, the corresponding plasmon is called a localized surface plasmon. Surface Plasmon Polaritons (SPPs) are quasi-two-dimensional electromagnetic excitations, propagating along a dielectric-metal interface and having the field components decaying exponentially into both neighboring media.

Photonic Crystals are optical materials that allow for controlling and manipulating the flow of light. Photonic crystals are composed of a regular arrangement of a dielectric material that shows strong interaction with light; any material exhibiting spatial periodicity in refractive index is a photonic crystal. Photonic Crystals are materials with repeating patterns spaced very close to one another, with separations between the patterns comparable to the wavelengths of light. When light falls on such a patterned material, the photons of light interact with it, and with proper design of the patterns, it is possible to control and manipulate the propagation of light within the material. Photonic Crystals (PCs) describe a class of semiconductor structures with a periodic variation of refractive index in 1, 2, or 3 dimensions. As a result, PCs possess a photonic band gap – a range of frequencies in which the propagation of light is forbidden. This unique characteristics of Photonic Crystals enables them to be used to manipulate light. The major challenge for higher dimensional photonic crystals is in fabrication of these structures, with sufficient precision to prevent scattering losses blurring the crystal properties and with processes that can be robustly mass produced. The methods of fabrication of photonic crystals are Self-Assembly Methods, Two-Photon Lithography, E-Beam Lithography, Etching Methods, and Holographic Methods, which has been discussed.

4.2 Future Outlook

The scientific quest for knowledge, along with societal demand for compact, energy-efficient, and multimodal technologies, ensures a bright future for nanophotonics. Like in most technology areas, market-driven inventions will create economic opportunities. However, recognizing that nanophotonics is an emerging area, new scientific discoveries will also play a dominant role in the development of new technologies. As we strive for cleaner and efficient sources of energy, solar energy conversion becomes a priority area in which nanophotonics play great role. A nanophotonic approach utilizing inorganic: organic hybrid nanostructures and nanocomposites can produce broadband harvesting of solar energy while using flexible low-cost, large-area roll-to-roll plastic solar panels and solar tents.

The information technology based on the nanotechnology varies, from the targets that can be realized in the comparatively near future to those with long-term goals such as quantum info-communication and quantum computing technology. In the quantum dot area, quantum dot laser, quantum dot optical amplifier, quantum dot nonlinearity devices, and quantum dot light detectors are about to emerge into the real world. The expectations are high for optical circuit of the optical router. This will be the basic component of the router in the future photonic network and quantum dot amplifier for application to optical 3R relay generator will play a key role. The expectation is that the quantum dot be sued for this single photon generator. The expectation is also high for the realization of nanophotonics based on the new principle. The nanophotonic element is an ultimate element that uses strongly connected condition of the light and electron that include the polariton laser. Investment in nanophotonics should lead to realization of low energy consumption society and promotion of heals of the people. There will come an age when nanophotonic elements will play dominant role including the fusion of quantum dot and photonic crystal. The quantum dot will be the basic component of future quantum computing elements and expectations are very large for emergence of new “non-continuous” technology based on the quantum dot technology.

Since Photonic Crystals offer prospects for numerous applications: low-threshold lasing, optical-power limiting, chemical and biosensing, and optical switching. It will play a major role in further development of this exciting field. Photonic components such as fiber optic cables can carry a lot of data but are bulky compared to electronic circuits. Electronic components such as wires and transistors carry less data but can be incredibly small a single technology that has the capacity of photonics and the smallness of electronics would be the best bridge of all. So ‘Light on a Wire,' Is Circuitry Wave of Future as predicted.

There is an ever-increasing need to enhance the capability of sensor technology for health, structural, and environmental monitoring. One area of great concern is new strains of microbial organisms and the spread of infectious diseases that require rapid detection and identification. This requires point detection as well as environmental monitoring. Another area of major concern, worldwide, is the threat of chemical and biological weapons. The detection here is not only for the danger posed to health, through chemical and biological agents, but also for structural damage (to bridges, monuments, etc., through explosives). Nanophotonics-based sensors utilizing nanostructured multiple probes provide the ability for simultaneous detection of many threats, as well as the ability for remote sensing where necessary. A useful future approach can utilize nanoscale optoelectronics with hybrid detection methods involving both photonics and electronics.

As an increasingly aging world population presents unique healthcare problems, new approaches for early detection and treatment of diseases will be required. Nanomedicine utilizing light-guided and light-activated therapy, with the ability to monitor real-time drug action, will lead to new approaches for more effective and personalized molecular-based therapy. A major concern already raised by many is any long-term adverse health effects (such as toxicity, accumulation in vital organs, obstruction of circulatory system, etc.) produced by nanoparticles. Another version of the nanomedicine approach can be useful for cosmetic industry. There is strong evidence that there will be numerous business opportunities for nanophotonics and that nanophotonic innovations will have both evolutionary and revolutionary impacts in a wide range of markets.Every new technology has good and bad sides that too in nanotechnology. However, we need to find intelligent and proper way of employing things that will be useful to civilization of mankind.

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