27

Nanophotonics for 21st Century

S. K. Ghoshal[1], M. R. Sahar[1], M. S. Rohani[1] and Sunita Sharma[2]
[1]*Advanced Optical Material Research Group, Department of Physics, Faculty of Science, Universiti Teknologi Malaysia, Skudai, Johor,*
[2]*Materials Science Group, Inter-University Accelerator Centre, Aruna Asif Ali Marg, New Delhi, India*

1. Introduction

Recent advances in the synthesis and understanding of material properties at nanoscale in addition to the development of the nanofabrication techniques has enabled researchers to control and manipulate photons at nanometer scales. These have given the birth of an emerging hybrid technology with multi-facets applied interests, popularly known as *nanophotonics*. Nanophotonics can be defined as the science and engineering of light-matter interactions. These interactions, which take, place, on the one hand, within the light wavelength and sub-wavelength scales and, on the other hand, are determined by the physical, chemical and structural nature of artificially or natural nanostructured matter. It is envisaged that nanophotonics has the potential to provide ultra-small optoelectronic components, high speed and greater bandwidth. Nanophotonics has significant potential applications in the field of science and technology. Some of them are sensors, lasers, optoelectronic chips, optical communications, optical microscopy (by overcoming the usual diffraction limit), bio-imaging, targeted therapy, barcodes, harvesting solar energy, etc., to cite a few (Kalele et al., 2007; Prasad, 2004; Shen et al., 2000). Nanophotonics are classified into three main branches as illustrated in the block diagram (figure 1) depicting various process and techniques in nanophotonics including plasmonics.

As mentioned, the field nanophotonics deals with a number of interestingly important topics in photonics and materials structures at nm length scales and their applications in general. Waves in the form of electromagnetic and quantum mechanical, and materials as semiconductors and metals are the focus. 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, micro-resonators, plasmonics are gaining tremendous applied interest. Localization of quantum mechanical waves in low dimensional structures such as 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 micro-cavity-based single photon sources are on the way of commercialization. Some system-level applications of the introduced concepts, such as optical communications, biochemical sensing and quantum cryptography are targeted for the near future.

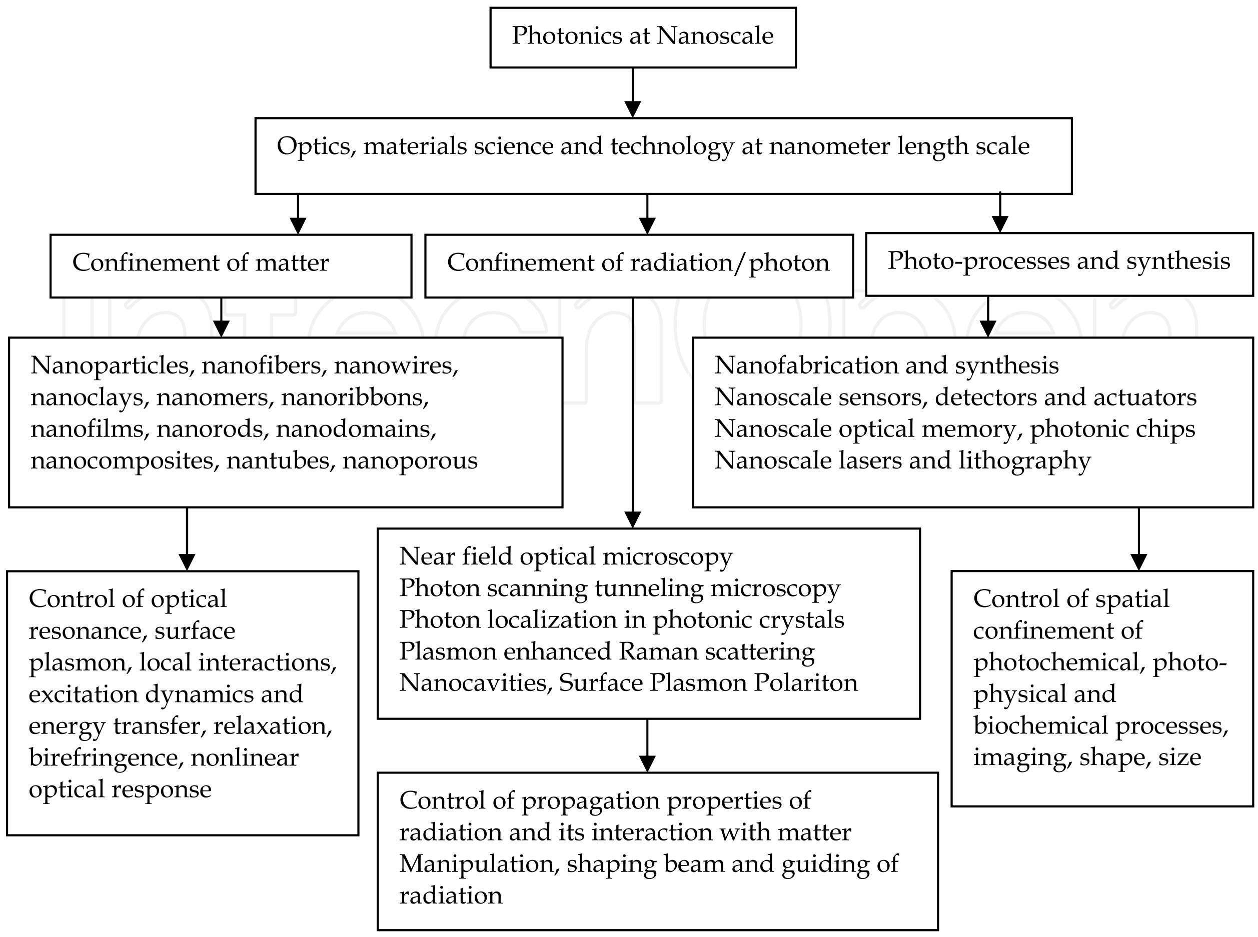


Fig. 1. A block diagram representing various major processes and techniques available in nanophotonics.

The main objectives of nanophotonics research is to control the optical energy and its conversion on the nanometer scale by combining the properties of metal, organic, semiconductor, organo-metallic, polymers and dielectric materials to create new, combined states of light and matter often called meta-materials. Specific examples of scientist's targets are:

- *Controlled quantum coupling at the nanoscale*: The ability to prepare coupled nanostructures presents tremendous opportunity to induce and control the interactions of photons, plasmons, polarons, polaritons and excitons, thereby producing new elementary excitations that have no bulk counterpart. Basic scientific research on these excitations is performed, with application to many disciplines such as solar energy conversion, nanoscale photonic devices, new photochemical processes, communications, sensing, imaging and quantum logic.
- *Understanding ultrafast processes at ultra-small length scales*: The outcome of ultrafast processes can be very different in nanoscale versus bulk materials, with potentially great impact on the physical properties and photochemical products of the nanoscale system. Research has been continuously performed to understand, manipulate, optimize and control these differences.
- *New routes to functional nanophotonic materials*: The development of novel optical materials via three main approaches are:

  - Advanced colloidal synthesis,
  - Lithographically assisted synthesis,
  - Advanced near-field optical lithography techniques for generating hybrid nanoscale structures over large areas,
  - Ion-beam milling and sputtering,
  - Chemical vapor deposition, and
  - Laser ablation
- *Efficient energy transport in plasmonic nanostructures*: Some research is ongoing for significant improvement of:
  - The range of plasmon propagation minimizing loss,
  - The manipulation of localized surface plasmon and surface plasmon polariton,
  - The spectral bandwidth that can be supported by plasmonic structures, and
  - The minimum lateral dimension for efficient plasmon propagation for guiding.

The art of research is the basis for entirely new, efficient solar concentrators, lasers or all optical nanoscale circuitry.

To achieve these objectives a four-pronged experimental and theoretical approach is often utilized:

- *Materials generation via physical and chemical synthesis and lithography,*
- *Optical instrumentation development for advanced characterization, fabrication,*
- *Materials modeling and rigorous numerical simulations, and*
- *Optimization and functionalization of devices via computer aided design*

Some of the leading equipments that are used to achieve this target are Near-field scanning optical microscope, Con-focal Raman microscope, Nanolithography, Ultra-fast transient absorption spectroscopy, Ultra-fast microscope, Chemical vapor deposition, Chemical synthesis, Atomic force and Scanning tunneling microscopy, Size-selected cluster facility and cluster-based nanomaterials for nanophotonics and nano(photo) catalysis (Sharma et al., 2005). Nanosphere lithography provides a very simple yet powerful way to fabricate nanoparticle arrays with precise control over size, shape and inter-particle spacing that is employed to fabricate sensors. They are made from mono-dispersed negatively charged silica or polystyrene nanospheres deposited on a negatively charged glass substrate that helps the nanospheres to diffuse freely until they reach their minimum energy configuration. The capillary forces draw these nanospheres together and finally form a close packed hexagonal pattern on the substrate. These self-assembled nanospheres thus form a mask through which a metal can be deposited by physical evaporation. The nanosphere mask is removed by sonicating the entire sample to obtain a triangular pattern of metal. The optical properties of these sensors can be tuned in the visible range by changing the size of nanospheres.

There is a great need to understand how electromagnetic waves behave in the presence of periodic or nearly periodic arrays of molecules and nanosized metal clusters, i.e. how to achieve optical frequencies in X-ray wavelength scales? Now there are the tools, to map topology, size and shape with optical properties. In the past, these tools were not available, and the tools still needed are the subjects of active research. It is the locally modified electromagnetic field, which allows one to make use of molecular photonics, taking nanophotonics to the molecular scale of a few nanometers. This, in turn, opens up possibilities not just for further miniaturization but also for radically enhanced light-matter interactions. Presently, some of the very genuine engineering concerns relates to when producing ultra-compact, low power and high-sensitivity optical devices, towards the level of single photon detection and emission, and onwards to computation by molecules.

Classes of materials, that inhibit the flow of light, within optical band frequencies, are called photonic band gap crystals or photonic band gaps for short. An array of closed packed nanospheres is the simplest realization of photonic band gap materials, made of polystyrene or silicon dioxide called opals. The range of the inhibited light depends mainly on both the size of the spheres and the number of layers. Another more advanced photonic band gap structure called an inverse opal structure can realize a photonic band gap around 1.5 μm that is made by using the nanospheres as a template. The spaces around the spheres are filled with silicon, and then the spheres themselves are removed. Photonic crystals or photonic band gap crystals are periodic dielectric or metallo-dielectric nanostructures that are designed to affect the propagation of electromagnetic waves in the same way as the periodic potential in a semiconductor crystal affects the electron motion by introducing allowed and forbidden electronic energy bands. Researchers in the field of photonic crystals are just beginning to understand the behavior of light in periodic media. Currently, there is an incipient understanding of what happens in periodic structures and, at the other end, optical processes in single molecules. Particular interest lies in materials with negative refractive indices and meta-materials. However, the gap in between is not bridged yet and requires in-depth investigations. The key issue is what happens when one has nearly periodic, or quasi-periodic, molecular or cluster arrays or clusters? The description of their optical properties is in rapid progress as is the behavior of light in complex media. For example, existing knowledge base is not enough to design novel devices, the associated platforms and system configurations.

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 either propagate in a single direction, 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. Therefore, creating a material with structural and compositional features on a length scale comparable to the wavelength of light i.e. 300 - 750 nm for the visible light enables us to guide light in any direction of our desire.

There are two major challenges to reach the molecular scale and develop mass production techniques. In molecular photonics the aim is to achieve sufficient control over light-matter interactions through nanoscale physical, chemical and structural modification interactions using a few or single molecules. Today, optical spectroscopy of single molecules provides a tool to sense the local environment, which complements and extends ensemble-averaged measurements performed in conventional bulk structures. The molecular-scale variables range from signal strength, orientation, emission spectrum and energy transfer to neighboring molecules. This has undeniable potential in areas requiring ultra-sensitive detection without suffering from random electrical noise. Therefore, molecular photonics holds the promise to key advances in quantum sources of light, efficient photon harvesting systems and optical tuning and switching, among others.

Nanophotonics comprises the fabrication of nanomaterials and their interaction with light, using near-field optics, and thereby controlling the spatial confinement of photo-physical and photochemical process. One way to induce interactions between light and matter on a nanoscale is to confine light to nanodimensions that are much shorter than the wavelength of light (Li et al., 2004; Rosa et al., 2005; Huang et al., 2008). The second approach is to confine matter to nanodimensions, thereby limiting interactions between light and matter to nanoscopic dimensions that are synthesized using nanotechnology lithographic techniques as indicated in figure 1. The last way is nanoscale confinement of photo-processes by inducing photochemistry or a light-induced phase change. This approach provides methods for nanofabrication of photonic structures and functional units. The three main applied areas of nanotechnology and their technical concepts are shown in figure 2, whereas the widespread utility in every sphere of basic and applied sciences as well as engineering is illustrated in figure 3. Similar to the periodic electron-crystal lattice, one can fabricate photonic-crystal lattice. The refractive index varies with a much larger period of around 200 nm. The similarity between electronic and photonic crystals is represented in figure 4. The following characteristics are essential for the materials for making nanophotonics devices:

- Nanoscale quantum dots can be formed in high density.
- Quantum dots are in isolated condition, when not in photo-excited state.
- Nanorods or nanowires large quantum yield and high aspect ratio.
- Highly excited level energy can be controlled by material mixture ratio and dimension.
- Light element excitation is stable at room temperature, and high-excited level does not degenerate.

The brilliant, yet simple result is that one can treat photons in a similar manner as one does with electrons, and begin to envision 'optical' circuit components as existed electronic circuit components.

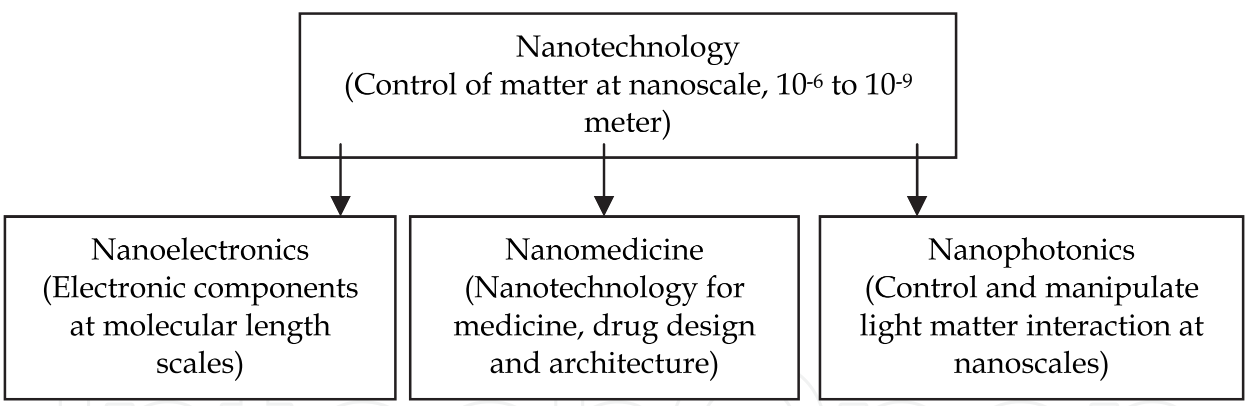


Fig. 2. Block diagram depicting three main branches of nanotechnology.

It is realized that an increasing number of novel materials, techniques, concepts and processes continue to be discovered in the context of nanotechnology and nanophotonics. There is an urgent need to develop the required understanding and to evaluate this new knowledge from the perspective of both novel science and potential applications. Understanding the fundamentals of nanophotonics is important because to fabricate a test structure it is necessary to home in on a window of parameters. The permutations on parameterization, optimization and functionalities are infinite, because there are millions of molecules, hundreds of different atoms and structures one can attach to them, and arranged them to realize a functional device. A window of parameters always helps to target the nanostructures and molecular laboratory samples into research objects, which can give information on device-relevant properties. The obvious boundary conditions are power consumption and cost that needs to be minimized for commercialization. The best option that is recently adopted is to work with molecules embedded in matrices; they are not only efficient but also relatively easier to handle and to manufacture.

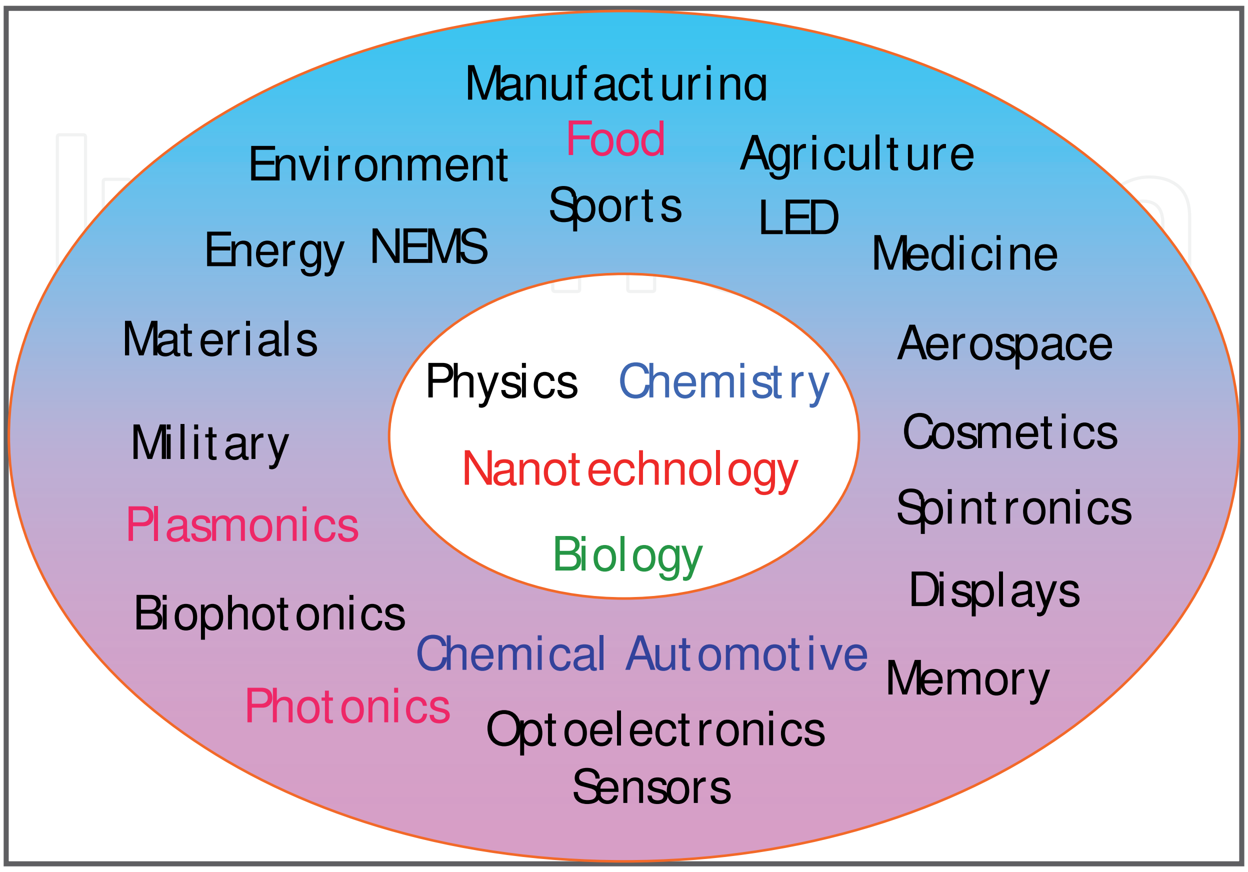


Fig. 3. Schematics representing various branches of nanotechnology and related applied fields in science and engineering.

Nanoscale photo-processes are comprised of nanoscale lithography, fabrication of nanoscale structures, and nanoscale optical memories. Foundations for nanophotonics require basic equations describing propagation of photons in dielectrics that has some similarities to the propagation of electrons in crystals (see figure 4). There are similarities between photons and electrons. Wavelength of light (photon) is given by

$$\lambda = \frac{h}{p} = \frac{c}{v} \tag{1}$$

Wavelength of electron is given by

$$\lambda = \frac{h}{p} = \frac{h}{mv} \tag{2}$$

The Maxwell's electromagnetic equations for the light (photon) describes the allowed frequencies of light and in a similar way Schrodinger's equation for the electrons describes allowed energies of electrons. Free space solution of the wave equation for both the photon and the electron are plane wave (see figure 5). Interaction potential in a medium for propagation of light affected by the refractive index of the dielectric medium and the propagation of electrons are affected by the Coulomb potential. In this case, both electrons and photons have propagation through classically forbidden zones. Photon tunnels through classically forbidden zones, the electric, and the magnetic fields decay exponentially that results k-vector is imaginary. Electron wave function decays exponentially in forbidden zones and has finite tunneling probability as shown in the figure 6.

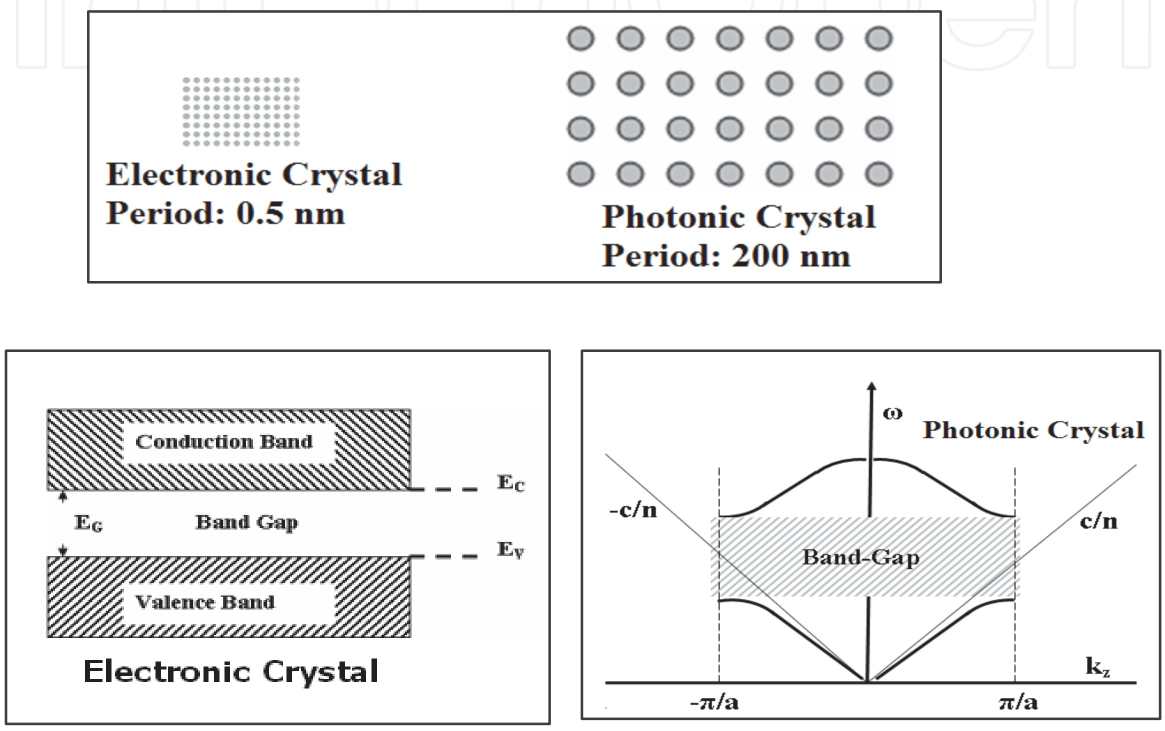


Fig. 4. The typical band structures of electronic and photonic crystals.

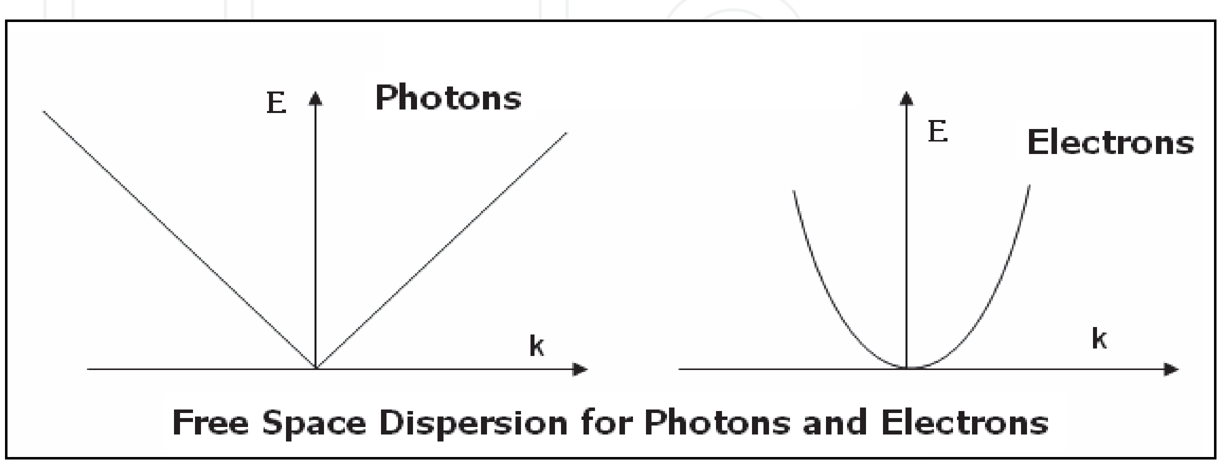


Fig. 5. Free space dispersion relations for photons (left) and electrons (right).

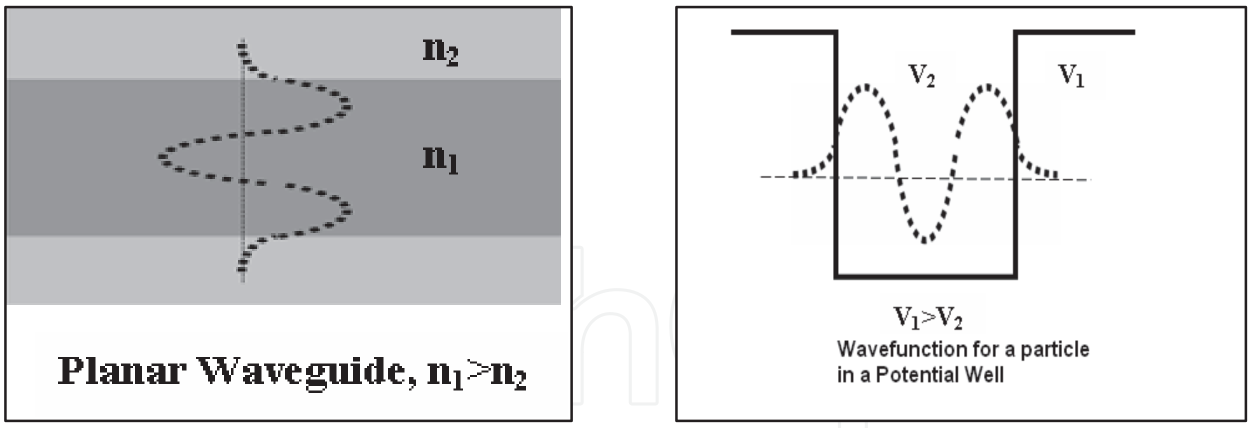


Fig. 6. Tunneling of photon (left) and electron (right) in the classically forbidden region.

Quantum confinement (see figure 7) causes manifestations of new optical effects due to the change in the nature of density of states from continuous to discrete structures as the dimension is reduced from three to zero. It is the density of states that guides optical and electrons correlation effects in quantum confined nanostructures. Size dependence of optical properties due to confinement produces a blue shift of the band-gap in semiconductors, and increases the oscillator strengths and in turn increases the optical transition probability. Location of discrete energy levels depends on the size and nature of the confinement. The oscillator strength increases with increasing confinement from bulk to quantum well to quantum wire to quantum dot. Confinement produces sub-bands within the conduction and valence bands, enabling intra-band optical transitions, which are not allowed in the bulk structures. These infrared transitions have applications in making new quantum cascade lasers and detectors. The oscillator strengths increase as the width of the quantum well decreases. The most important optical feature of these structures is that absorption/emission spectra shift to shorter wavelengths as the size become smaller. In case of metallic nanostructure, somewhat spectacular things happen due to which they show strong luminescence and plasmon absorption bands.

Artificial structures or meta-materials with the optical equivalent of the energy gap in semiconductors promise a wealth of new devices that could satisfy the demand for ever-faster computers and optical communications (Ozbay et al., 2004). Presently, the availability of personal computers that operate at 1 GHz (10^9 Hz), are really very impressive, but what is the likelihood of a 100 GHz desktop computer appearing on the market at affordable price? Indeed, with the current understanding of semiconductor technology, even producing a 10 GHz personal computer would seem to be difficult. However, by transmitting signals with light rather than electrons (a domain of optical computing), it might be possible to build a computer that operates at hundreds of terahertz (10^{12} Hz) which is of the order of the processing speed of the fastest earth simulator computer.

Researchers now believe that such an awesome processing engine could be built from optical components made from so-called photonic crystals and quasi-crystals. These materials possess structures with periodically modulated refractive indices that can be designed to control and manipulate the propagation of light. They are attracting more and more attention not only in the field of photonics but also in the fields of chemistry, physics, and microelectronics. This is because the photonic crystals enable us to control the flow of photons by means of photonic band gaps, which is a photonic analogue of energy band gaps in semiconductors. In recent years, much of the developments on the photonic band gap materials are made using insulators and semiconductors. However, metals or metallo-organic structures can also be used for the photonic band gap in the form of photonic surfaces using the surface plasmon resonance. The photonic band gaps can be introduced by texturing metal surfaces with three-dimensional patterns using spheres or any other shape with a spatial period roughly half of the free-space wavelength of light. Excitation of surface plasmons leads to the formation of standing waves and opening of the stopgap useful for channeling, guiding and controlling photons.

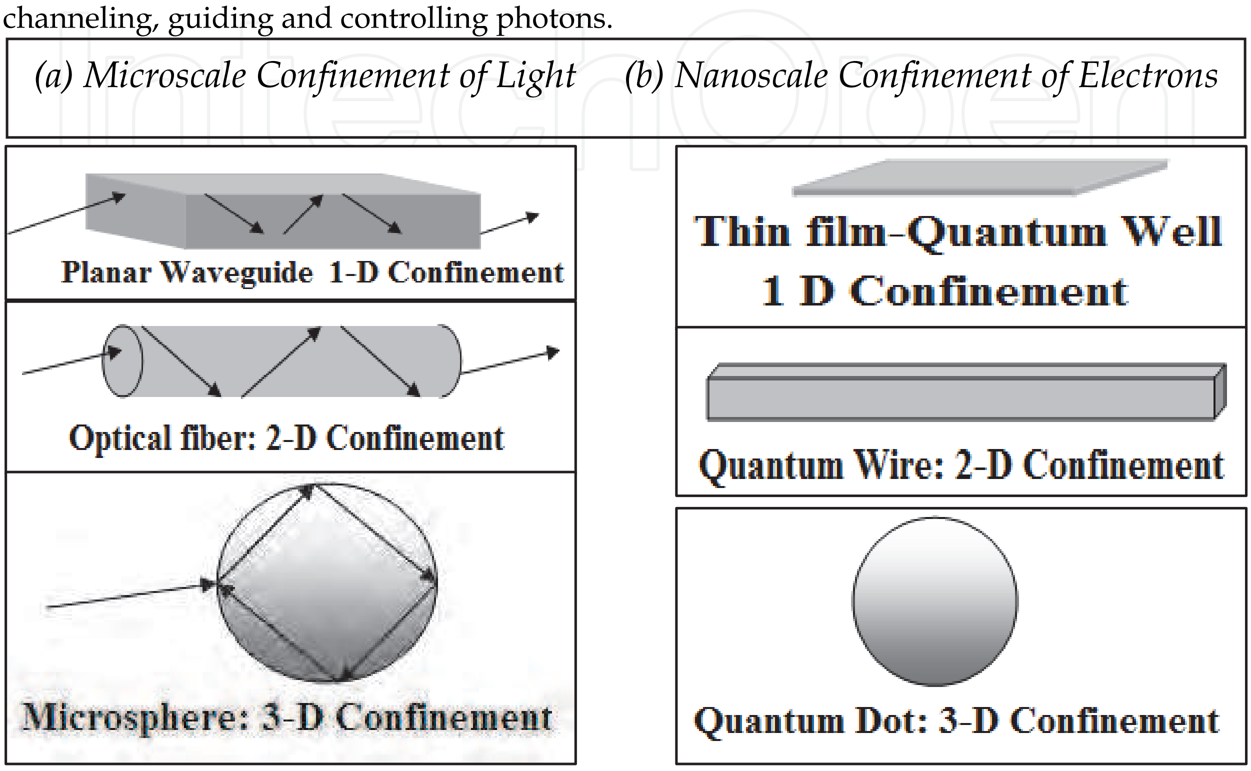


Fig. 7. Nanoscale confinements of photon (left) and electron (right) in different spatial dimensions.

The structures of traditional optical waveguides cannot be smaller than $\lambda/2$. Furthermore, wave guiding along bent guides causes dramatic loss. The problem associated with loss is overcome in photonic band gap structures, a potential candidate for nanophotonics device as already mentioned. However, the dimensions of the structures are still limited by the wavelength of light. This restriction can be overcome by wave guiding of the plasmonic excitation in closely placed metal nanoparticles. The photonic band gap crystals (see figure 8) and photonic band gap fibers involve periodic variation of dielectric constant over wavelength-scale. In common, electronic crystals like sodium chloride, the periodicity is of the order of one nm. Photonic crystals are produced by periodically varying refractive index in one, two or three dimensions and the period is comparable to the wavelength of light. Thus, the field of photonic crystals can be thought as microphotonics. However, in order to fabricate photonic crystals with micron-scale period, the fabrication technique must have nanoscale resolution. Therefore, it is appropriate to include photonic crystals in the domain of nanophotonics.

Basic electromagnetic equations describing propagation of photons in dielectrics have some similarities to propagation of electrons in crystals. The inspiration and very idea of photon localization in photonic band gap materials is drawn from nature. Undoubtedly, nature has demonstrated its advance capability in synthesizing nanomaterials to a level of sophistication and functionality far beyond our own. This inspiration comes from the glittering appearance of butterfly's wing and peacock's feathers, which has a highly ordered periodic structure at the nanoscale. The key to confining and guiding light within a material lies in the periodicity of the structures. An even more recent discovery is the capability of the weevil beetle to produce opals, a precious silica base gem, which have been synthetically produced to make three-dimensional photonic crystals. This discovery opens many doors for accessing the advanced molecular machinery of nature for fabricating photonic materials. Figure 9 illustrates an inverse opal photonic band gap structure that has been realized.

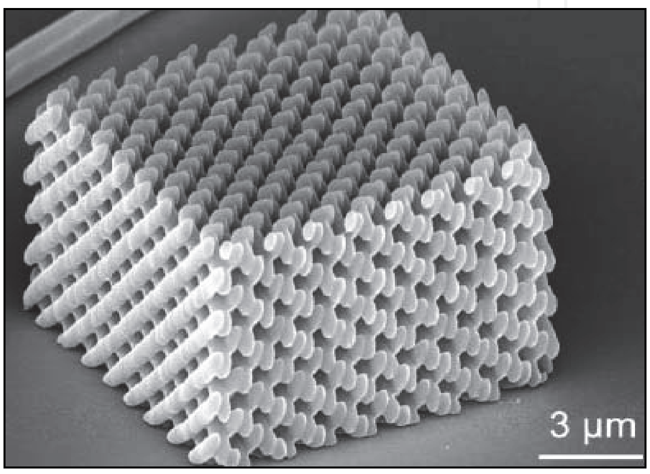


Fig. 8. A photonic band gap structure used for channeling light scaled in microns.

It is well known fact that electronics is the aspect ratio and is limited in speed, whereas, photonics is the diffraction that is limited in size. Plasmonics can go beyond the sub-diffraction limit and is not limited my any means because the surface plasmon wavelengths can reach to nanoscale at optical frequencies. Plasmonics will enable an improved synergy between electronic and photonic devices by naturally interfacing with similar size of electronic components and similar operating speed photonic network. Surface plasmon resonance has already been used by biochemists to detect the presence of a molecule on a surface. In recent years, plasmons are being exploited in many applications by manipulating and guiding light at resonant frequencies. There is a need to understand the origin and the fundamentals of physics associated with surface plasmon resonance before they are employed to many revolutionary applications. Rapid progresses in materials synthesis and nanofabrication techniques over the last decade have led to variety of applications. Some of the examples of plasmon-assisted nanophotonics are, high-resolution plasmon printing, laser shaping, solar concentrators, nanoscale waveguides, sensing, bio-detection at the single-molecule level and enhanced transmission through sub-wavelength apertures, to cite a few.

Since the inception of surface plasmon optics there has been a gradual transition from fundamental research to more applied oriented research. Presently, the surge in surface plasmon-based studies is happening at a time when crucial technological areas such as advanced 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. 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.

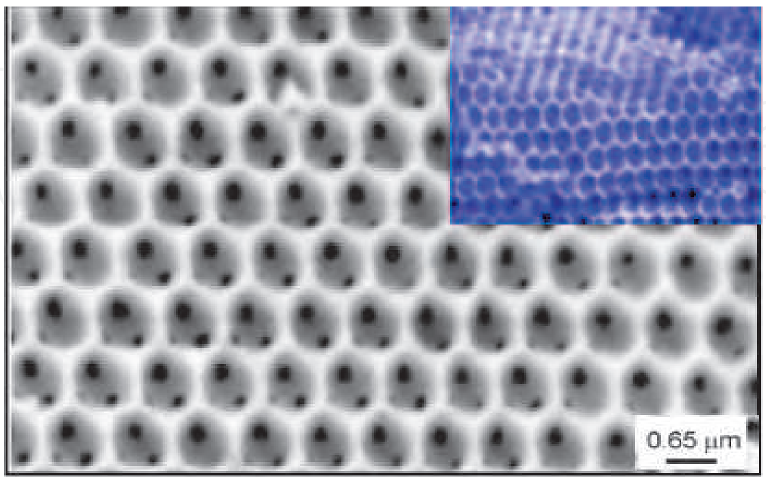


Fig. 9. An inverse opal photonic crystal structure (inset shows dielectric and air holes).

In photonics, metals are not usually thought of as being very useful, except perhaps as mirrors. In most cases, metals are strong absorbers of light, a consequence of their large free-electron density. However, in the miniaturization of photonic circuits, it is now being realized that the metallic structures can provide unique ways of manipulating light at length scales smaller than the wavelength. Surface plasmons, the light-induced excitations of electrons on metal surfaces, may provide integration of electronics and optics on the nanoscale. The optical manipulation of micron/submicron sized particles and bio-molecules through plasmonics have been investigated by Miao et al., and the schematic diagram of the experimental set-up is shown in figure 10. In recent years, a new horizon in nanophotonics has opened up called 'plasmonics' that consists of interaction of light wave with metal nanoparticles (Gopinath et al., 2009). Electromagnetic point of view metals are plasmas, comprising fixed, positive ion cores and mobile conduction electrons. At the plasma frequency, the real part of the dielectric constant changes sign. Therefore, the miniaturization of photonic circuits, allows metallic structures to manipulate light at length scales smaller than the wavelength. The typical thinking about metals is either conductors in electronics or reflectors in optics; however, metals as mirrors are not always desirable. Their residual absorption and low damage threshold makes them unsuitable for lasers and gyroscopes. Plasmonics has given photonics the ability to go to the nanoscale. Plasmonics utilizes the collective oscillations of conduction electrons in metallic nanostructures called plasmons, excited by the incident electromagnetic waves. In the following section, we will discuss in detail the basics of plasmonics, which includes the origin of surface plasmon resonance (see figure 11(a)), their propagation characteristics (figure 11(b)) and their exploitation in innumerable applications. Some of the interesting phenomena in this field are:

- Generation of the surface plasma waves and the dependence of plasmon resonance on metal particle size, and geometry.
- Dependence of the plasmon resonance condition on the dielectric adjacent to the metal film.

- Enhancement of the electromagnetic field close to metal nanoparticles.
- Effects of the metal nanoshells on plasmon resonance.
- Propagation of high-frequency electromagnetic waves along sub-wavelength-wide metal wave-guides.
- Effect of metal surface on radiative decay of molecules.

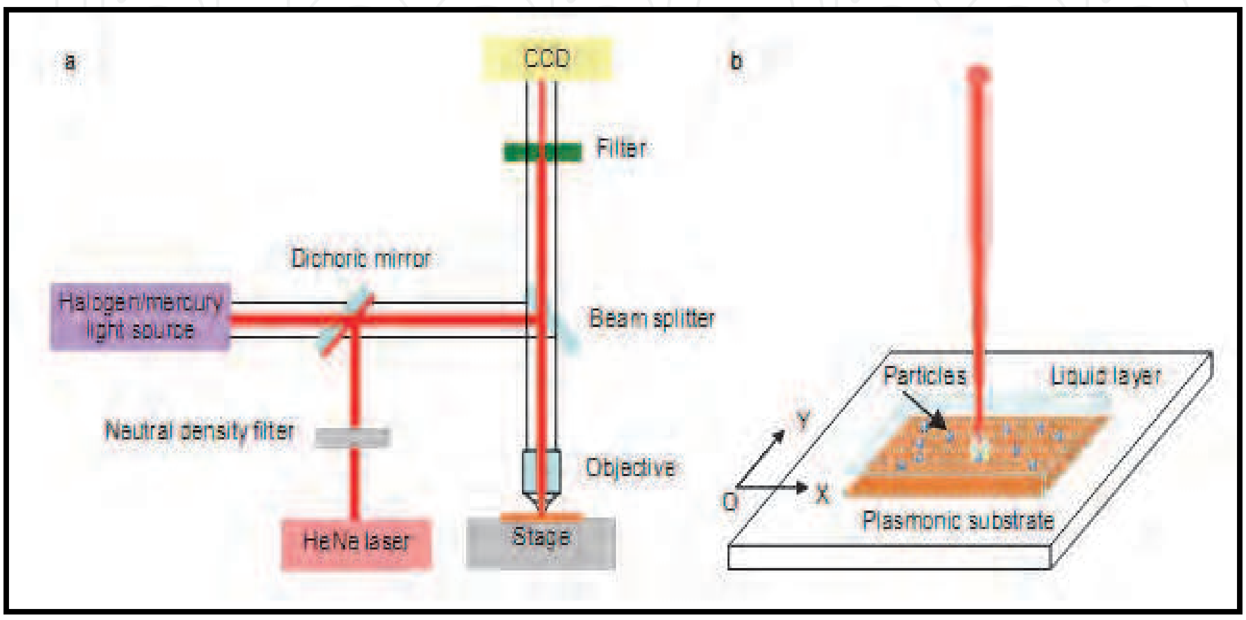
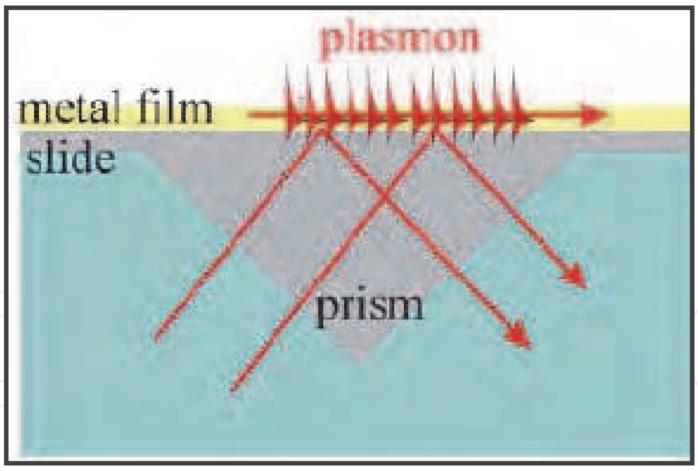


Fig. 10. a) Experimental set up for the trapping and concentration experiments on the plasmonic substrate. b) Detailed configuration of the sample chamber.

The published scientific literatures containing the words 'surface plasmon' over last decade clearly indicates the exponential growth of the field of plasmonics. This rapid growth is stimulated by the development and commercialization of advanced sample preparation methods, powerful electromagnetics simulation codes, nanofabrication techniques and physical analysis techniques providing scientists 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 the end of last century. Presently, an estimated fifty percent of all publications on surface plasmons involve the use of plasmons for bio-detection and bio-photonics applications.

The chapter is organized as follows. In Section 2, we review the salient features of photonic crystals and photonic band gaps. A birds' eye view of the recent development in plasmonics and its future prospects is presented in Section 3. The recurring theme of Section 4 is the main challenges in nanophotonics research and the upcoming market strategies. The physics behind the quantum confinement and the behavior of quantum-confined materials are discussed in Section 5 and 6. Section 7 describes the possibility of widespread exciting applications and the need of further research. Conclusions and further outlook are summarized in Section 8.



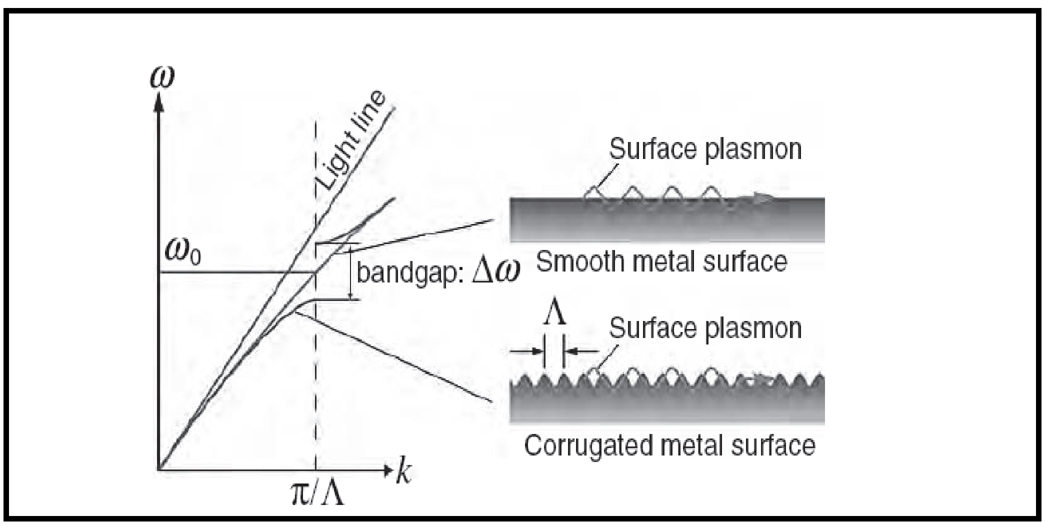


Fig. 11 (a) The origin of surface plasmon resonance at metal dielectric interface (Left panel). (b) The dispersion relation of the surface plasmon travelling on a flat metal surface and a corrugated metal surface (Right panel).

2. Photonic crystals: an amazing material for ultrafast technology

This section focuses on the importance of the photonic crystals called photonic band gap materials. In an age when technology influences society on daily basis, there is an increased demand for new ways to process and exchange information quickly and efficiently. One solution is to implement optical circuits, which use light instead of electricity to relay and process information. However, with the current methods of building optical circuits, it is difficult to manipulate light without losing efficiency. In fact, nanotechnology is helping the photonics to grow at rapid space. Nanotechnology will not just be about electrons moving through circuits but will go beyond our imagination. Information has been transmitted for many years using electromagnetic waves. Most of the communication technology developments exploited radio- and micro-waves and in more recent time information, technology is using much shorter wavelength of light in optical fibers. The natural progression here is towards what are called photonic devices, in which light is channeled through microscopic tubes or lattices of tubes, which are now a topic of ever-increasing active research and debate.

The solution to the problem of rapid information processing and safe transfer at cheaper rates is to use photonic crystals as waveguides in optical circuits. They are small-fabricated crystals, which can efficiently manipulate the direction in which light travels. Photonic crystals are usually viewed as an optical analog of semiconductors that modify the properties of light similar to a microscopic atomic lattice that creates a semiconductor band-gap for electrons. It is therefore believed that by replacing relatively slow electrons with photons as the carriers of information, the speed and bandwidth of advanced communication systems will be dramatically increased. The present century's exciting application possibilities of these materials in science and technology, its present status and future scope are briefly explored in this section.

The various issues addressed here related to the field of photonic crystals are:

- What are photonic crystals?
- What is meant by photonic band gap materials?
- What are the methods used to analyze theory of photonic crystals?
- How do they look like?
- What physics make them so potential for devices?
- Is there any use of these crystals so far?
- What are their fabrication processes?
- What potential applications do they have?
- What are challenges and difficulties?
- How promising are they for future technology?

Microelectronics has allowed by miniaturization of components, such as transistors, resistors, and capacitors on one single chip. On the other hand, photonics has not achieved the same level of miniaturization yet while there are demands for cheaper, faster, and more compact laser-based communication systems in modern time. The integration of photonic components such as lasers, detectors, couplers, and wave-guides is still at a very primitive stage, compared with that of microelectronics. This is due to difficulties with implementing integrated optical components smaller than certain sizes. For instance, small bends or curves of wave-guides lead to the leakages of optical signals, so the bends have to be bigger than certain critical length. Photonic crystals can then be used as they offer a potential to provide solutions to the challenge of photonic component integration by means of its nature to confine photons within their structures. Moreover, intriguing phenomena in photonic crystals can be exploited, which are not achievable by conventional isotropic media. Photonic crystals can be a breakthrough in photonic technology in the near future (Miao et al., 2008).

The absence of allowed propagating electromagnetic modes inside the structures in a range of wavelengths called a photonic band gap, gives rise to distinct optical phenomena such as inhibition of spontaneous emission, high-reflecting omni-directional mirrors and low-loss-wave guiding amongst others. Since the basic physical phenomenon is based on diffraction, the periodicity of the photonic crystal structure has to be in the same length-scale as half the wavelength of the electromagnetic waves ~300 nm for photonic crystals operating in the visible part of the spectrum (Rayleigh, 1888). The periodicity, whose length scale is proportional to the wavelength of light in the band gap, is the electromagnetic analogue of a crystalline atomic lattice. This periodicity acts on the electron wave function to produce the familiar band gaps as in the case of semiconductors in condensed matter physics. The study of photonic crystals is likewise governed by the Bloch-Floquet theorem, and intentionally introduced defects in the crystal. The later is similar to electronic dopants give rise to localized electromagnetic states in linear waveguides and point-like cavities. The crystal can thus form a kind of perfect optical insulator that can confine light without loss around sharp bends, in lower-index media, and within wavelength-scale cavities, among other novel possibilities for control of electromagnetic phenomena (Joannaopoulos et al., 2008). The periodicity of the photonic crystals can be in one, two, and three dimensions that allow interesting properties such as bending light at 90º around corners as shown in figure 12.

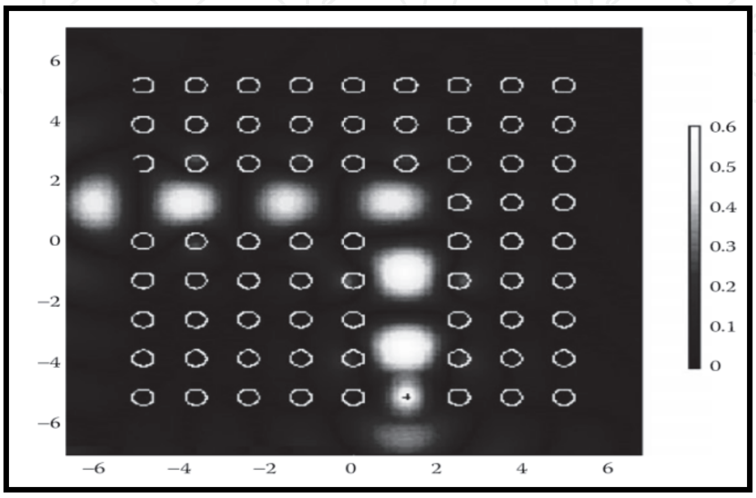


Fig. 12. Bending of light at 90º around corners in the photonic crystals.

One-dimensional periodic system continued to be studied extensively, and appeared in applications from reflective coating to distributed feedback diode lasers. In the former case, the reflection band corresponds to the photonic band gap and for the later, a crystallographic concept is inserted in the photonic band gap to define the laser wavelength. Yablonovitch and co-workers (Yablonovitch, 1987) produced the first photonic crystal by mechanically drilling holes a millimeter in diameter into a block of material with a refractive index of 3.6. The material, which became known as Yablonovite, prevented microwaves from propagating in any direction and exhibited a 3-dimensional photonic band gap. Other structures that have band gaps at microwave and radio frequencies are currently being used to make antennae that direct radiation away from the heads of mobile-phone users (Sajeev, 1987; Lodahl, 2004; Kim, 2008; Sonnichsen, 2005). Later on, photonic crystals of semiconducting colloidal particles were fabricated for realizing photonic band gaps in the visible region of the electromagnetic spectrum. They are also fabricated by the spontaneous self-organization of mono-disperse colloidal spheres such as silica or polystyrene to form a three-dimensional crystal having long-range periodicity. As mentioned, the photonic crystals are materials with periodically varying relative permittivity and are optical equivalents of semiconductors. However, the true potential of these materials lies in manipulating light of wavelength comparable with their lattice parameter. The voids between the particles form regions of low relative permittivity, while the spheres form regions of high relative permittivity, i.e. periodically varying refractive indices (see figure 13). The refractive index variation contrasts for photons in a similar manner to the periodic potential that an electron experiences while traveling in a semiconductor. For sufficiently large contrast, the creation of a complete photonic band gap may occur that results a frequency range where light cannot propagate inside the photonic crystal. This is the underlying principle by which a colloidal photonic crystal blocks certain wavelengths in the photonic band gap, while allowing other wavelengths to pass. The photonic band gap can be tuned by changing the size, shape and symmetry of the particles and the geometry of voids. Using core-shell particles similar photonic crystals are prepared with a large contrast in the refractive indices of the core and shell materials, where the photonic band gap are tuned from the visible to the infrared ranges by changing the refractive indices contrast. It has taken over a decade to fabricate photonic crystals that work in the near infrared (780 - 3000 nm) and visible (300 - 750 nm) regions of the spectrum. The main challenge has been to find suitable materials and processing techniques to fabricate structures that are about a thousandth the size of microwave crystals (Kalele et al., 2007; Sajeev, 1987).

One of the most important features in photonic crystals is the photonic band gap, which is analogous to band gaps or energy gaps for electrons traveling in semiconductors. In case of semiconductors, a band gap arises from the wave-like nature of electrons. Electrons as waves within a semiconductor experience periodic potential from each atom and are reflected by the atoms. Under certain conditions, electrons with certain wave vectors and energy constitute standing waves. The range of energy, named 'band gap', in which electrons are not allowed to exist. This phenomenon differentiates semiconductors from metals and insulators. In the similar manner, standing waves of electromagnetic waves can be formed within a periodic structure whose minimum features are about the order of the wavelength. In this case, the medium expels photons with certain wavelengths and wave vectors. Such a structure acts as an insulator of light, and this phenomenon is referred to as photonic band gap ((Yablonovitch, 1987; Sajeev, 1987; Lodahl, 2004). The origin of photonic band gap in photonic crystals can be explained with the help of Maxwell's equations.

It is well known that in a silicon crystal, the atoms are arranged in a diamond-lattice structure in which the electrons moving through this lattice experience a periodic potential while interacting with the silicon nuclei via the Coulomb force, that results in the formation of allowed and forbidden energy states. No electrons can be found in the forbidden energy gap or simply the band gap for pure and perfect silicon crystals. However, for real materials with defects the electrons can have energy within the band gap due to the broken periodicity caused by a missing silicon atom or by an impurity atom occupying a silicon site, or if the material contains interstitial impurities. Now, consider a situation in which the photons are moving through a block of transparent dielectric material that contains a number of tiny air holes arranged in a regular lattice pattern. The photons will pass through regions of high refractive index of the dielectric intersperse with regions of low refractive indexed air holes. In case of a photon, this contrast in refractive index looks just like the periodic potential that an electron experiences traveling through a silicon crystal. Indeed, if there is large contrast in refractive index between the two regions then most of the light will be confined within either the dielectric material or the air holes. This confinement results in the formation of allowed energy regions separated by a forbidden region, photonic band gap. As the wavelength of the photons is inversely proportional to their energy, the patterned dielectric material will block light with wavelengths in the photonic band gap, while allowing other wavelengths to pass freely (Mia et al., 2008). It is also possible to create energy levels in the photonic band gap by changing the size of a few of the air holes in the material. This is the photonic equivalent to breaking the perfect periodicity of the crystal lattice. The diameter of the air holes is a critical parameter, in addition to the contrast in refractive index throughout the material. Photonic band gap structures can also be made from a lattice of high-refractive-index material embedded within a medium with a lower refractive index (core-shell for example). A naturally occurring example of such a material is opal. However, the contrast in the refractive index in opal is rather small, and hence the appearance of a small band gap (Kalele et al., 2007).

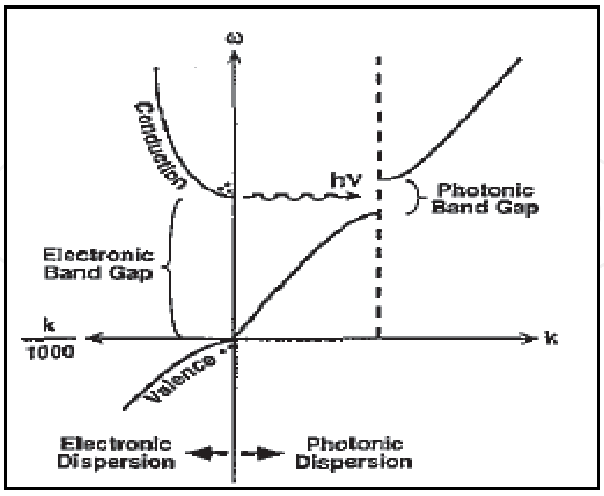


Fig. 13. Schematic representing the electronic and photonic band gaps in the Brillouin zone.

Let us consider the simplest one-dimensional (1D) structure in order to describe the phenomenon of formation of photonic band gap in the photonic crystals that has alternating layers of two dielectrics. The incident wave in entering a periodic array of dielectric sheets is partially reflected at the boundaries of the dielectric layers. If the partially reflected waves are in phase and superimposed, they form a total reflected wave, and the incident wave is unable to enter the medium, as depicted in figure 14. The range of wavelengths in which incident waves are reflected is called a 'stop band'. A structure that exhibits stop bands to every direction for given wavelengths, the stop bands are considered a 'photonic band gap'. On the other hand, when the wavelength of an incident wave does not lie within the band gap, destructive interferences occur and partially reflected waves cancel one other. Consequently, the reflection from the periodic structure does not happen and the light passes through the structure as illustrated in figure 15.

For two-dimensional (2D) structure, the condition in which such reflections occur at the interfaces of two dielectrics and a photonic band gap arises from the superposition of partial reflected waves are somewhat complex. To realize an effective photonic band gap, back-scattered waves should be in phase, forming one reflected wave in which the Bragg's condition has to satisfy, the same condition has to be satisfied for incident waves from every direction to attain a photonic band gap. An intuitive idea regarding the nature photonic crystal structure obtained from Bragg's law indicates that the distance from one lattice point to neighboring ones should be same so that scattered waves are superimposed and in phase at any point of the structure. Moreover, the structure should possess symmetry to as many directions as possible so that scattered waves from one lattice point experiences the same orientation of neighboring lattice points. The same concept can be extended to three-dimensional (3D) periodic structure, where the incident waves turned into partially reflected waves and the transmitted waves at boundaries between the two media. If the partially reflected waves are in phase, the scattered waves add up to a net reflected wave, resulting in a stop band. The condition for Bragg's law must be satisfied at each lattice point that can be either a dielectric material or an air hole surrounded by a dielectric. If the stop bands exist for every direction and those '*stop bands*' overlap within certain wavelength

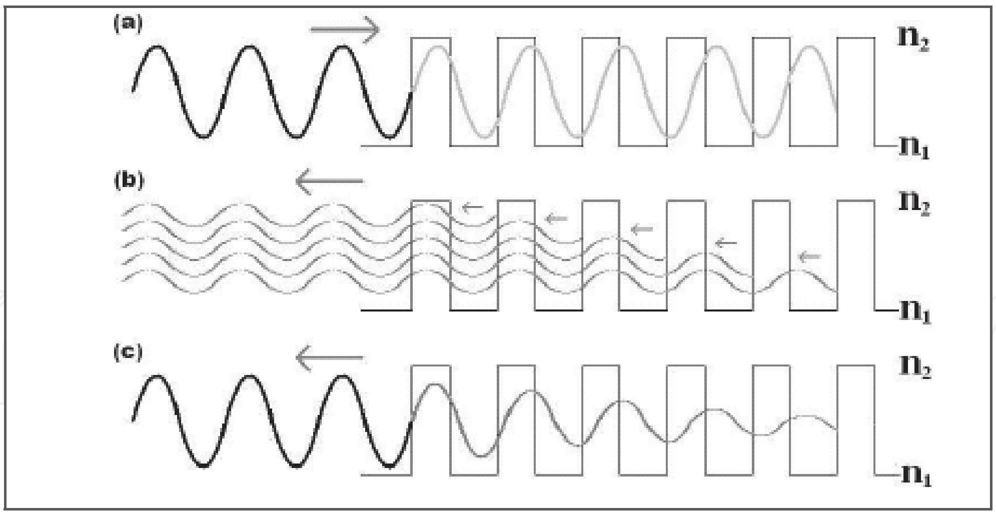


Fig. 14. The constructive interference for the photonic band gap in one dimension. (a) An incident wave within the photonic band gap enters the periodic structure with two different refractive indices n_1 and n_2. (b) The incident wave is partially reflected by the boundary of the structure. (c) The incident wave is totally reflected when each reflected wave is in phase, and is unable to penetrate the structure.

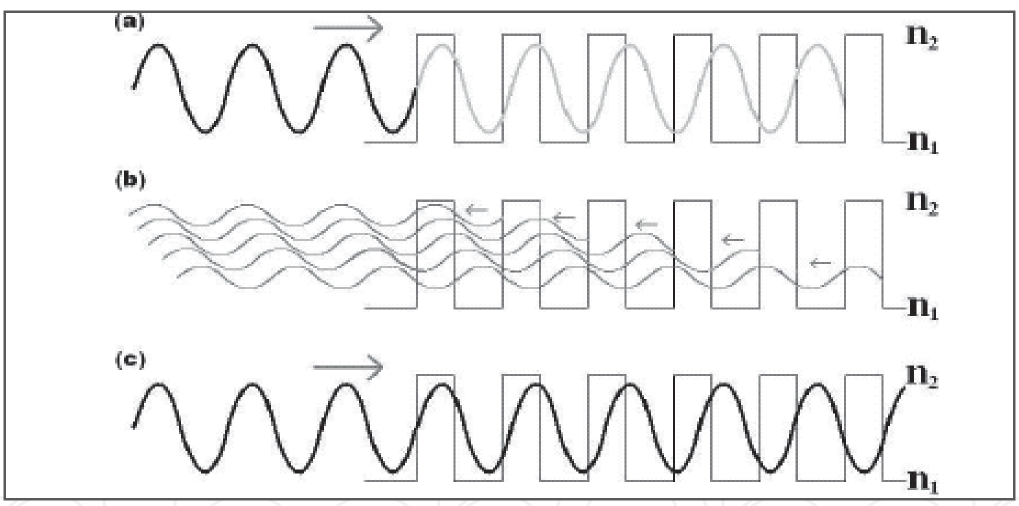


Fig. 15. The destructive interference. (a) An incident wave outside the photonic band gap enters the periodic structure. (b) The incident wave is partially reflected by the boundary of the structure, but each reflected wave is out of phase and interfere destructively. (c) The incident wave penetrates the structure without being reflected.

region then a complete photonic band gap arises in three-dimension. Photonic band gaps results from the net interferences of scattered incident light waves from lattice points of a periodic structure. It is important to note that high refractive index contrasts of the periodic structures play pivotal role for the photonic band gaps to occur or to become more pronounced for a given structure (Joannaopoulos et al., 2008).

There are two reasons for the importance of high refractive index contrasts. First, each photonic crystal structure has a threshold value of refractive index contrast to exhibit a photonic band gap as depicted in figure 16. This phenomenon is attributed to the fact that interfaces of two dielectrics with higher contrast of refractive indices tend to scatter waves from any direction, so stop bands to any direction, a photonic band gap, are more likely to take place. Second, the higher the refractive index contrast is, the fewer layers are necessary to have sufficient photonic band gap effects. As explained in figure 14, each layer or lattice of photonic crystal partially reflects the propagating wave. Consequently, if each layer reflects more waves due to a higher refractive index contrast, sufficient net reflections can be achieved by fewer layers of lattices than a structure with the same configuration but with a lower refractive index contrast. This condition helps us to choose materials such as semiconductors for photonic crystals (Mia et al., 2008; Rayleigh, 1888; Yablonovitch, 1987).

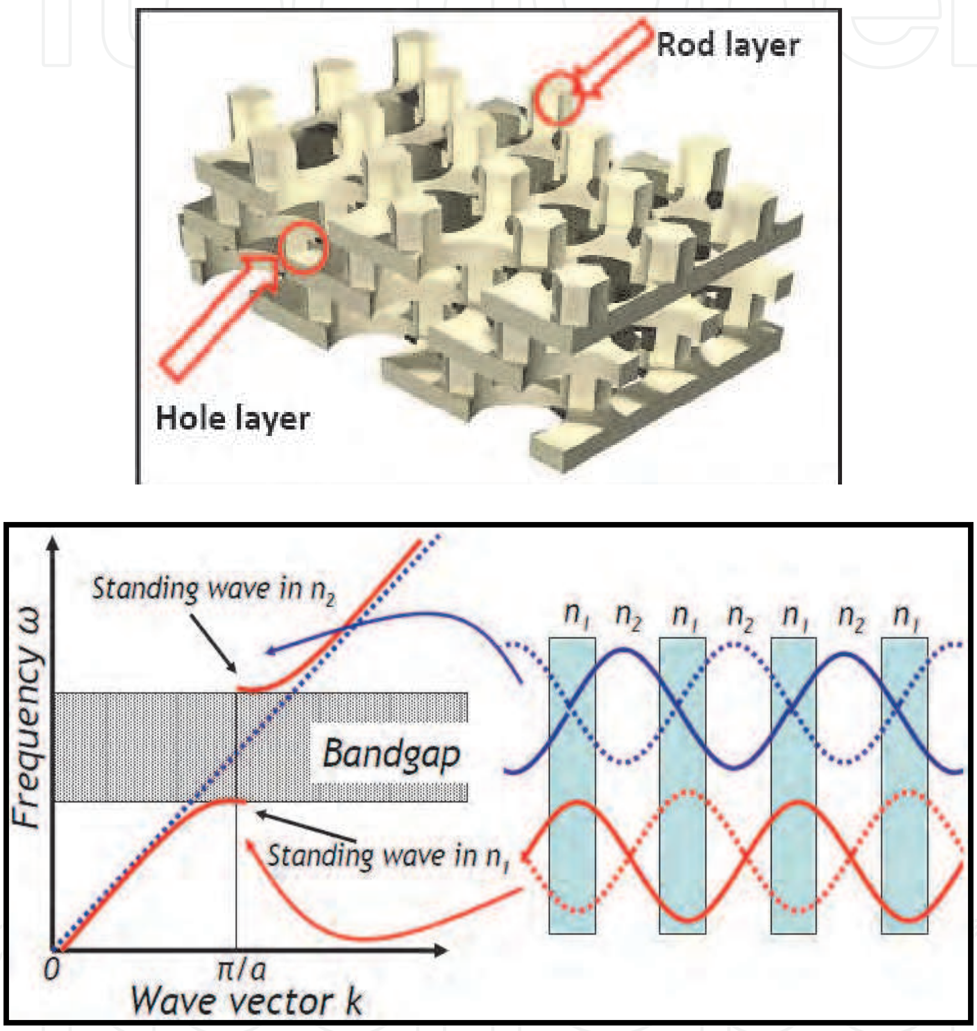


Fig. 16. (Left) A 3D photonic crystal consisting of an alternating stack of triangular lattices of dielectric rods in air and holes in dielectrics (courtesy Yablonovitch). (Right) Projected band diagrams and the band gap for a finite-thickness slab of air holes in dielectric with the irreducible Brillouin zone.

By combining Maxwell's equations with the theorems of solid-state physics a surprising and simple result emerges, that explain the phenomena of light bouncing among infinity of periodic scatterers. Like electrical insulators, which keep the currents in the wires where they belong, one can also build an optical insulator, a photonic crystal to confine and channel photons. The emergence of photonic crystals is due to the cooperative effects of *periodic* scatterers that occur when the period is of the order of the wavelength of the light.

They are called 'crystals' because of their periodicity and 'photonic' because they act on light i.e. photon. Once such a medium is obtained, impervious to light, one can manipulate photons in many interesting ways. By carving a tunnel through the material, an optical 'wire' can be achieved from which no light can deviate. Even more interesting things can happen by making a cavity in the center of the crystal, an optical 'cage' can be created in which a beam of light could be caught and held, because the very fact that it cannot escape would render it invisible. These kinds of abilities to trap and guide light have many potential applications in optical communications and computing (Joannaopoulos et al., 2008). A typical photonic crystal slab structure with tunnels and cavities that are made to confine and control light is presented in figure 17.

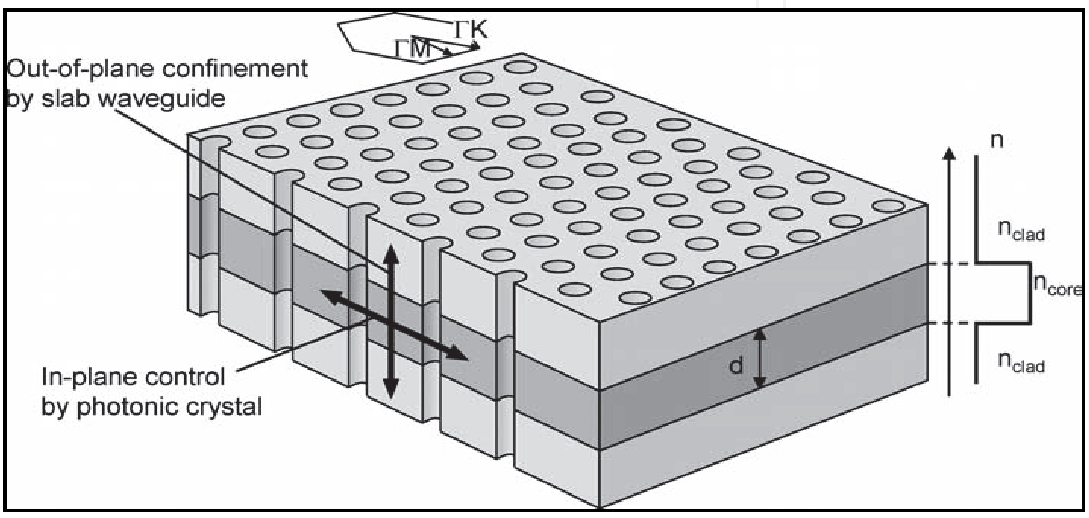


Fig. 17. A 2D photonic crystal slab. In-plane, light is controlled by the photonic crystal, while in the vertical direction it is confined by the layer with the higher refractive index.

To achieve a large band gap, the dielectric structure should consist of thin, continuous veins/membranes along which the electric field lines can run. This way, the lowest band(s) can be strongly confined, while the upper bands are forced to a much higher frequency because the thin veins cannot support multiple modes (except for two orthogonal polarizations). The veins must also run in all directions, so that this confinement can occur for all wave vectors and polarizations, necessitating a complex topology in the crystal. Furthermore, in two or three dimensions one can only suggest rules of thumb for the existence of a band gap in a periodic structure. The design of 3D photonic crystals is a trial and error process (Sanjeev, 1987). The typical band structure for photonic crystals for transverse electric and transverse magnetic mode is shown in figure 18. Interestingly, the 2D systems exhibit most of the important characteristics of photonic crystals, from nontrivial Brillouin zones to topological sensitivity to a minimum index contrast, and can also be used to demonstrate most proposed photonic-crystal devices (Yablonovitch, 1987).
The numerical computations are the crucial part of most theoretical analyses for photonic band gap materials due to their complexity in high index-contrast directional dimensionality of the systems. Computations are typically fall into the following three categories:

1. The time-evolution of the fields with arbitrary initial conditions in a discretized system are modeled and simulated by the time-domain 'numerical experiments' using finite difference method.

2. The scattering matrices are computed in some basis to extract transmission/reflection through the structure (mainly eigenvalues) and the definite-frequency transfer matrices can be achieved.
3. The frequency-domain methods can directly extract the Bloch fields and frequencies by diagonalizing the eigenoperator.

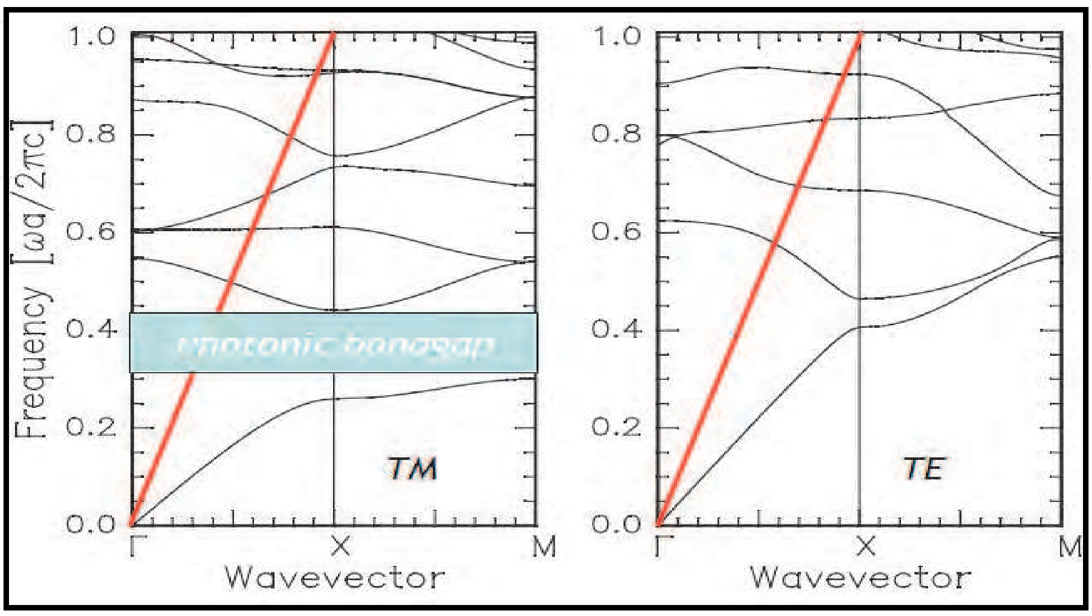


Fig. 18. Band diagrams and photonic band gaps for the two polarizations TE/TM (electric field parallel/perpendicular to plane of periodicity).

The directly measurable quantities such as transmission can be obtained intuitively from the first two categories. The third category is more abstract, yielding the band diagrams that provide a guide to interpretation of measurements as well as a starting point for device design and semi-analytical methods. For many systems, several band diagrams are computed by the frequency-domain method.
Photonic-crystal slabs have two new critical parameters that influence the existence of a gap. Firstly, it must have mirror symmetry in order that the gaps in the even modes and odd modes can be considered separately. Such mirror symmetry is broken in the presence of an asymmetric substrate. In actual practice, the symmetry breaking can be weak if the index contrast is sufficiently high so that the modes are strongly confined in the slab. Secondly, the height of the slab must not be too small that weakly confines the modes or not too large so that higher-order modes will fill the gap. The required optimum height must be around half a wavelength relative to an averaged index that depends on the polarization (Joannaopoulos et al., 2008). The photonic-crystal slabs are one way of realizing 2D photonic-crystal effects in 3D. A 3D periodic crystal is formed by an alternating hole-slab/rod-slab sequence by stacking of bi-layers that has a 21 % plus complete gap for ε = 12, forbidding light propagation for all wave vectors and all polarizations (Sanjeev, 1987). This kind of crystal slabs confines light perfectly in 3D, because its layers resemble 2D rod/hole crystals, it turns out that the confined modes created by defects in these layers strongly resemble the TM/TE states created by corresponding defects in 2D. Therefore, it can be used for direct transfer of designs from two to three dimensions while retaining omni-directional confinement (Joannaopoulos et al., 2008).

Over the years, it is realized that the fabrication of photonic crystals can be either easy or extremely difficult depending upon the desired wavelength of the band gap and the level of dimensionality. Lower frequency structures that require larger dimensions are easier to fabricate because the wavelength of the band gap scales directly with the lattice constant of the photonic crystals. At microwave frequencies, where the wavelength is of the order of 1 cm, the photonic crystals are decidedly macroscopic and simple machining techniques or rapid prototyping methods can be employed in building the crystals. Moreover, at the optical wavelengths, photonic band gaps require crystal lattice constants less than 1 μm and are difficult to fabricate. Building photonic band gaps in the optical regime requires methods that push current state-of-the-art micro and nanofabrication techniques. Since 1D photonic band gaps require periodic variation of the dielectric constant in only one direction, they are relatively easy to build at all length scales compare to 3D one (Sanjeev, 1987; Lodahl et al., 2004; Kim et al., 2008; Sonnichsen et al., 2005; Joannaopoulos et al., 2008).
The 1D photonic band gap mirrors commonly known as distributed Bragg reflectors that have been used in building optical and near-infrared photonic devices for many years. Two common examples of devices that have been realized using 1D photonic band gaps are distributed feedback lasers and vertical-cavity surface-emitting lasers. The 2D photonic band gaps require somewhat more fabrication, but relatively ordinary fabrication techniques can be employed to achieve such structures. There are several examples of 2D photonic band gaps operating at mid- and near-IR wavelengths. Clearly, the most challenging photonic band gap structures are fully 3D structures with band gaps in the IR or optical regions of the spectrum. As mentioned above, the fabrication of 3D photonic band gaps is complicated by the need for large dielectric contrasts between the materials that make up the photonic band gap crystal, and the relatively low filling fractions that are required. The large dielectric contrast demands dissimilar materials, and often the low-dielectric material is air with the other material being a semiconductor or a high-dielectric ceramic. The low dielectric filling fraction ensures that the photonic band gap crystal has mostly air, while the high dielectric material must be formed into a thin network or skeleton. Combining these difficulties with the need for micron or sub-micron dimensions to reach into the optical region, the fabrication becomes extremely difficult indeed (Sanjeev, 1987; Lodahl et al., 2004).
The deep x-ray lithography and other techniques are useful to fabricate the photonic band gaps structures in which the resist layers of polymethyl methacrylate are irradiated to form a 'three-cylinder' structure. The holes in the polymethyl methacrylate structure are usually filled with ceramic material due to their low value of dielectric constant not favorable for the formation of a photonic band gap. A few layers of this structure can be fabricated with a measured band gap centered at 2.5 THz. The layer-by-layer structure can be fabricated by laser rapid prototyping using laser-induced direct-write deposition from the gas phase. The photonic band gap structure consisted of oxide rods and the measured photonic band gap is centered at 2 THz. The measured transmittance shows band gaps centered at 30 and 200 THz, respectively. In this way, it is possible to overcome very difficult technological challenges, in planarization, orientation and 3D growth at micrometer length scales. Finally, the colloidal suspensions have the ability to form spontaneously the bulk 3D crystals with submicron lattice parameters. In addition, 3D dielectric lattices have been developed from a solution of artificially grown mono-disperse spherical SiO_2 particles. However, both these procedures give structures with a quite small dielectric contrast ratio (< 2), which is not enough to give a full band gap. A lot of effort is being devoted to find new methods in

increasing the dielectric contrast ratio. Several groups are trying to produce ordered macro-porous materials from titania, silica, and zirconia by using the emulsion droplets as templates around which material is deposited through a sol-gel process (Xing-huang et al., 2008). Subsequent drying and heat treatment yields solid materials with spherical pores left behind the emulsion droplets. Another very promising technique in fabricating photonic crystals at optical wavelengths is 3D-holographic lithography (Miao et al., 2008).

Materials with photonic band gaps could speed up the internet by improving the transmission of long-distance optical signals. One drawback with conventional optical fibers is that different wavelengths of light can travel through the material at different speeds. Over long distances, time delays can occur between signals that are encoded at different wavelengths. This kind of dispersion is worse if the core is very large, as the light can follow different paths or 'modes' through the fiber. A pulse of light traveling through such a fiber broadens out, thereby limiting the amount of data that can be sent. These problems could be solved by an extremely unusual 'holey fiber' as show in figure 19. The fiber has a regular lattice of air-cores running along its length and transmits a wide range of wavelengths without suffering from dispersion. It is made by packing a series of hollow glass capillary tubes around a solid glass core that runs through the centre. This structure is then heated and stretched to create a long fiber that is only a few microns in diameter. The fiber has the unusual property that it transmits a single mode of light, even if the diameter of the core is very large. This fiber can be produced even in a better way by removing the central solid glass core to form a long air cavity. In this case, the light is actually guided along the low-refractive-index air core by a photonic-band-gap confinement effect. Since the light is not actually guided by the glass material, very high-power laser signals could potentially be transmitted along the fiber without damaging it.

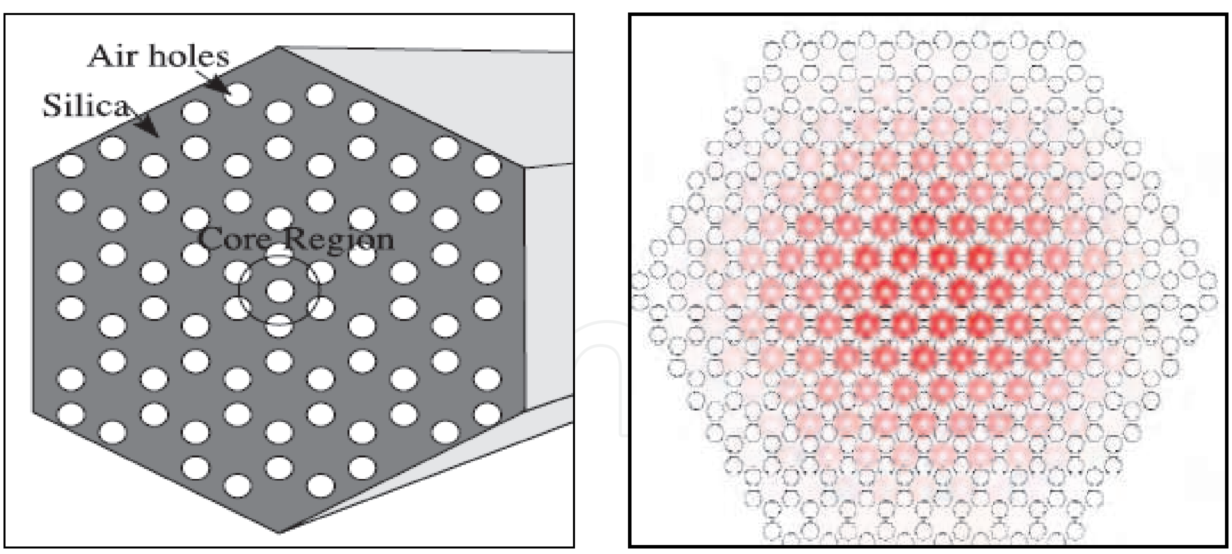


Fig. 19. Air-core photonic crystal fibers. Arrangements of voids and dielectric media (left) and light propagations through holes (right).

Defects in photonic band gap structure allow designing small, but highly efficient micro lasers. A point defect in the crystal gives rise to a resonant state with a defined resonant frequency in the band gap. Light is trapped in this cavity as the photonic band gap prevents it from escaping into the crystal. The photonic crystals built from the photo emissive materials, such as III-V semiconductors and glasses doped with rare-earth atoms, can also be used to make narrow-line width lasers that could potentially be integrated with other components in an optical-communications system. These lasers are made by introducing a small number of holes that are slightly smaller or larger than the other holes in the photonic-crystal lattice. These 'micro cavities' generate a narrow defect mode within the photonic band gap. While the material emits light in a wide spectral range, only the wavelength that matches the wavelength of the defect mode is amplified because it can propagate freely through the material. The laser cavity is formed either by the crystal surface or by external mirrors that surround the glass. The intensity of the propagating light increases as it undergoes successive reflections and travels back and forth through the photonic crystal. Meanwhile, light at other wavelengths are trapped within the photonic crystal and cannot build up. This means that the laser light is emitted in a narrow wavelength range that is directly related to the diameter of the micro cavity divided by the diameter of the regular holes. Moreover, the line width can be reduced further by using unusual geometries of the photonic-crystal lattice (Sanjeev, 1987). Such micro cavities are also much more efficient at trapping light than the cavities formed in semiconductor diode lasers since there are fewer directions in which the photons can escape from the cavity. The rate of photoemission in an active medium can be greatly increased by maintaining a high optical flux density. As micro cavities act as light traps, they provide a good method of enhancing the rate of photoemission in light emitting diodes, and are crucial for the operation of lasers. Moreover, the increased rate of photoemission means that micro cavity light emitting diodes and photonic-crystal lasers can be switched on and off at far greater speeds compared with conventional devices, which could lead to higher data-transmission rates and greater energy efficiency.

Preliminary experiments have been performed at microwave frequencies on defect structures within photonic crystals made from 'passive' materials that do not emit light. Photonic-crystal micro cavities that are fabricated from passive materials, such as silicon dioxide and silicon nitride, could also be used to create filters that only transmit a very narrow range of wavelengths. Such filters could be used to select a wavelength channel in a '*dense wavelength division multiplexing'* communications system (Lodahl, 2004). Indeed, arrays of these devices could be integrated onto a chip to form the basis of a channel de-multiplexer that separates and sorts out light pulses of different wavelengths. Figure 20 shows a photonic-crystal device that works as a simple filter. This is made by growing a thick layer of silicon dioxide on the surface of a silicon substrate, followed by a layer of silicon nitride. The positions of the holes were defined by patterning the top surface of the waveguide with electron-beam lithography. The underlying silicon dioxide was then etched away to create a freestanding porous silicon-nitride membrane that blocks light over the wavelength range 725 - 825 nm. Similar devices can also be fabricated with band gaps at shorter visible wavelength. Miniature wave-guides that could be used to transmit light signals between different devices are a key component for integrated optical circuits. However, the development of such small-scale optical interconnects has so far been inhibited by the problem of guiding light efficiently round very tight bends.

Conventional optical fibers and waveguides work by the process of total internal reflection. The contrast in refractive index between the glass core of the fiber and the surrounding cladding material determines the maximum radius through which light can be bent without any losses. For conventional glass waveguides, this bend radius is about a few millimeters. However, inter-connects between the components on a dense integrated optical circuit require bend radii of 10 μm or less. It is possible to form a narrow-channel waveguide within a photonic crystal by removing a row of holes from an otherwise regular pattern. Light will be confined within the line of defects for wavelengths that lie within the band gap of the surrounding photonic crystal. Since a porous material has no available modes at this wavelength, an optical quantum well forms in the waveguide region and traps the light. Under these conditions, we can introduce a pattern of sharp bends that will either cause the light to be reflected backwards or directed round the bend.

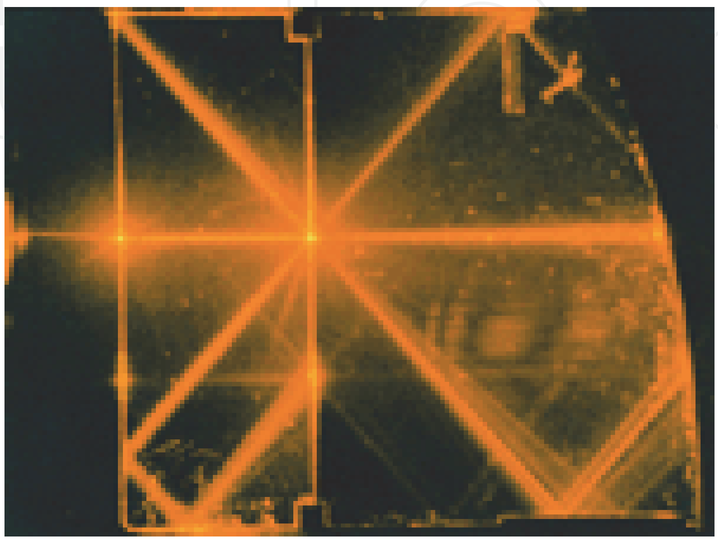


Fig. 20. A photonic crystal devices that work as a simple filter.

We conclude with the note that the original innovative research into photonic crystals/photonic band gap materials is necessary to achieve immediate commercial applications, but without intense research, it would not have been possible to set into these new classes of structures or a whole host of other tangential pursuits. The most important and useful thing that comes out of the research is *new ideas and paths of investigation*. Research breeds more research, which will eventually lead to something that genuinely be commercialized. Though the field of nanophotonics and nanotechnology is growing up exponentially and newer applications are coming at rapid space, however, more focused research is needed to get position in the market by defeating the existing technology.

3. Plasmonics: a new avenue of nanoscale optics

The term 'plasmonics' refers to the science and technology dealing with the manipulation of the electromagnetic signals by coherent coupling of photons to free electron oscillations at the interface between a conductor and a dielectric. Plasmons are electrons density waves and is created when light hits the surface of a metal at the precise frequency. Because these density waves are generated at optical frequencies, very small and rapid waves, they can theoretically encode a lot of information; more than what is possible for conventional electronics (Kim et al., 2008). Surface plasmons are optically induced oscillations of the free electrons at the surface of a metal. Plamonics is thought to embody the strongest points of both optical and electronic data transfer. Optical data transfer, as in fiber optics, allows high bandwidth, but requires bulky 'wires', or tubes with reflective interiors. Electronic data transfer operates at frequencies inferior to fiber optics, but only requires tiny wires. Plasmonics, often-called 'light on a wire', would allow the transmission of data at optical frequencies along the surface of a tiny metal wire, despite the fact that the data travels in the form of electron density distributions rather than photons (Sonnichsen, 2005). We would like to address the following relevant issues in plasmonics:

- What is plasmonics and plasmon resonance?
- How to get materials for plamonics applications?
- Why research is necessary in plasmonics?
- What is the present status for commercialization?
- Why are they so interesting?
- What are challenges and difficulties in plasmonics?
- How promising are they for future technology?

Since the middle of nineteenth century, after the first demonstration of stable dispersion of gold nanoparticles by Michael Faraday the scientific insight and queries on the interaction of light with matter has intrigued scientists. Without invoking the word nano in ancient time, artists have been exploiting sparkling red, yellow and green colors exhibited by metal nanoparticles especially of gold and silver as colorants in glasses for the decoration of windows and doors of many cathedrals, palaces, mosques and temples. Faraday concluded that metal nanoparticles having size much smaller than the wavelength of light exhibit intense colors that has no bulk counterpart. Gustav Mie in 1908 successfully explained the origin of such colors of dispersion using Maxwell's theory of classical electromagnetic radiation in which the phenomena was attributed to strong absorption and scattering of light by dispersion of metal nanoparticles (Kalele et al., 2007). However, during last two decades a series of noble-metal particles fabricated using advanced nanotechnology route showed a strong absorption band in the visible region of electromagnetic spectrum, arising from a resonance between collective oscillations of conduction electrons with incident electromagnetic radiation. Consequently, scientists are interested to guide, manipulate and control such strong absorption band associated with plasmon and hence the genesis of plasmonics. The formation of electric dipoles originates from the interaction of incident electromagnetic field that induces strong polarization of conduction electrons and weaker polarization to the immobile heavier ions. The net charge difference between the electrons and the ions acts as a restoring force that can be visualized as simple harmonic oscillator in the Lorentz model. The plasmon resonance is the resonance between the frequency of oscillation of the electrons and the frequency of the incident photon and is characterized by a strong absorption band. For nanoscale matter, the surface by volume ratio is high and most of the optical and electronic structure properties are dominated by the surface rather than the bulk. In this case, since a net charge difference is felt at the surface of a nanoparticle, the resonance is also known as *surface plasmon resonance*. The pictorial representation of surface plasmon resonance on the metal dielectric interface and on an array of two gold nanoparticle is shown in figure 21 (left panel) and (right panel) respectively.

The generation of *surface plasmon* is like *'an ocean of light'*. Dropping a piece of stone into a quiet lake one creates the ripples that spread out across its surface. The same thing happens when a photon hits the surface of a metal, where the 'ripples' consist of collective oscillations of electrons and have wavelengths of the order of nanometers. During such oscillations these 'surface plasmons' can pick up more light and carry it along the metal surface for comparatively large distances. Using plasmons light can not only be focused into the tiniest of spots but can also be directed along complex circuits or manipulated it many different ways. It is possible to achieve all of this at the nanoscale that is several orders of magnitude smaller than the wavelength of light (Pendry, 2000). This nanoscale is far below the resolution limits of conventional optics. Due to this reason, plasmonics has occupied a place in naophotonics in its own right. Several potential applications such as lasers, sensors, memory, communications, solar cells, biochemical sensing, optical computing and even cancer treatments are widely explored. Some of the exciting features of this field will be explored in this Section.

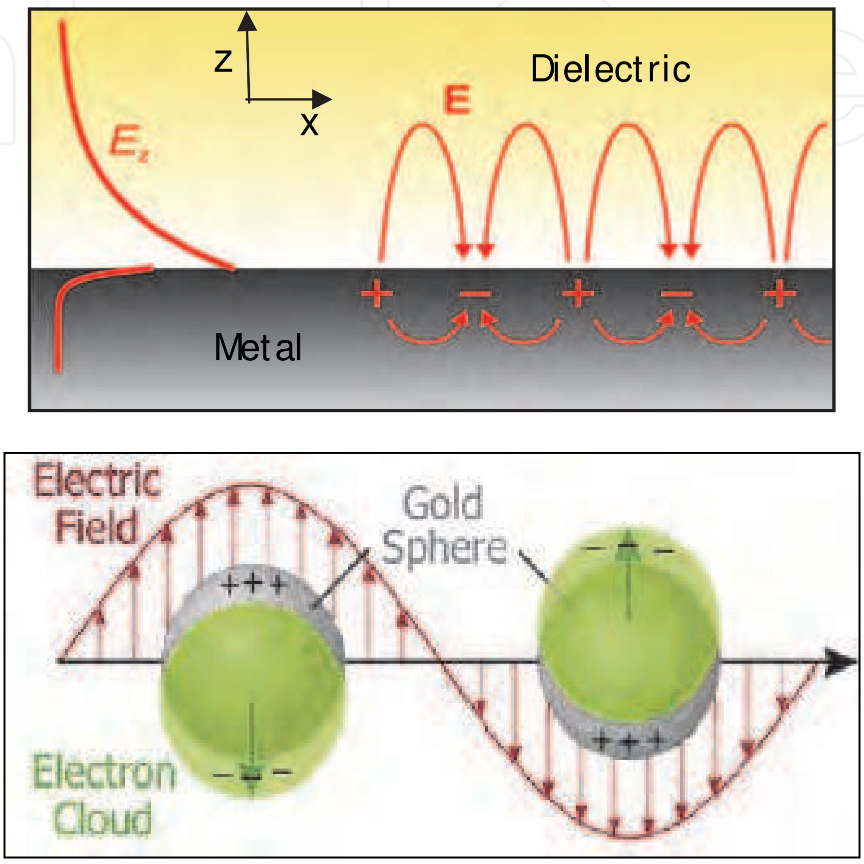


Fig. 21. The surface plasmon resonance: EM wave at metal-dielectric interface (left), and in gold nanoparticles (right).

The optical extinction properties of small metal particles have been studied for many years. Noble metal nanoparticles embedded in a dielectric exhibit a strong absorption peak due to a collective motion of free electrons, that is, a surface plasmon resonance. For isolated spherical particles, the resonance peak occurs generally in the visible part of the spectrum. The particular frequency depends on the particle size, and the dielectric constants of the metal and of the surrounding medium. For particle ensembles, however, electromagnetic coupling between neighboring particles shifts the plasmon absorption bands. Numerical calculations have demonstrated that nanoparticle size, nearest neighbor spacing, the overall ensemble size and shape have a critical effect on extinction spectra. The extinction coefficient that is the sum of the absorption and the scattering cross-sections is a useful parameter for surface plasmon resonance to occur in metals. The field plasmonics, the optical properties of metal structures at the nanoscale has made rapid development due to the ability of engineering metal surfaces and particles at the nanoscale. Advanced techniques like, electron beam lithography, chemical vapor deposition, and deep-UV lithography, focused ion beam milling and self-assembly has provided routes to engineer complex arrays of metal

nanostructures. These chains of metal nanoparticles are exploited to excite, control, guide, direct and manipulate plasmons. The plasmons are attractive because they can effectively confine the optical excitation in a nanoscale volume and thereby mediate strong optical interactions. In addition, the wavelength at which these phenomena are observed can be tuned by varying the metal nanostructure shape, size and dielectric environment. This in turn, provides a broad domain with flexibility from which it is possible to choose the desired optical properties for an application (Kim, 2008; Sonnichsen, 2005; Prodan, 2003).
The coupling of light with electronic surface excitations, specifically, surface plasmon polaritons offers the opportunity to bridge the orders of magnitude difference in sizes between optical and electronic carriers. To develop schemes for coupling and transporting surface plasmons around a chip, the determination of their propagation lengths is particularly important. Researchers have already excited surface plasmons using a focused beam of electrons and then detected the luminescence emitted as the plasmons decayed. Based on these cathode-luminescence intensity decay profiles, they could determine propagation lengths as a function of wavelength. Gold and silver thin films on silicon and quartz substrates respectively were patterned with gratings to direct the emission, allowing the measurement of propagation lengths as short as several hundred nanometers. However, the resolution of the technique is limited by the excitation volume, which in principle, would increase as the film thickness decrease (Sonnichsen, 2005). Using surface plasmon we can obtain ultra-small, wavelength-sensitive directional sensors or detectors. The resonant coupling between the nanoparticles can concentrates light into well-defined hot spots and acts as antennas by suitably engineering the metal nanostructures (Waele et al., 2007). Coupling metal nanoparticle arrays to optical emitter's directional emitters may be achieved. In order to provide the control over the color, directionality and polarization of light-emitting diodes the enhanced optical density of states near the surface of metal nanoparticles can be used. The enhancement of optical density of surface states is highly efficient for the large-scale applications of solid-state lighting, bio imaging, sensing and solar concentrators. Recent calculations and experiments confirms that light scattering from metal nanoparticle arrays can effectively fold the path of sunlight into the layer and thereby strongly enhance its effective absorption (Pillai et al., 2007).
It is known from Maxwell's equations that an interface between a dielectric (e.g. silica glass) and a metal (e.g. silver or gold) can support a surface plasmon. A surface plasmon is a coherent electron oscillation that propagates along the interface together with an electromagnetic wave. These unique interface waves result from the special dispersion characteristics (dependence of dielectric constant on frequency) of metals. What distinguishes surface plasmons from 'regular' photons is that they have a much smaller wavelength at the same frequency. For example, a He-Ne laser, whose free-space emission wavelength is 633 nm, can excite a surface plasmon at a silicon/silver interface with a wavelength of only 70 nm. When the laser frequency is tuned very close to the surface plasmon resonance, surface plasmon wavelengths in the nanometer range can be achieved. The short-wavelength surface plasmons enable the fabrication of nanoscale optical integrated circuits, in which light can be guided, split, filtered, and even amplified using plasmonic integrated circuits that are smaller than the optical wavelength (Kim, 2008; Loo et al., 2005). The reduction in wavelength comes at a price and as a result, surface plasmons are often having loss. One way to achieve long propagation lengths is to use very thin metal films. In this case, surface plasmons on both surfaces of the metal film interact, and both a symmetric and an asymmetric field distribution can exist. One of these modes has low loss

and, for metal films as thin as 10 nm, the centimeter propagation lengths can be achieved for surface plasmons in the infrared. At a given frequency, the surface plasmon wavelength is strongly dependent on the metal thickness. Thus, the plasmonic integrated circuit engineer has an extensive toolbox, including choice of metal (dispersion), metal thickness, and excitation frequency (Loo et al., 2005).

When a light source such as a luminescent quantum dot or dye molecule is placed close to a metal, it can excite a surface plasmon through a near-field interaction. With a light-emitting diode embedded in a plasmonic structure, surface plasmons can be electrically excited. Such surface plasmons may serve as an alternative to overcome the information bottlenecks presented by electrical interconnects in integrated circuits. Coupling to surface plasmons can also enhance the extraction efficiency of light from light emitting diodes. Metallic nanoparticles have distinctly different optical characteristics than surface plasmons at planar interfaces. Nanoparticles show strong optical resonances, again because of their large free-electron density. As a result, a plane wave impinging on a 20 nm diameter silver particle is strongly 'focused' into the particle, leading to a large electric field density in a 10 nm region around the particle. Ordered arrays of nanoparticles can possess even further enhanced field intensities because of plasmon coupling between adjacent particles. By varying nanoparticle shape or geometry, it is possible to tune the frequency of surface plasmon resonance over a broad spectral range. For example, gold ellipsoids or silica colloids covered with a gold shell show resonances that coincide with the important telecommunications wavelength band. The ability to achieve locally intense fields has many possible applications, including increasing the efficiency of light emitting diodes, (bio) sensing, and nanolithography. The light-carrying phenomenon when light falls on a thin film of metal containing millions of nanometer-sized holes shows some surprising results. Interestingly, the film was found to be more transparent than expected, and thus generate many applied research possibilities. The holes were much smaller than the wavelength of visible light, which should have made it almost impossible for the light to get through at all. When the incoming photons struck the metal film, they excited surface plasmons, which picked up the photons' electromagnetic energy and carried it through the holes, re-radiating it on the other side and giving the film its transparency (Ebbesen, 1998).

Arrays of metal nanoparticles can also be used as miniature optical waveguides. In linear chain arrays of nanoparticles, a plasmon wave propagates by the successive interaction of particles along the chain. The propagation length is small (~100 nm), but may be increased by optimizing particle size and anisotropy. The effect of quantum confinement make these nanoparticle array waveguides attractive as they provide confinement of light within ~50 nm along the direction of propagation, a 100-fold concentration compared to dielectric waveguides. A very peculiar effect occurs in metal films with regular arrays of holes, in which, local field enhancements are predicted to occur along the holes. This effect leads to much larger optical transmission through the holes than expected, based on consideration of their geometric areas. The precise role of surface plasmons in these effects is still the subject of lively scientific debate, but applications of the enhanced transmission characteristics in nanoscale optical storage appear promising (Prodan et al., 2003).

Clearly, there is a plenty of plasmonic concepts still waiting for exploration. The clinical studies are ever increasing and encouraged with promising results (Loo et al., 2005). The applications spanning from (bio) sensing, optical storage, solid-state lighting, interconnects and waveguides. Indeed, it appears that metals can shine a bright light toward the future of nanoscale photonics. Most of the early work in plasmonics focused on the study of resonances and electromagnetic field enhancements in individual metal nanoparticles and particle assemblies (Prasad, 2004; Rayleigh, 1888; Pendry, 2000). It is possible to form nanoscale hot spots through plasmon coupling within arrays of metal nanoparticles. In these hot spots, the intensity of light from an incident beam can be concentrated by more than four orders of magnitude that lead to a large improvement in sensing techniques that use optical radiation, such as Raman spectroscopy, with potential applications in medical diagnostics (Polman, 2008). In phenomena that are nonlinear in light intensity the effect of light concentration via plasmons are robust. This has recently been demonstrated by the on-chip generation of extreme-ultraviolet light by pulsed laser high harmonic generation (Kim et al., 2008). This opens up a new avenue in lithography or imaging at the nanoscale with soft x-rays. The methodology of fluorescence energy transfer that is routinely used in biology is limited in length scale (Sonnichsen et al., 2005). Using the highly sensitive plasmonic interaction between metal nanoparticles this can be overcome. Due to the very high sensitiveness to nanoparticles separation, precise measurements of the plasmon resonance wavelength of metal particle assemblies functionalized with bio-molecules can be used as a molecular-scale ruler that operates over a much larger length scale. Practical applications of this concept in systems biology, such as imaging of the motion of molecular motors, bio labeling and bio sensing are being exploited (Polman, 2008). The standard commercial pregnancy tests and the detection of bio-molecules are based on the measurement principle of plasmonic resonance shifts. The possibility of using of particles composed of a dielectric core and a metallic shell in future cancer treatments is underway. The injected shell-core nanoparticles are selectively bound to malicious cells and then laser irradiation at a precisely engineered plasmon resonance wavelength is focused to heat the particles and thereby destroy the cells (Atwater et al., 2009).

One of the main challenges of present plasmonic research is to shrink visible wavelength regime into the soft x-ray wavelength regime. The long distance propagation of surface plasmons along metal waveguides using plasmonic structures based on metal nanoparticles is a new paradigm of research. Using the tools of nanotechnology one can precisely controls material structures and geometry that allows the wave-guiding properties to be controlled in ways that cannot be achieved with regular dielectric waveguides. Particularly, extremely short wavelengths can be achieved at optical frequencies using plasmonic waveguides. A recent experiment demonstrate that light with a free-space wavelength of 651 nm can be squeezed to only 58 nm in a metal-insulator-metal plasmonic waveguide (Miyazaki et al., 2006). The propagation speed of plasmons can be further reduced well below the speed of light by suitably engineering the structures of plasmonic waveguide. Integrating nanoholes in metal films that acts as efficient color filters a more efficient plasmonic waveguide structures have been fabricated. In some complex geometry by tailoring the plasmon waveguides, a negative refractive index for the guided plasmon has been observed. This is very interesting because the two-dimensional negative refraction in these plasmonic waveguides may be useful for plasmonic lens and high resolution imaging (Lezec et al., 2007). The research on planar plasmon propagation is targeted to the design of plasmonic integrated circuits. Using these plasmonic integrated circuits optical information can be generated, manipulated, switched, amplified, guided and detected within dimensions much smaller than the free space wavelength of light. The dream is the integration of optics with nanoscale semiconductor integrated circuit technology. So far, it seems plasmo-eletronic integration is impossible because of the different length scales of optics and electronics. It is hoped that in these devices of nanoscale dimensions a relatively small propagation lengths

could be tolerated despite of plasmons decay during their propagation. The plasmo-electronic technology may open a wealth of prospects in designing plasmon laser or amplifier of nanodimension.
As mentioned before, optical 'meta-materials' with artificially engineered permittivity and permeability will fulfill the ever-growing market demand of advanced materials for optoelectronics and nanophotonics circuitry. The fabrication of metallic nanoresonators in 2D and 3D arrangements employing meta-materials is a step forward in this direction. A stack of metallic 'fishnet' structures shows negative index of refraction at near infrared light wavelength (Valentine, 2008). It is possible to achieve sub-wavelength optical imaging due to the peculiar nature of light refraction in the materials of negative refractive indices (Pendry, 2000). Surprisingly, precisely engineered geometries with negative refractive indices may even act as invisibility cloaks for visible wavelengths. It is needless to mention that, the field plasmonics has grown from an embryo with fundamental insights to a vast field with important applications and commercialization. To shape up the plasmonic research, several novel basic and applied research topics are undertaken, including the femto- and atto-second dynamics and coherent control of plasmons, 4D imaging, plasmo-electronic integration, lasing spacers cloaking using novel geometries (Engheta, 2008) and quantum mechanical effects at the sub-nanoscale level. These studies are very exploratory with innovations and enriched with novel scientific thoughts as well. Many new exciting applications of plasmonics are waiting to capture the market. These efforts, in turn, have benefited greatly from the flowering of nanotechnology in general over the past decade, which brought with it a proliferation of techniques for fabricating structures at the nanoscale, exactly what plasmonics needed to progress from laboratory curiosity to practical applications (Brongersma et al., 2007).
The plasmonics made a breakthrough in the field of the solar cell design using semiconductors to enhance the efficiency. In this route, gold nanoparticles on the surface of semiconductors are fabricated that act as reflectors and focus light into the semiconductor and thereby increase the absorption efficiency by concentrating more light (see figure 22). The other route in which, tiny gold nanoantennas could redirect sunlight vertically allows it to propagate along the semiconductor rather than passing straight through the surface. In both the approach, the cell could get by with a much thinner semiconductor layer and acts as a superior concentrator of light. Using plasmonic techniques, not only the cost of the solar cells is decreasing but the efficiency at extracting the available energy from sunlight also drastically improving. An optimistic model calculation and theoretical estimate shows that the use of plasmonics in photovoltaics could increase the absorption two to five times and commercialization of such solar cells look promising. The amorphous silicon based solar cells available in the market have efficiencies of around 10–15 % and the predicted enhancements could translate into efficiencies of about 20 %. Currently available crystalline silicon solar cells have efficiencies around 21 % and the new figure could approach the theoretical maximum of about 30 %. The large scale and low-cost commercial applications are facing the challenges of developing workable device designs, architecture and fabrication techniques for mass production (Atwater et al., 2009).
The beauty of plasmonics is that it can bring the optics closer in size to the transistor, which can offer optical pathways on virtually the same scale as the silicon structures found in advanced microchips. The design of chip with the integration of metals is possible to distribute light over an integrated circuit by surface plasmons. Structures of gold and silver nanowires, nanorods, nanodots (Verhagen, 2009) or grooves are etched into metal surfaces

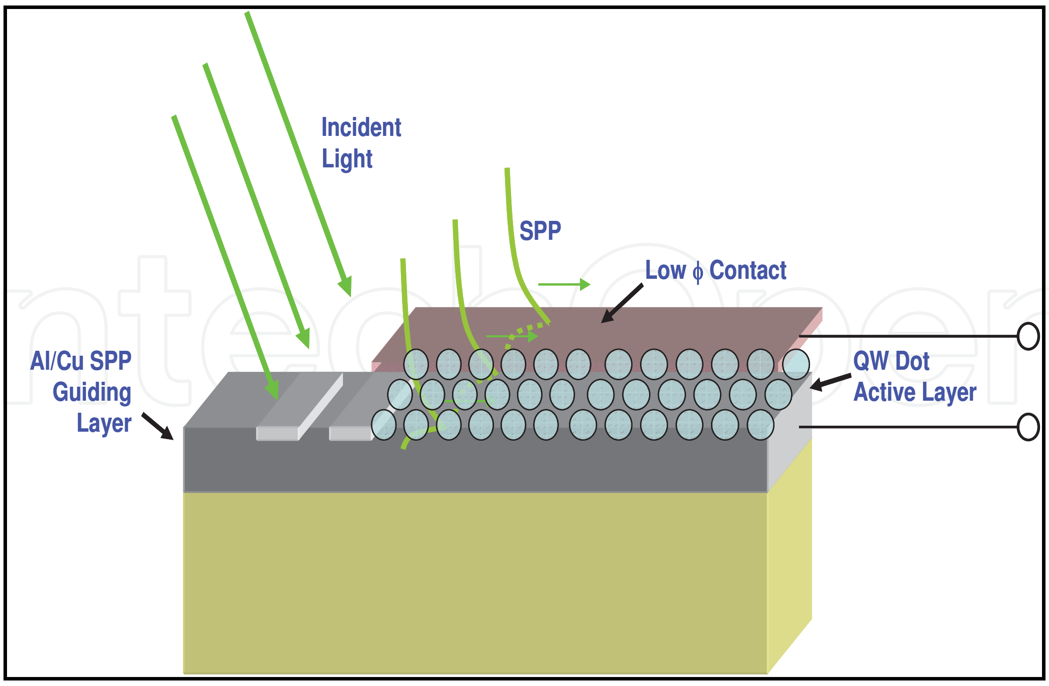


Fig. 22. Light manipulation in plasmonic quantum dot solar cell; the surface plasmons are generated to help direct light using nanoantennas in devices such as solar cells.

(Bozhevolnyi, 2006). They are expected to provide pathways that guide light across a chip irrespective of the designer's directionality. The only trade-off here is with the smallness of the structure, in which forcing the plasmons to travel through too narrow channels can cause leak out from the sides and thereby gets lost. However, guiding surface plasmons over distances of more than 100 μm is possible, which is roughly a thousand times bigger than the features on a current generation microchip. This research has opened new possibilities for plasmonic nanocircuits to carry information using light waves along complex paths and through many processing steps. Recent progress in the laser miniaturization has shown the promise to fabricate plasmonic waveguides. Moreover, plasmonics offers the possibility of integration of plasmo-electro chip at the nanoscale, at lengths much shorter than the wavelength of laser light. Rather than amplifying light in a conventional laser cavity, a plasmonic '*spaser*' would amplify it with the help of plasmons and the first experimental evidence for such plasmon-based lasing has already been reported (Noginov, 2009; Oulton 2009).

The full integration of these plasmon lasers into standard micro-circuitry, however, needs a suitable way to trigger the spasers using standard electrical currents. '*SPASER*' the Surface Plasmon Amplification by Stimulated Emission of Radiation is a new device that has been introduced very recently. In a spaser, a surface plasmon plays the same role as a photon in a laser. A plasmon enters the resonator as a nanoparticle embedded in a gain material containing chromophores such as semiconductor nanocrystals or dye molecules. The gain medium must be capable of producing population inversion, which allows it to lase or '*spase*' in this case. Spacers are ultrafast nanoplasmonic chips with high degree of integration. In addition to creating light and guiding it across, spacers communicate and control each other through their near fields or are connected with nanoplasmonic wires and perform ultrafast microprocessor functions (Noginov, 2009). The plasmonics based optical computing requires a series of bits in a digital data stream that can be obtained by turning the flow of plasmons on and off at high speeds. A plasmonic modulator using silicon technology has been realized and the working principle of this device is based on the use of an electric field to control the propagation of surface plasmons through the device (Dionne, 2009). They are not only much smaller in size compared to conventional optical counterparts but their operation frequency can easily reach tens of terahertz that is much above the gigahertz limit of modern computers.

One of the niche areas in plasmonics is surface-enhanced Raman spectroscopy. One can enhance the signal by several orders of magnitude larger and is strong enough to detect a single molecule (Fleischmann, 1974; Nie, 1997). The surface-enhanced Raman spectroscopy is very useful in the biochemical and materials sciences for providing information on the chemical composition of molecules at very small concentrations and detail microstructures. Surface-enhanced Raman spectroscopy is a plasmonic effect in which silver/gold nanoparticles act as nanontennas to gather the incoming laser light and, through their surface plasmons, concentrate it. In this case, a dual amplification results gigantic signal enhancement by concentrating the light first and then scattered by nearby molecules and amplified again by the silver/gold nanoparticles on the way back out (Atwater et al., 2009). Presently, the surface-enhanced Raman spectroscopy faces some problem for commercialization. This is due to formidable difficulties in achieving highly accurate control over the surface nanostructures and their mass production. Other sensing techniques such as localized surface plasmon resonance may be a suitable alternative in which the surface is covered with nanostructures in the shape of rods or triangles plays important role. The plasmonic properties depend strongly on the properties of the surrounding medium and the changes to the refractive index lead to experimentally measurable changes to the wavelength of surface plasmon resonance (Anker et al., 2008). Surprisingly, the huge sensitivity of localized surface plasmon resonance based devices can reach to the limit of single-molecule detection, and can even focus to destroy cancer cells! For cancer treatments, gold nanoparticles can be injected and guided to the tumor by antibodies bound to the particles' surface. By illuminating the area near nanoparticles with a low dose, using infrared laser light gets absorbed to create plasmons in the gold and burn the infected cells and leaves healthy tissue undamaged. The cancer cells are finally killed by heating up the nanoparticles with accumulated energy through localized surface plasmons (Hirsch et al., 2003). This kind of cancer therapy has successfully been tested on mice for complete elimination of the tumors and waiting for the human clinical trials with patients having head and neck cancers.

Exponential rise in nanophotonics research provided amazing data processing and signal transport capabilities that have the potential to enhance computer performance remarkably. However, to realize this objective much powerful integration techniques for newly emerging nanophotonic devices with conventional nanoelectronics components are urgently required. Undoubtedly, a natural choice for an ideal platform for the marriage of these distinct technologies would be the silicon. Consequently, the lack of an intrinsic source of surface plasmon polaritons compatible with silicon-based complementary metal-oxide semiconductor fabrication techniques slowed down the growth of the integration of plasmonic components with silicon. Presently, complementary metal-oxide semiconductor has reached to true nanoscale devices composed of complex and intertwined dielectric, semiconductor and metallic structures. The impressive developments and availability in computer aided circuit design, lithography, Monte Carlo method, electronic and photonic-device simulations, an increasingly wide variety of integrated optoelectronic functionalities are making the silicon-based technology more robust (Hryciw et al., 2010). Plasmonics is playing major role in the design of future silicon-based optoelectronic and plasmo-electronic chips based on the manipulation of surface plasmon polaritons. The plasmonics research began with passive routing of light in waveguides with diameters much smaller than the wavelength of the light. The surface plasmon polariton waveguides was not perceived as a superior alternative to high-index dielectric waveguides as the propagation length in such high-confinement is limited to a few tens of μm. It is important to keep in mind that the size of dielectric waveguides is limited by the fundamental laws of diffraction, which is much larger than the electronic devices on a chip. However, the sub-wavelength dimensions of plasmonic devices are uniquely capable of reconciling the size mismatch and bridge the gap between dielectric micro-photonics and nanoelectronics. The passive waveguides and light-concentrating structures are the two exciting outcome of the plasmonic studies.

Using surface plasmons, by channeling and concentrating light on sub-wavelength structures miniaturized photonic circuits with waveguides having nanometer length scales have been fabricated. This photonic circuit first converts the incident light to a surface plasmon wave that propagates and eventually converts back to light. These waveguides are realized by depositing gold stripes on a dielectric surface. It is possible to channel the electromagnetic energy using a linear chain of gold and silver nanoparticles over a distance of ~200 nm without any significant loss. In this geometry, each nanoparticle with dimension much smaller than the wavelength of incident light acts as an electric dipole and thereby produces surface plasmon. The inter-particle spacing in the array plays an important role in deciding the interactions. The near-field electric-dipole interactions dominates when the inter-particle separation become much smaller than the wavelength of incident light. This is highly desirable for the wave guiding application of arrays of gold or silver nanoparticles. Active plasmonic devices are designed to switch and detect light in ultra-compact geometries that may exceed the stringent requirements of complementary metal-oxide semiconductor technology (Walters et al., 2010). A crucial ingredient called complementary metal-oxide semiconductor-compatible plasmonic sources can now be added through surface plasmon polaritons. These surface plasmon polariton emitters will play a crucial role in chip-scale optical information links useful for novel integrated bio-sensing applications. A silicon-based source for active Plasmon waveguide using Si nanocrystals as the active medium whose operation principle is similar to other device are created. This device is fabricated using atomic layer deposition and low-pressure chemical vapor deposition processes occurred at around room temperature to be compatible with complementary metal-oxide semiconductor processing (Pavesi, 2003).

The silicon microelectronics world is currently defined by length scales that are many times smaller than the dimensions of typical micro-optical components, the process scaling driven by Moore's law. The size mismatch poses severe challenge to integrate photonics with complementary metal-oxide semiconductor electronics technology. One promising solution is to fabricate optical systems at metal/dielectric interfaces, where surface plasmon polaritons offer totally new and unique opportunities to confine and control light at length scales below 100 nm. Many passive components developed using plasmonics suggests the potential of surface plasmon polaritons for applications in sensing and communication. Active plasmonic devices based on III–V materials and organic materials and an electrical source of surface plasmon polaritons using organic semiconductors have been reported. It is established that a silicon-based electrical source for surface plasmon polaritons can be fabricated using low temperature micro technology processes that are compatible with back-end complementary metal-oxide semiconductor technology (Hryciw et al., 2010). The highly confined modes of metal–dielectric–metal called metal–insulator–metal plasmonic waveguides dramatically alter the light-emission properties of optical emitters located between the metals (Jun et al., 2008). Moreover, there exist an efficient electromagnetic decay pathway for the surface plasmon polariton emission thereby the radiative decay rate of excited emitters can be increased order of magnitude, a direct consequence of the Purcell effect (Hryciw et al., 2010). The small size of the surface plasmon polariton mode that is directly translates to a strong coupling to the surface plasmon polariton emitter is primarily responsible for the large modification of the decay rate in these plasmonic structures. Other high-confinement metal oxide semiconductor and silicon slot waveguides shows similar beneficial effects and lay the foundation of an entire new set of silicon-based sources (Hryciw et al., 2009; Galli et al., 2006; Jun et al., 2009). The enhancements in high-confinement waveguides are very broadband in nature that allows effective use of emitters across the entire visible and near-infrared spectrum to achieve power-efficient incoherent light sources. Even for poor emitters the reduced radiative lifetime is beneficial in increasing the efficiency that allows faster source modulation. The other important benefit of metal-dielectric-metal waveguides is that they only support a single propagating mode and provide low-loss dielectric waveguides (Veronis et al., 2007). The wave guiding based on high-confinement sources is altogether a new class of chip scale devices. They combine efficient charge injection and facile photon extraction by an electrically pumped, plasmon-enhanced light source that inspires new way of designing truly nanoscale photonic devices and circuits for future miniaturization (Brongersma et al., 2007).

Surface plasmon polaritons are quasi-two-dimensional electromagnetic excitations. They propagate along a dielectric-metal interface in which the field components decay exponentially into both neighboring media. The field of a plane surface plasmon polariton comprises a magnetic field component, which is parallel to the interface plane and perpendicular to the propagation direction. It has two electric field components, of which the main one is perpendicular to the interface. The numerical simulations shows that nanometer sized metal rods can support extremely confined surface plasmon polariton modes that propagates over hundreds of nanometers. Similar observations have been made for the electromagnetic excitations supported by chains of metal nano-spheres. Metal stripes of finite width are employed for lateral confinement of the surface plasmon polariton along the stripes. In conventional integrated optics based on dielectric waveguides, the problem of miniaturization is approached. This is achieved by making use of the photonic band gap effect that is essentially a manifestation of Bragg reflection of waves propagating in any direction because of periodic modulation of the refractive index (Maier, 2007; Brongersma et al., 2007).

The efficient wave guiding along straight and sharply bent line defects in 2D photonic band gap structures has been demonstrated for light wavelengths inside the photonic band gap. It became clear that these photonic band gap structures, when properly designed and realized, might be advantageously used for miniature photonic circuits allowing for an unprecedented level of integration. Furthermore, one can conjecture that other (quasi) 2D waves, e.g., surface plasmon polaritons, might be employed for the same purpose. The surface plasmon polariton photonic band gap effects for all directions in the surface plane of a silver/gold film having a 2D periodic surface profile has also been demonstrated. It should be emphasized that the interaction of surface plasmon polariton with a periodic surface corrugation, similarly to the interaction of a waveguide mode with a periodic array of holes, produces inevitably scattered waves propagating *away* from the surface. This unwanted process results in the additional propagation loss and has to be taken into account when considering the surface plasmon polariton photonic band gaps structures. The surface plasmon polariton guiding along line defects in surface plasmon polariton photonic band gap structures with ~45 nm high and 200 nm wide gold bumps arranged in a 400 nm period triangular lattice on the surface of a 45 nm thick gold film is also reported. The efficient surface plasmon polariton reflection by such an area and surface plasmon polariton guiding along channels free from scatterers was observed, as well as significant deterioration of these effects at ~800 nm, indicating the occurrence of the surface plasmon polariton photonic band gaps effect in these structures (Veronis et al., 2007; Kalele et al., 2007).

There are many uses of gold and silver nanoparticles and nanorods from cancer-cell diagnostics, cancer-cell imaging and photo-thermal therapy. In the plasmonics applications of bio imaging or drug delivery, mostly the nanoparticles of gold and silver are used as it offers highly favorable and biocompatible optical and chemical properties. Moreover, metal nanoshells having the same volume as metal nanoparticles show much stronger and sharper surface-plasmon-resonance bands due to its enhanced surface area. Therefore, the nanoshells are preferred for the detection of macromolecules, DNA, proteins and microorganisms. The integration of biology and the materials science at nanoscale has the potential to revolutionize many fields of science and technology. The relevance of nanometer scale stems from the natural dimensions of bio-molecules, such as, DNA, proteins, viruses and sub-cellular structures as they fall in the length scale of 1 to 1000 nm. Gold nanoparticles are mostly exploited for bio imaging and therapeutic applications due to their strong properties of light scattering. In addition, the scattered intensity depends on the size and shapes of nanoparticles and their aggregation states (Hryciw et al., 2009; Kalele et al., 2007).

The non-photo-bleaching character of gold is suitable for detecting very low concentration and can be used as contrast agents in various biomedical imaging techniques. It is demonstrated that the antibody-conjugated gold nanoparticles bind specifically to the surface of malignant cells with much more affinity than healthy cells; also, malignant cells required half the energy to be destroyed photo-thermally than healthy cells. Gold nanocages have been employed in optical coherence tomography by using scattered light for noninvasive imaging to detect cancer at an early and treatable stage. The materials structures fabricated using nanosphere lithographic technique can be used for chemosensing and biosensing by realizing through shifts in the surface Plasmon resonance peak. The mechanism of the shift can be attributed to the changes in the local relative permittivity as well as charge transfer interactions between the adsorbed analyte and the metal. The wavelength shifts are more reliable rather than the intensity changes in biophotonics. Some spectacular observation on the shift of surface-plasmon absorption bands has been made in recent years using nanosphere lithography-deposited silver and gold nanotriangles and nanorods having size ~50 nm (Kalele et al., 2007; Walters et al., 2010).

Despite of many roadblocks remain to the commercialization of plasmonic technologies ranging from the plasmo-electronic integration on a single microchip to device issues there is renewed research interests. The future challenge would be to minimize the losses in the metal nanostructures, and he smart design of the plasmonic structures has been attempted to reduce the losses to acceptable levels. Although, the plasmonics research has already made remarkable progress but the understanding of physics very close to the metal surface still far from being fully understood. Current commercially available optical devices are too large and show rather high losses in the optical signal strength. Plasmonic-based devices will perhaps overcome this problem because a light beam could in principle, relay information through the chip on more channels and at a higher speed than conventional integrated circuitry can handle. Nevertheless, the plasmonics has given to photonics the ability to go to the nanoscale and properly take its place among the nanosciences.

4. Challenges of nanophotonics

Nanophotonics has the potential to improve optoelectronic products in a wide array of new applications. There are no yardsticks or a clear roadmap yet regarding the stability, efficiency, tolerances, longevity and large-scale production. However, the promises of 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 (Ghoshal et al., 2007; Chu et al., 2005). Some of them are

- Market strategy

Nanophotonics has the potential to improve optoelectronic products in a wide array of new applications, including multi target markets each worth few billions of dollars. Making market strategy is a greater challenge than the technology. These findings are presented in most of the studies in recent time.

- Single –molecule addressing (pre-requisite for architectures work)
- Optical nanoscopy of molecules
- Designing plasma-optic chip
- Assessment of nanowires, nanoparticles and nanoarrays in nanophotonics
- Assessment of metal nanoparticles, nanoarrays and nanorods
- Hierarchy of interactions with other quasi particles
- Energetically sound
- Amplification and gain
- Integration, costs, standards, etc.

Although, these are the main challenges but there are expected benefits from nanophotonics. Some of them are:

- Bridge the gap between current photonic systems and future approaches bringing in example:
    - access to further integration
    - lower noise
    - mass production techniques and accurate fabrication
    - plasma-electro integration
    - cheaper and efficient devices
- Moving towards molecular photonics as the probable limit of integration which
    - will dissipate less energy
    - will occupy less volume
    - will require lower input signal
    - will probably rely on self assembly
    - will be more lasting
    - will be more flexible
    - will be more sensitive

- Molecules might compute, sense, act and serve building block of more complex structures
    - time scale
    - length scale
    - input-output schemes, algorithms.

Majority of the present fabrication techniques are based on expensive technologies and processes belonging to the very high technology pursuits at an expensive category, such as e-beam lithography, projection lithography, ion-beam milling and extreme ultraviolet lithography. There is great interest and need for approaches as well as strategies for large-scale production, which are more cost-effective and environment friendly. The development of the emerging nanopatterning methods that is recently established may overcome certain barriers related to mass production. The parallel-processes including self-assembly for polymeric materials with matrices can be tested with few milligrams to optimize a novel optical materials. Moreover, getting devices within the next one or two decades would require to produce kilograms of nanophotonic and molecular photonic materials and manufacture them cost efficiently. Thus, preparation techniques are needed that can be scaled up. The criteria on tolerances, efficiency of energy transfer and longevity are other significant issues that manufacturer have to meet when it comes to material purity because this will be an important cost factor, as will lateral size control. Nevertheless, much of these techniques have to be well established with the relevant industrial standards and free of hazards. Until now, it is far from being understood that how efficiently the energy can be converted from a molecular transition into an electronic transition. How efficient a photonic device will be to convert photons to electrons and finally back to photons? The stability of such processes is major concern to the researchers.

5. Nanoscale optical confinement

Size quantization in materials is the manifestation of quantum-confinement in low dimensional quantum structures. Materials at nanometer length scale having large surface to volume ratio possess different electronic and optical density of states and shows many emerging properties those absent in bulk structures. The change in the nature of optical band gaps and the opening up the gap are the manifestations of optical confinement due to which plasmon can be localized and photons can be confines in nanostructures. They have quantum optical properties that are absent in the bulk material due to the confinement of electron-hole pairs (called excitons) in a region of a few nanometres. For example, bulk metals was never thought of as useful candidates for photonics applications, and due to their high reflection and absorption coefficients they have been generally overlooked as elements to guide, focus and switch light at visible and infrared wavelengths. However, at the nanoscale the intriguing guiding and refractive properties of metal structures can be realized since the metal components become semi-transparent due to their small size (Pavesi, 2007; Ghoshal et al., 2007).

Light can be localized and manipulated in appropriately designed metallic and metallo-dielectric nanoparticle array structures. Interesting phenomena occur near the plasmon frequency where optical extinction is resonantly enhanced due to the effect of quantum confinement. Recent interest exploits the collective oscillations of the conduction electrons of this plasma in arrays of metal nanoparticle can also be used as miniature optical waveguides in linear chain arrays of nanoparticles. A plasmon wave propagates by the successive interaction of particles along the chain. The propagation length is small (~100 nm) but may increase by optimizing particle size and anisotropy. A nanoparticle array waveguides is attractive because they provide confinement of light within ~50 nm along the direction of propagation and a 100-fold concentration compared to dielectric waveguide (Koller et al., 2008; Stockman et al., 2007). The confinement of photons in a nanoscale optical cavity offers other possibilities. The spontaneous emission rate depends on cavity properties, increasing with quality factor and decreasing with mode volume. Photonic-crystal cavities can be made with model volumes smaller than the cube of the wavelength (measured as the wavelength λ in air divided by refractive index n of the medium) and can be fabricated with high quality factors. That greatly enhances the spontaneous-emission rate and the fraction of those photons coupled into a single-cavity mode. This allows a single nanocavity to operate as a laser with a very low threshold (Kobayashi et al., 2002).

The surface plasmon resonance associated with array of nanoparticles of noble metals within the size range ~ 10 to 100 nm can be localized to each nanoparticle known as *localized surface plasmon resonance.* On the other hand, the surface plasmon resonance associated with a metallic thin film of thickness in the 10 - 100 nm range can travel across the metal dielectric interface called *propagating surface plasmon resonance*. Although light is not able to propagate through a bulk metal, plasmons are able to propagate at a metal–dielectric interface over distances as large as several centimeters. Furthermore, the plasmon wavelength can be tuned by proper control of the metal film's thickness, size, shape and geometry of nanoparticles. The fabrication of plasmonic waveguide with wavelength shorter than that in free space is in fact the practical realization of this concept. The nanostructures made of gold and silver have been studied much more extensively due to their unique optical and electronic structure properties. In addition to the size and the shape of nanoparticles, surface plasmon resonance also greatly influenced by diverse phenomena such as Rayleigh scattering from nanoparticles, aggregation of nanoparticles, charge transfer interactions, changes in local refractive index, presence of defects, etc. These kinds of interactions are highly useful and are often explored for the detection of bio-molecules using metal nanostructures. The detection process involves monitoring the changes associated with the surface plasmon of the metal nanostructures on addition of the bio-molecules. Surface plasmon resonance can also be tuned over a very wide spectral range using novel nanostructure such as nanoarrays, nanorods and nanoshells (Prasad, 2004; Shen et al., 2000; Kalele et al., 2007).

The optical properties of silicon nanocrystallites of known sizes, present in super-critically dried porous silicon films of porosities as high as 92 %, have been measured by a variety of techniques. The band gap and luminescence energies have been measured as a function of size for the first time. The band gap increases by more than 1 eV due to quantum confinement (Bettoti et al., 2003; Pavesi, 2003). The peak luminescence energy, which also shifts to the blue, is increasingly Stokes shifted with respect to the band gap, as the size decreases. The measured band gap is in agreement with realistic theories and the Stokes-shift between band gap and luminescence energies coincides with the exciton binding energy predicted by these theories. These results demonstrate unambiguously and quantitatively the role of quantum confinement in the optical properties of this indirect gap semiconductor (Behren et al., 1998). Optical confinement effects in nanostructured materials enable new innovative device concepts that can radically enhance the operation of traditional semiconductor devices. A larger fraction of the solar spectrum can be harnessed while maximizing the solar cell operating voltage by using quantum wells, quantum wires and quantum dots embedded in a higher band-gap barrier material.

Nanostructured devices thus provide a means to decouple the usual dependence of short circuit current on open circuit voltage that limits conventional solar cell design. Ultra-high conversion efficiencies are predicted for solar cells that collect both low and high-energy photons from the solar spectrum while maintaining high voltage operation. Unprecedented opportunities are arising for re-engineering existing products. For example, cluster of atoms (nanodots, macromolecules), nanocrystalline structured materials (grain size less than 100 nm), fibres less than 100 nm in diameter (nanorods and nanotubes), films less than 100 nm in thickness provide a good base to develop further new nanocomponents and materials in nanophotonics. The buckyball (C_{60}) has opened up an excellent field of chemistry and material science with many exciting nanophotonic applications because of its ability to accept electrons. Carbon nanotubes (CNTs) have shown a promising potential in the safe, effective and risk free storage of hydrogen gas in fuel cells, increasing the prospects of wide uses of fuel cells and replacement of internal combustion engine. In addition, one can exploit the potential of CNTs in oil and gas industry. Nanotechnology offers a myriad of applications for production of new gas sensors, optical sensors, chemical sensors, and other energy conversion devices to bio implants. Nanoporous oxide films of TiO_2 to enhance photo voltaic cell technology are used. Nanoparticles are perfect to absorb solar energy and that is useful in very thin layers on conventional metals to absorb incident solar energy. New solar cells based on nanoparticles of semi conductors, nanofilms and nanotubes by embedding in a charge transfer medium is an active field of research. Films formed by sintering of nanometric particles of TiO_2 (diameter 10-20 nm) combine high surface area, transparency, excellent stability and good electrical conductivity and are ideal for photovoltaic applications. Nonporous oxide films are highly promising material for photovoltaic applications (Zhiyong et al., 2009).

Nanoscale slab-slot-waveguides that provides high optical confinement have found abundant applications in silicon photonics. After developing an analytical mode solver for general asymmetric slot waveguides, the confinement performance of symmetric as well as asymmetric geometries was systematically analyzed and compared. For symmetric structures, 2D confinement optimization by varying both low-index slot and high-index slab width revealed a detailed saturation trend of the confinement factor with the increase of the studied width. Furthermore, simple design rules on how to choose the slot and slab width for achieving optimal confinement was obtained. For asymmetric structures, we demonstrated that the confinement performance was always lower than the 2D optimized confinement of the symmetric structures providing the two high-index slab layers and the two cladding layers have same refractive indices, respectively. In addition, the sensitivity of the confinement to the degree of asymmetry was studied, and we found that the fabrication tolerance on the material and structural parameters might be reasonably large for symmetric structures designed at optimal confinement (Ma et al., 2009). A change in shape of nanoparticles can produces much larger shifts in the surface-plasmon resonance band due to spatial confinement effect. The surface-plasmon resonance band often splits in to two bands due to the elongation of nanoparticle along some particular axis of aisotropy. The shorter-wavelength band termed as the transverse plasmon resonance band corresponds to the oscillations of electrons along any minor axis, while the longer-wavelength band termed as the transverse plasmon resonance band corresponds to the oscillations of the electrons along the major axis. In some semiconductor nanoparticles different kinds of excitations such as bi-exciton, dark and bright exciton, polaron, bi-polaron and polariton etc. emerges due to the effect of quantum confinement in contrast to their bulk counterpart.

6. Quantum-confined materials

There is much current interest in the nonlinear optical properties of quantum confined semiconductor nanocrystals, particularly for their potential use in nonlinear photonic devices. Glass is an attractive host matrix for the nanocrystals in such applications (Dvorak et al., 1995). Quantum-confined materials refer to structures, which are constrained to nanoscale lengths in one, two or all three dimensions that possess density of states entirely different from bulk structure as shown in figure 23. The length along which there is quantum confinement must be smaller than de Broglie wavelength of electrons for thermal energies in the medium. The thermal energy is given by $E = mv^2/2 = k_BT$ and de Broglie wavelength is $\lambda = h/mv$. For effective quantum-confinement, one or more dimensions must be less than 10 nm. Quantum-confined structures show strong effect on their optical properties. Artificially created structures with quantum-confinement on one, two or three dimensions are called, quantum wells, quantum wires and quantum dots respectively (Botez et al., 2005). Low-dimensional semiconductors and other materials can modify the density of states by restricting their size to the order of an electron wave function and thereby show many fascinating effects. The quantized energy levels in quantum structures became the driving force for next-generation solar cells and other nanophotonic chip design due to the mitigation of the thermal scattering as well as the control of the light absorption range.

The quantum efficiency of the photoluminescence and electroluminescence from a bulk noble metal is very low (~ 10^{-10}) compared to the corresponding nanosystems, which is several orders of magnitude higher (~10^{-4}). However, in the case of silver and gold nanorods or nanoparticles, the luminescence efficiency is enhanced by six to seven orders of magnitude, and in addition, a red (blue) shift for the luminescence maximum is observed with increasing (decreasing) aspect ratio of the nanorods or diameter of nanoparticles. A linear increase in the photoluminescence efficiency with square of aspect ratio (diameter) is remarkable. The enhancement of the luminescence efficiency is also observed for rough surfaces of gold and silver. The rough surface can be modeled as an ensemble of randomly oriented hemispheroids of nanometer size, and the surface plasmon resonance arises from them amplifies the local fields, thereby resulting in the enhancement of photoluminescence often called lightening rod effect. All these are primarily attributed to quantum confinement effects.

Nanoparticulate metals and semiconductors that have atomic arrangements at the interface of molecular clusters and 'infinite' solid-state arrays of atoms have distinctive properties determined by the extent of confinement of highly delocalized valence electrons. At this interface, the total number of atoms and the geometrical disposition of each atom can be used significantly to modify the electronic and photonic response of the medium. In addition to the novel inherent physical properties of the quantum-confined moieties, their 'packaging' into nanocomposite bulk materials can be used to define the confinement surface states and environment, inter-cluster interactions, the quantum-confinement geometry, and the effective charge-carrier density of the bulk. Current approaches for generating nanostructures of conducting materials, especially the use of three-dimensional crystalline super-lattices as hosts for quantum-confined semiconductor atom arrays (such as quantum wires and dots) with controlled inter-quantum-structure tunneling (Sucky et al., 1990) are getting momentum. Quantum-confined nanocrystallites of GaAs are fabricated in porous glass and the bound electronic nonlinear refractive index, the two-photon absorption coefficient, and the refraction from carriers generated by two-photon absorption are simultaneously determined using the Z-scan method and compared to those of bulk GaAs. The quantum-confined Stark effect in single cadmium selenide (CdSe) nanocrystallite quantum dots has also been widely studied due to their potential application in displays and renewable energy. The electric field dependence of the single-dot spectrum is characterized by a highly polarizable excited state (~10^5 cubic angstroms, compared to typical molecular values of order 10 to 100 cubic angstroms), in the presence of randomly oriented local electric fields that change over time. These local fields result in spontaneous spectral diffusion and contribute to ensemble inhomogeneous broadening. Stark shifts of the lowest excited state more than two orders of magnitude larger than the line width were observed, suggesting the potential use of these dots in electro-optic modulation devices (**Empedocle et al., 1997**).

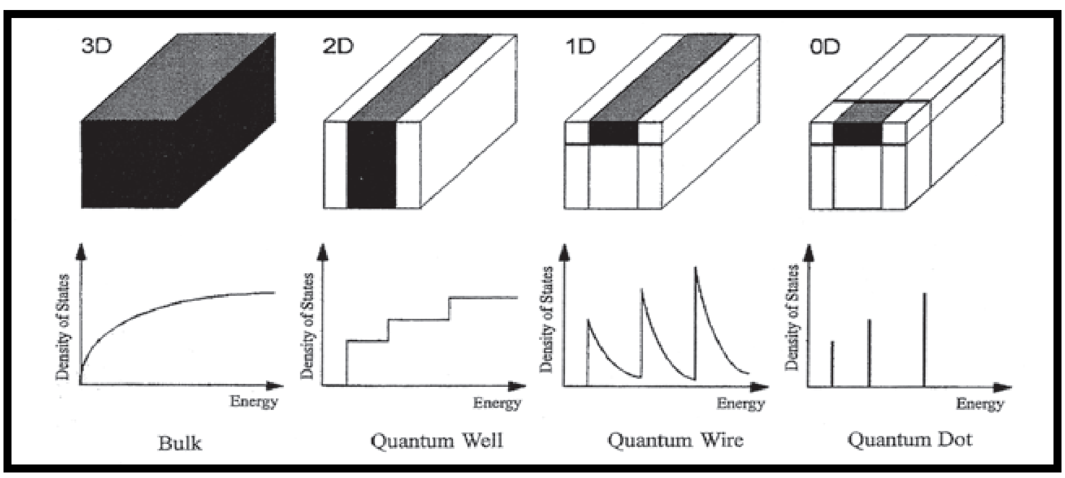


Fig. 23. The change in the density of states with confinement dimensions. Bulk structure suffers no confinement but 0D structure has confinement in all three spatial dimensions and hence density of states is discrete delta functions.

The carrier contribution to elastic constants in quantum confined heavily doped non-linear optical compounds has been studied. The basis of this newly formulated electron dispersion law take into account the anisotropies of the effective electron masses and spin orbit splitting constants together with the proper inclusion of the crystal field splitting in the Hamiltonian within the framework of k.p formalism. It has been found, taking different heavily doped quantum confined materials that, the carrier contribution to the elastic constants increases with increase in electron statistics and decrease in film thickness in ladder like manners for all types of quantum confinements with different numerical values, which are entirely dependent on the energy band constants. This contribution is greatest in quantum dots and least in quantum wells together with the fact the heavy doping enhances the said contributions for all types of quantum-confined materials (Baruah et al., 2007).
To understand the size quantization on the luminescence (see figure 24) from the metal nanoparticles a simplified model for the band structure is developed. This model includes the s-p conduction band and two sets of occupied d bands. The luminescence from metal nanoparticles can be attributed to the transition of electrons from a completely filled d band

(highest occupied molecular orbital) to the unoccupied levels in the sp band (lowest unoccupied molecular orbital). The excitation involves a transition from states in the upper d band to the unoccupied levels in s-p band at and above the Fermi level. The emission arises from the direct recombination of conduction electrons with holes in the d bands of the quantum confined structures. The emission bands either appear due to radiative inter-band recombination of electrons and holes in the s-p and d bands, or originate from radiative intra-band transitions within the s-p band across the band gap. This model has been employed for describing luminescence from silver, gold and other nanoparticles (Link et al., 2002).

Fig. 24. The effect of size quantization: light emission from gold colloids with varying size of nanoparticles , smallest particles emit violet and the largest emit red color.

7. Applications

Nanophotonics is a unique field because it combines scientific challenges with large variety of near- term applications (Koller et al., 2008; Stockman et al., 2007). Fundamental research on nanophotonics leads to applications in communications technology, lasers, solid-state lighting, data storage, lithography, biosensors, optical computers, imaging, solar cells, light-activated medical therapies, displays, and smart materials to cite a few (**Empedocles et al., 1997;** Baruah et al., 2007; Rahmani et al., 1997; Nezhad et al., 2007; Shen et al., 2000; Levy et al., 2004). Some of the important areas that will find large market in next ten to fifteen years from now are identified and represented in figure 25.

Two-dimensional photonic crystal lasers have been fabricated on III-V semiconductor slabs. Tuning of the spontaneous emission in micro and nanocavities has been achieved by accurate control of the slab thickness. Different structures, some of them of new application to photonic crystal lasers, have been fabricated like the Suzuki-phase or the coupled-cavity ring-like resonators. Laser emission has been obtained by pulsed optical pumping. Optical characterization of the lasing modes has been performed showing one or more laser peaks centred around 1.55 µm. Far field characterization of the emission pattern has been realized showing different patterns depending on the geometrical shape of the structures. These kinds of devices may be used as efficient nanolaser sources for optical communications or optical sensors (Postigo et al., 2007).

Nanoscale confinement of matter is achieved on nanoscale crystals and they are used for: (i) optical up-conversion of radiation in rare-earth nanocrystals, (ii) size-dependent emission properties of nanoscale semiconductor crystals (quantum dots), and (iii) size-dependent absorption and confinement is exploited in plasmonic solar cells and biosensing. Metal nanoparticles and nanotips used in surface enhanced Raman spectroscopy. Photonic band gap crystals and photonic band gap fibers (photonic fibers) involve periodic variation of dielectric constant over wavelength-scale. They find applications in fabrication of Micro-Opto-Electro Mechanical Systems, Micro-Optics, i.e. Micro-lasers, Directional Couplers between waveguides, Bio-photonic Chips etc. Optical wires (wave-guides), filters, and transistors are now possible, and all of them could harness the speed of light for optical communications, sensing, data processing and storage.

Silicon photonics offers high-density integration of individual optical components on a single chip. Strong light confinement enables dramatic scaling of the device area and allows unprecedented control over optical signals. Silicon nanophotonic devices have immense capacity for low-loss, high-bandwidth data processing. Fabrication of silicon photonics system in the complementary metal–oxide–semiconductor-compatible silicon-on-insulator platform also results in further integration of optical and electrical circuitry. Following the Moore's scaling laws in electronics, dense chip-scale integration of optical components can bring the price and power per a bit of transferred data low enough to enable optical communications in high performance computing systems (Bettoti et al., 2003; Pavesi, 2003).

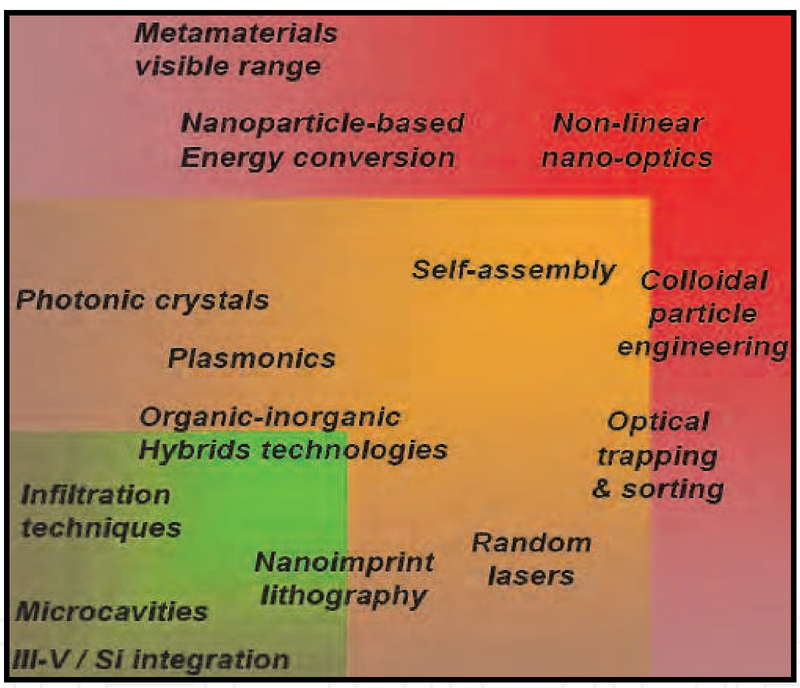


Fig. 25. Schematic diagram for the required technology and materials development in next fifteen years from now in every five years periods as shaded by different colors.

Photonic crystals and photonic band gap materials have a myriad of uses. These uses range from computing to telecommunication and from lasers to circuits that can also be found in almost anything digital. Light-emitting diodes play a key role in optical-communication systems. These devices are made from so-called photo emissive materials that emit photons once they have been excited electrically or optically. These photons are typically emitted in many different directions and have a range of wavelengths, which is not ideal for communications applications. A type of light emitting diode can be created that only emits light in the forward direction by placing a reflector behind the photo emissive layer. However, the efficiency of such a device is limited by the efficiency of the reflector.

Some of important applications of the photonic crystals include, perfect dielectric mirror in which the reflectivity of photonic crystals derives from their geometry and periodicity, not a complicated atomic-scale property (unlike metallic components mirror). The only demand on such materials is that for the frequency range of interest, these should be essentially lossless. Such materials are widely available all the way from the ultraviolet regime to the microwave. The nonlinear effects of the materials exploits the non-linear properties for construction of photonic crystal lattices open new possibilities for molding the flow of light. In this case, the dielectric constant is additionally depending on intensity of incident electromagnetic radiation and any non-linear optics phenomena can occur. In wave-guides and junctions, the existence of guided modes with different parities is an important factor that deeply influences the transmission through the Y junction. The cavity now produces a skewed field that can be understood as a superposition of modes with odd and even parities.

Photonic crystals could be used to design a mirror that reflects a selected wavelength of light from any angle with high efficiency. Moreover, these could be integrated within the photo emissive layer to create a light emitting diode that emits light at a specific wavelength and direction. Ideally, one needs to build a truly 3-D lattice structure to gain complete control of the light in all three dimensions. Fortunately, 2-D periodic lattices exhibit some of the useful properties of a truly 3-D photonic crystal, and are far simpler to make. These structures can block certain wavelengths of light at any angle in the plane of the device, and can even prevent light entering from certain angles in the third dimension (i.e. perpendicular to the surface). Thus, 2-D photonic crystals are a good compromise for many applications and are easily incorporated within planar waveguides.

Improving the existing concepts of light sources is a hot topic in nanophotonics, particularly, flat-panel displays through photo-detectors. However, the ambitions of nanophotonics and molecular photonics go well beyond this simple and straightforward demand. In the field of displays one needs to produce images using liquid crystals or with fluorescent molecules in a polymer matrix. In the near future, the target would be to obtain the internet screen being displayed in the living rooms on a larger screen, with electronic wallpaper acting as the display that is, realizing a component of ambient intelligence. Therefore, nanophotonics can bridge the gap between existing optoelectronic devices and future optics circuitry by incorporating optically active nanostructures and molecules.

Predictions are always difficult to make, however, the future for photonic-crystal circuits and devices looks certain. Within few years, a number of basic applications will start making an appearance in the market place. Among these will be highly efficient photonic-crystal lasers and extremely bright light emitting diodes. It will be possible to implement optical manipulation, signal processing and electronic circuitry all in one chip. Photonic crystals may also be used for high-speed computers of the next generation. Progress has already been made towards replacing the slow copper connections in computers with ultra-fast optical interconnects. Then photons, rather than electrons, will pass signals from board to board, from chip to chip and even from one part of a chip to another. Imagine a computer that operates at the speed of light!

Metal nanostructures have received considerable attention for their ability to guide and manipulate electromagnetic energy in the form of surface plasmon polaritons. The unique properties of surface plasmon polaritons may enable an entirely new generation of chip-scale technologies, known as plasmonics. Such plasmonic devices could add functionality to the already well-established electronic and photonic device technologies. The patterned metal structures are used as tiny wwaveguides to transport electromagnetic energy between nanoscale components at optical frequencies. Interestingly, the surface plasmons and surface plasmon polaritons, which are collective oscillations of electrons in small particles (nanosystems) or on metal dielectric interfaces induced by an incident electromagnetic radiation, is a topic of tremendous interest with ever-growing surprises and promises. In recent years, the potential of plasmonics has been realized in making highly sensitive and very small photonic devices (nanolasers as an example). A wide range of applications emerging from controlling and manipulating the light at the nanoscale such as high-resolution optical imaging below the diffraction limit, enhanced optical transmission through sub-wavelength apertures, bio-detection at femto-mole level, nanoscale wave guiding, THz communications, optical computing and surface-enhanced Raman scattering have been established. Many futuristic applications regarding plasmonic materials rendering invisibility are also inspiring researchers. Surface plasmon polaritons can be tightly bound to the metal surface, penetrating ~100 nm into the dielectric and ~10 nm into the metal. This feature implies the possibility of using surface plasmon polaritons for miniature photonic circuits and optical interconnects and has attracted a great deal of attention to surface plasmon polaritons.

Plasmonic nanoparticles have tremendous technological importance and found applications in therapy and imaging. Beyond biosensing, plasmonic nanoparticles have further applications in biology and medicine. For example, they simultaneously give contrast in electron and optical microscopy such that a labeled cell can be imaged in optical and subsequently in electron microscopy. A modified version uses fluorophore-gold nanoparticle conjugates for simultaneous contrast in electron and fluorescence microscopy. Gold nanoparticles are also promising in hypothermal cancer therapy. In these experiments, nanoparticles that rae attached to cancer cells are heated by the absorption of light until the cancer cell overheats and dies (Shalaev et al., 2007). Plasmonics have wide applications in the energy sector as of improving lighting technologies by improving the efficiency of light emitting diodes up to 14 times. In medicine, for selectively destroying cancer cells by radiation absorption it is very useful. It is even possible in theory to make an object invisible by using plasmonics with metaparticles who have extraordinary optical properties for electronic waves. In computing technology for processing information with speed of light, it is recommended. If it can be combined with graphene, a newly emerged transparent conducting material, innovations beyond our wildest dreams may be achieved. Applications of surface plasmons in solid-state lighting and lasing are just appearing, but it may be that traffic lights are composed of surface plasmon light emitting diodes in a few years time!

Recent advancements in laser science using nanophotonics have tackled physical limitations to achieve higher power, faster and smaller light sources. The quest for ultra-compact laser that can directly generate coherent optical fields at the nanoscale, far beyond the diffraction limit of light, remains a key fundamental challenge. Microscopic lasers based on photonic crystals, carbon nanomaterials, micro-disks, semiconductor quantum structures, metal clad cavities and nanowires can now reach the diffraction limit, which restricts both the optical mode size and physical device dimension to be larger than half a wavelength (Bonaccorso et al., 2010). While surface plasmons are capable of tightly localizing light, ohmic loss at optical frequencies has inhibited the realization of truly nanoscale lasers. Progress in theory and modeling has paved the way to reduce significantly the plasmonic loss while maintaining ultra-small modes by using a hybrid plasmonic waveguide. Experimental demonstration of nanoscale plasmonic lasers producing optical modes 100 times smaller than the diffraction limit, utilizing a high gain CdS semiconductor nanowire atop a silver surface separated by a thick insulating gap has been reported. Direct measurements of emission lifetime reveal a broadband enhancement of the nanowire's spontaneous emission rate by up to 6 times due to the strong mode confinement and the signature of apparently *threshold-less lasing*. Since plasmonic modes have no cut-off the downscaling of the lateral dimensions of both device and optical mode are possible. As these optical coherent sources approaches molecular and electronics length scales, *plasmonic lasers* offer the possibility to explore extreme interactions between light and matter, opening new avenues in active photonic circuits, bio sensing and quantum information technology. Let us turn our attention to the wonder material graphene and see its future promises for plasmonic-based devices for photonics and optoelectronics (Zouhdi et al., 2009; Jablan et al., 2009).

Amongst many, the novel material '*graphene*' has become something of a celebrity material due to its unusual conductive, thermal, electronic, plasmonic and optical properties, which could make it useful in a range of sensors, lasers and semiconductor devices. In addition to flexibility, robustness and environmental stability it possesses high mobility and optical transparency. Most of the recent studies mainly focused on fundamental physics and electronic devices. Undoubtedly, its true potential lies in nanophotonics and optoelectronics, where the combination of its unique optical and electronic properties can be fully exploited, even in the absence of a band gap, and the linear dispersion of the Dirac electrons enables ultra-wideband tunability. Graphene being a potential candidate of advanced plasmonic materials is a rapidly rising star on the horizon of materials science and condensed-matter physics (Bonaccorso et al., 2010; Murray et al., 2007). Graphene's ultra-wide broadband capability will be useful for future nonlinear optical devices including high speed, transparent and flexible photosensitive systems, which could be further functionalized to enable chemical sensing. With an ever-growing interest in the widespread applications of graphene, ultrafast and tunable lasers have become a reality. The combination of graphene photonics with plasmonics could lead to a wide range of advanced devices. The charge carriers in graphene are negative electrons and positive holes, which in turn are affected by plasmons. The '*plasmaron*' is a composite particle; a charge carrier coupled with a plasmon has recently been observed. The rise of graphene in photonics and optoelectronics is shown by several recent results, ranging from solar cells and light-emitting devices to touch screens, photo-detectors and *ultrafast lasers*. Electroluminescence has also been reported recently in pristine graphene. This observation could lead to new light emitting devices based entirely on graphene. In this communication, we will briefly discuss the state-of-the-art in this emerging field (Maier, 2007; Brongersma et al., 2007).

Optical properties of plasmons in graphene are in many relevant aspects similar to optical properties of surface plasmons propagating on dielectric-metal interface, which have been drawing a lot of interest lately because of their importance for nanophotonics. It is reported that plasmons in doped graphene simultaneously enable low-losses and significant wave localization for frequencies below that of the optical phonon branch. Large plasmon losses occur in the inter-band regime via excitation of electron-hole pairs that can be pushed towards higher frequencies for higher doping values. For sufficiently large dopings, there is a bandwidth of frequencies where a plasmon decay channel via emission of an optical phonon together with an electron-hole pair is non-negligible. There are certain frequencies in which plasmons have the low losses and that makes graphene potentially interesting for nanophotonic applications (Zouhdi et al., 2009).

Nanohole arrays have emerged from an interesting optical phenomenon to the development of applications in photo-physical studies, photovoltaics, in imaging chips for digital cameras, and as a sensing template for chemical and biological analyses. Numerous methodologies have been designed to manufacture nanohole arrays, including the use of focus ion-beam milling, soft-imprint lithography, colloidal lithography and modified nanosphere lithography. Hole-arrays in plasmonics are increasingly finding their way into applications as selective filters for color sensors and channeling light into optical devices. Hole-arrays can be made into highly selective filters for sensors that depend on detecting specific colors, or for efficiently extracting monochromatic light from light emitting diodes and lasers. For commercialization NEC laboratory is focusing on prototypes of plasmon-enhanced devices for displays and telecommunications. To reduce pixel noise and improve camera sensitivity hole arrays are placed on top of individual pixels that helps to capture incoming light more efficiently. Another plasmonic technique for channeling light into a device is to sprinkle its surface with nanoscale particles made of a metal such as gold. These nanoparticles function like an array of tiny antennas: incoming light is taken up by plasmons and then redirected into the device's interior.

With nanosphere lithography or colloidal lithography, the experimental conditions control the density of the nanosphere mask and, thus, the aspect of the nanohole arrays. Low surface coverage of the nanosphere mask produces disordered nanoholes. Ordered nanohole arrays are obtained with a densely packed nanosphere mask in combination with electrochemical deposition of the metal, glancing angle deposition or etching of the nanospheres prior to metal deposition. The optical properties of nanoholes have interesting applications in analytical chemistry. In particular, applications of these novel plasmonic materials are demonstrated as substrates for a localized surface plasmon resonance, surface plasmon resonance, surface enhanced Raman spectroscopy and in electrochemistry with nano-patterned electrodes (Polman, 2009). Perhaps, the most promising application of nanohole-arrays called nanoantennas is in the improvement of solar cell efficiency because the currently used solar cells made from silicon has reached to saturation and is expensive. However, to harvest the wide range of wavelengths from the solar spectrum, particularly in the red and infrared part of the spectrum, the semiconductor layer has to be relatively thick and that makes it bulky up to 350 μm thick. Other solar-cell materials except few recently developed nanosystems and organic materials have the same problem and the efficiency is low. Nanoantennas based on surface-enhanced Raman spectroscopy solar cell can overcome this difficulty. Some applications of surface-enhanced Raman spectroscopy have reached the market. For example, in specifically prepared colloids of gold nanoparticles, a clustering of these nanoparticles is triggered by the presence of pregnancy hormones. This leads to a color change induced by plasmonic effects that has been widely commercialized in pregnancy tests.

The other important application of surface plasmons in nanophotonics is the enhanced optical transmission through sub-wavelength- apertures. For light transmission through an aperture having lateral dimensions smaller than $\lambda/2$, the efficiency is extremely low as a result light cannot propagate freely because transmission is possible only via the highly inefficient photon tunneling mechanism. Surprisingly, a substantial enhancement of transmitted light at resonant wavelengths could be achieved for nanoscale apertures (diameter ~200 nm and period ~500 nm) in the form of arrays of holes or slits fabricated on a metal film. This enhancement of the transmission intensity which is much larger than that predicted by classical diffraction theory is primarily due to the coupling of the incident light (photons) with surface plasmons. This finding on enhanced transmission through a large number of nanoholes suggests that even the photons impinging between the nanoholes can be transmitted. Furthermore, the evanescent waves that originate from the diffraction of the incident radiation by the nanoholes diffract while tunneling through the nanoholes and produce interference with the incident waves. Eventually, the surface plasmons enhance the field associated with the evanescent waves, thereby resulting in the enhancement of the transmitted light intensity.

Nanophotonics have potential to make significant impact on military and warfare systems, in both symmetric and asymmetric warfare. The technology parameters identified are real and can be translated into military applications. It is very likely that nanotechnology insertion into disruptive technologies that could pose threats is difficult to anticipate by the very nature of such threats and the sometimes-embryonic state of research in nanophotonics relative to other technologies. Some applications may take substantial investments and time before they are realized. Nanophotonics definitely requires a fabric of supporting and enabling technologies that must be smart, fast and environment friendly. This technology set-up at least in part does not exist today, which further complicates our further outlook. Provoked by the computer games and software development strong emphasis has been placed on information technology as a possible 'game changer,' with nanophotonics. Certainly, it could potentially enable a much more ubiquitous and pervasive data processing and sensing capability than is currently available.

8. Conclusions & future outlook

This new frontier called nanophotonics offers numerous opportunities for both fundamental research and application. The information technology based on the nanotechnology is varied from the targets that can be realized in the 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 and like which 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 used 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 the key roles including the fusion of quantum dot and photonic crystal. The quantum dot will be the basic component of future quantum computing elements in the future 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 bio sensing, 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 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.* Nanophotonics, according to world leaders, has the potential to transform telecommunications technologies in a way even more radical than the emergence of electron-based integrated circuits. People are talking about components such as single photon sources, single photon detectors in the quest for low-noise signals. Components like waveguides, which carry light from one part of the optical circuit to another, and switches are essential. There are good prospects of switching functionality, because optical properties of some molecules are highly non-linear, which is an essential condition for fast switching devices. Therefore, there are very promising device-relevant properties here, suitable for future optical circuits and systems.

The main limitation to plasmonics today is that plasmons tend to dissipate after only a few millimeters, making them too short-lived to serve as a basis for computer chips, which are a few centimeters across it. For sending data even longer distances, the technology would need even more improvement. The key is using a material with a low refractive index, ideally negative, such that the incoming electromagnetic energy is reflected parallel to the surface of the material and transmitted along its length as far as possible. There exists no natural material with a negative refractive index, so nanostructured materials must be used to fabricate effective plasmonic devices. For this reason, plasmonics is frequently associated with nanotechnology. Before all-plasmonic chips are developed, plasmonics will probably be integrated with conventional silicon devices. Plasmonic wires will act as high-bandwidth freeways across the busiest areas of the chip. Plasmonics has also been used in biosensors. When a particular protein or DNA molecule rests on the surface of a plasmon-carrying metallic material, it leaves its characteristic signature in the angle at which it reflects the energy. Therefore, it is necessary to develop smart integration techniques to fabricate plasmo-electronic chips.

Future commercial opportunities of nanophotonics lay ahead in each of the following fields: solar energy, biophotonics, solid-state lighting and displays, computing, telecommunications, sensors and security, etc, to cite a few. This field is expected to revolutionize many aspects of modern life. The commercial potential is frankly overwhelming and mind boggling. Nanophotonics promises solar cells that provide cheap, clean power wherever it is needed. Solid-state lighting systems those are much more efficient and versatile than current light bulbs. Flexible electronic displays that allow cell phones will be the size of credit cards. The computer screens as thin and flexible as a sheet of heavy paper is possible. Computers that connect to the internet at the speed of light are targeted. The new medical devices that give doctors the power to detect and treat diseases in novel ways are up coming. This is just the beginning! The movement from nanophotonics to molecular photonics provides a link to developments in molecular electronics. Ultimately, there is a need to bring together the advantages of molecular photonics with those of molecular electronics, based on the common strategies of preparation, handling and integration. It may well be that molecular electronics is the electronics of the future and molecular photonics, the photonics of the future.

In conclusion, this chapter on 'nanophotonics for 21st century' focuses on the paramount importance and tremendous technological potential of this field for nanoscale device miniaturization at low cost and with maximum efficiency. Nanophotonics is newly developed very vast and expanding paradigm of nanoscience, and is a unique part of physics/chemistry/materials science because it combines a wealth of scientific challenges with a large variety of near-term applications. Nanophotonics is the use of materials nanotechnology in photonics or the use of photonic materials in nanotechnology. The exciting application possibilities of nanophotonics related upcoming areas in science and technology, its present status and future scope are explored in this presentation. Nanophotonics could well revolutionize the fields of telecommunications, computing, imaging and sensing in particular. This presentation argues, why is the research into nanophotonics important? Nanophotonics is all about the manipulation and emission of light in both the far field and near-field using materials at nanoscale. 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 the nanoscale that has been developed in recent years called nanotechnology is the main thrust. Nanotechnology is defined as a novel and multidisciplinary use of materials or processes at the nanometer scale (below 100 nm). However, we attempt to give a panoramic overview of nanophotnics, the science of light-matter interaction at nanometer scale (< 1 μm to ≥ 1 nm), 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 ramifications. Quantum-confined materials are structures that can constrain to nanoscale lengths in one, two or all three dimensions are employed for implementations of devices in nanophotonics. Confinement of light results in field variations similar to the confinement of electron in a potential well. For light, the analogue of a potential well is a region of higher refractive index bounded by a region of lower refractive index.

It is important to note that the overview on nanophotonics provided here cannot do justice to all the different research directions in the field of photonic crystals and plasmonics. Without attempting to be exhaustive, we have tried to present a short but somewhat complete perspective including the fundamentals and some of the current burning research topics. Together, these represent the true state-of-the art in the field of nanophotonics. Several applications are highlighted. In addition, the importance in understanding the electromagnetic wave propagation in photonic crystals/photonic band gap materials and meta-materials are briefly discussed. The chapter concludes with the future of nanophotonics that seems bright and close to reality. The ever-ending research activities aimed in this field are expected to revolutionize many aspects of modern life and will remain fertile ground for basic and applied research.

9. Acknowledgements

S. K. Ghoshal is indebted to Prof. K. P. Jain (IIT, Delhi) and Prof. Sir Roger Elliott (Oxford University) for introducing this field and educating him with many critical concepts. S. K. G gratefully acknowledges the financial support from Universiti Teknologi Malaysia through the research grant (VOTE 4D005/RMC and Q.J130000.7126.00J39/GUP).

10. References

Alu, A. & Engheta, N. (2008). Multifrequency Optical Invisibility Cloak with Layered Plasmonic Shells. *Phys. Rev. Lett.*, 100, 113901(1-4), ISSN 0031-9007.

Anker, J. N.; Hall, W. P.; Lyandres, O.; Shah, N. C.; Zhao, J. & Van Duyne, R. P. (2008). Biosensing with plasmonic nanosensors. *Nature Mater.*, 7(6), 442–453, ISSN 1476-1122.

Atwater, H. & Polman, A. (2009). Surfing the Waves, a Report by Joerg Heber. *Nature*, 461, 720-722, ISSN 0028-0836.

Baruah, D.; Choudhury, S.; Singh, K. M. & Ghatak, K. P. (2007). Influence of quantum confinement on the carrier contribution to the elastic constants in quantum confined heavily doped non-linear optical and optoelectronic materials: simplified theory and the suggestion for experimental determination, *Journal of Physics: Conference Series*, 61, 80-84, ISSN 0953-8984.

Behren, J. V.; Buuren, T. V.; Zacharias, M.; Chimowitz, E. H. & Fauchet, P. M. (1998). Quantum confinement in nanoscale silicon: The correlation of size with bandgap and luminescence. *Solid State Communication*, 105(5), 317-322, ISSN 0038-1098.

Bettoti, P.; Cazzanelli, M.; Dal Negro, L.; Danese, B.; Gaburro, Z.; Oton, C. J.; Vijaya Prakash, G. & Pavesi, L. (2003). Silicon nanostructures for photonics. *J. Phys.: Cond. Mat.*, 14, 8253-8265, ISSN 1361-648X.

Bonaccorso, F.; Sun, Z.; Hasan, T. & Ferrari, A. C. (2010). Graphene Photonics and Optoelectronics. *Nature Photonics*, 4, 611-614, ISSN 1749-4885.

Botez, D. (2005). Intersubband Quantum-Box Semiconductor Lasers: High-Power, Efficient CW Sources for the 3–10μm Wavelength Range. *Laser Physics,* 15(7), 966-974, ISSN 1054-660X.

Bozhevolnyi, S. I.; Volkov, V. S.; Devaux, E.; Laluet, J. Y. & Ebbesen, T. W. (2006). Channel plasmon subwavelength waveguide components including interferometers and ring resonators. *Nature,* 440, 508–511, ISSN 0028-0836.

Brongersma, M. L. & Kik, P. G. (2007). *Surface Plasmon Nanophotonics*. Springer, ISBN 978-1-4020-4349-9, UK.

Chu, T.; Ishida S. & Arakawa, Y. (2005). Compact 1 × N thermo-optic switches based on silicon photonic wire waveguides. *Opt. Express*, 13(25), 10109-10114, ISSN 1094-4087.

Dionne, J. A.; Diest, K.; Sweatlock, L. A.; Atwater, H. A. & Plasmostor, A. (2009). Metal−Oxide−Si Field Effect Plasmonic Modulator. *Nano Lett.*, 9(2), 897–902, ISSN 1530-6984.

Dvorak, M.D.; Justus, B.L.; Gaskill, D.K & Hendershot, D.G. (1995). Nonlinear absorption and refraction of quantum confined InP nanocrystals grown in porous glass. *Appl. Phys. Lett.*, 66 (7), 804-806, ISSN 0003-6951.

Ebbesen, T. W.; Lezec, H. J.; Ghaemi, H. F.; Thio, T. & Wolf, P. A. (1998). Extraordinary optical transmission through sub-wavelength hole arrays. *Nature,* 391, 667–669, ISSN 0028-0836.

Empedocles, S. A. & Bawendi, M. G. (1997). Quantum-Confined Stark Effect in Single CdSe Nanocrystallite Quantum Dots. *Science,* 278 (5346), 2114-2117, ISSN 0036-8075.

Fleischmann, M.; Hendra, P. J. & Mc Quillan, A. (1974). Raman spectra of pyridine adsorbed at a silver electrode. *J. Chem. Phys. Lett.*, 26, 163–166, ISSN 0009-2614.

Galli, M.; Politi, A.; Belotti, M.; Gerace, D.; Liscidini, M.; Patrini, M.; Andreani, L. C.; Miritello, M.; Irrera, A.; Priolo, F. & Chen, Y. (2006). Strong enhancement of Er3+ emission at room temperature in silicon-on-insulator photonic crystal waveguides. *Appl. Phys. Lett.*, 89, 241114-241116, ISSN 0003-6951.

Ghoshal, S. K.; Mohan, D.; Kassa T. T. & Sharma, S. (2007). Nanosilicon for Photonic Application. *Int. J. Mod. Phys. B*, 21(22), 3783-3796, ISSN 0217-9792.

Gopinath, A.; Boriskina, S. V.; Svetlana, V.; Reinhard, B. M. & Bjoern, M. L. (2009). Deterministic aperiodic arrays of metal nanoparticles for surface-enhanced Raman scattering (SERS). *Opt. Express,* 17(5), 3741-3753, ISSN 1094-4087.

Hirsch, L. R.; Stafford, R. J.; Baukson, J. A.; Sershen, S. R. & Rivera, B. (2003). Nanoshell-mediated near-infrared thermal therapy of tumors under magnetic resonance guidance. *Proc. Natl. Acad. Sci. USA,* 100, 13549–13554, ISSN 0028-0836.

Hryciw, A.; Chul, Y. J. & Brongersma, M. L. (2010). Electrifying plasmonics on silicon. *Nature Mater.,* 9, 3-4, ISSN 1476-1122.

Hryciw, A.; Jun, Y. C & Brongersma M. L. (2009). Plasmon-enhanced emission from optically-doped MOS light sources. *Opt. Express,* 17, 185–192, ISSN 1094-4087.

Jablan, M.; Buljan, H. & Soljačić M. (2009). Plasmonics in graphene at infrared frequencies. *Phys. Rev. B.,* 80, 245435- 245439, ISSN 1094-1622.

Joannaopoulos, J. D.; Johnson, S. D.; Winn, J. N. & Meade R. D. (2008). *Photonic Crystals Molding the Flow of Light.* Princeton University Press, ISBN 978-0-691-12456-8, Princeton, New Jersy.

Jun, Y. C.; Briggs, R. M.; Atwater, H. A. & Brongersma. M. L. (2009). Broadband enhancement of light emission in silicon slot waveguides. *Opt. Express,* 17, 7479–7490, ISSN 1094-4087.

Jun, Y. C.; Kekatpure, R. D.; White, J. S. & Brongersma M. L. (2008). Nonresonant enhancement of spontaneous emission in metal-dielectric-metal plasmon waveguide structures. *Phys. Rev.* B, 78, 153111(1-4), ISSN 1550-235.

Kalele, S. A.; Tiwari, N. R.; Gosavi, S. W. & Kulkarni, S. K. (2007). Plasmon-assisted photonics at the nanoscale. *J. Nanophotonics,* 1, 012501-012520, ISSN 1934-2608.

Kim, S.; Jin, J.; Kim, P; Young-Jin Kim, Y.; Kim & Seung-Woo (2008). High-harmonic generation by resonant plasmon field enhancement. *Nature*, 453, 757-760, ISSN 0028-0836.

Kobayashi, M.; Kawazoe, T.; Sangu, S. & Yatsui, T. (2002). Nanophotonics: design, fabrication, and operation of nanometric devices using optical near fields. *J. Selected Topics in Quantum Electronics,* 8, 839-862, ISSN 1077-260X.

Koller, D. M.; Hohenau, A.; Ditlbacher, H.; Galler, N.; Reil, F.; Aussenegg, F. R.; Leitner, A. N.; List, E. J. W. & Krenn, J. R. (2008). Organic plasmon-emitting diode and references therein. *Nature* Photonics, 2, 684–687, ISSN 1749-4885.

Levy, U. C.; Nezhad, H.; Nakagawa, W.; Tetz; Chen, K.; Pang, L. & Fainman, Y. (2004). *Quantum Sensing And Nanophotonic Devices Book Series: Proceedings of The Society of Photo-Optical Instrumentation Engineers*, Ed.(s): M. Razeghi, G. J. Brown 5359 (SPIE) pp. 126-144.

Lezec, H. J. ; Dionne, J. A. & Atwater, H. A. (2007). Negative Refraction at Visible Frequencies. *Science*, 316, 430-432 *ISSN* 0036-8075.

Li, X.; Liu, H.; Wang, J.; Zhang, X. & Cui, H. (2004). Preparation and properties of YAG nano-sized powder from different precipitating agent. *Opt. Mater.,* 25, 407-412, ISSN 0925-3467.

Link, S.; Beeby, A; Fitzgerald, S.; El-Sayed, M. A.; Schaaff, T. G. & Whetten, R. L. (2002). Visible to infrared luminescence from a 28-atom gold cluster. *J. Phys. Chem.,* 106, 3410-3415, ISSN 1089-5647.

Lodahl, P.; van Driel, A. F.; Nikolaev, I. S.; Irman, A.; Overgaag, K.; Vanmaekelbergh, D. & Vos, W. L. (2004). Controlling the dynamics of spontaneous emission from quantum dots by photonic crystals. *Nature,* 430, 654-657, ISSN 0028-0836.

Loo, C.; Lowery, A.; Halas, N.; West, J. & Drezek, R. (2005). Immunotargeted Nanoshells for Integrated Cancer Imaging and Therapy. *Nano Lett*., 5(4), 709-711, ISSN 1530-6984.

Ma, C.; Zhangand, Q. & Van Keuren, E. (2009). Analysis of symmetric and asymmetric nanoscale slab slot waveguides. *Optic Communication,* 282(2), 324-328, ISSN 0030-4018.

Miao, X.; Wilson, B. K.; Pun, S. H. & Lin, L.Y. (2008). Optical manipulation of micron/submicron sized particles and biomolecules through plasmonics. *Opt. Express,* 16(18), 13517-13525, ISSN 1094-4087.

Maier, S. A. (2007). *Plasmonics: Fundamentals and Applications*. Springer, ISBN 978-0-387-33150-8, Germany.

Miyazaki, H. T. & Kurokawa, Y. (2006). Squeezing Visible Light Waves into a 3-nm-Thick and 55-nm-Long Plasmon Cavity. *Phys. Rev. Lett.,* 96, 097401(1-4), ISSN 0031-9007.

Murray, W. A. & Barnes, W. L. (2007). Plasmonic Materials. *Adv. Mater.,* 19, 3771-3776, ISSN 1521-4095.

Nezhad, M.; Abashin, M.; Ikeda, K.; Pang, L.;. Kim, H. C.; Levy, U.; Tetz, K.; Rokitski, R. & Fainman, Y. (2007). *Optoelectronic Integrated Circuits IX Book Series: Proceedings of The Society of Photo-Optical Instrumentation Engineers*, Ed.(s): L. A. Eldada, E. H. Lee 6476 (SPIE), pp. A4760-A4760.

Nie, S. & Emory, S. R. (1997). Probing Single Molecules and Single Nanoparticles by Surface-Enhanced Raman Scattering. *Science*, 275, 1102–1106, ISSN 0036-8075.

Noginov, M. A.; Zhu, G. & Belgrave, A. M. U. (2009). Demonstration of a spaser-based nanolaser. *Nature,* 460, 1110–1112, ISSN 0028-0836.

Oulton, R. F.; Sorger, V. J.; Zentgraf & Thomas, X. (2009). Plasmon lasers at deep subwavelength scale. *Nature,* 461, 629–632, ISSN 0028-0836.

Pavesi, L. (2003). Will Silicon be the photonics material of the third millennium. *J. Phys.: Cond. Mat.,* 15, R1169-1196, ISSN 1361-648X.

Pendry, J. B. (2000). Negative Refraction Makes a Perfect Lens. *Phys. Rev. Lett.,* 85, 3966-3969, ISSN 0031-9007.

Pillai, S.; Catchpole, K. R.; Trupke, T. & Green, M. A. (2007). Surface plasmon enhanced silicon solar cells. *J. Appl. Phys.,* 101, 093105(1-8), ISSN 1089-7550.

Polman, A. (2008). Plasmonics Applied. *Science,* 322, 868-869, ISSN 0036-8075.

Postigo, P. A.; Alija A. R.; Martinez, L. J.; Dotor, M. L.; Golmayo, D.; Sanchez-Dehesa, J.; Seassal, C.; Viktorovitch, P.; Galli; Politi, M. A.; Patrini, M. & Andreani, L. C. (2007). *Photonics and nanostructures*, 5(2-3), 104, ISSN 1569-4410.

Prasad, P. N. (2004). Polymer science and technology for new generation photonics and biophotonics. *Current Opinion in Solid State and Materials Science,* 8, 11–19, ISSN 1359-0286.

Prodan, E; Radloff, C; Halas, N. J. & Nordlander, P (2003). A Hybridization Model for the Plasmon Response of Complex Nanostructures. *Science,* 302, 419-422, ISSN 0036-8075.

Rahmani, A.; Chaumet, P. C.; Fornel, F.de & Girard, C. (1997). Fluorescence lifetime calculations in a confined geometry field propagator of a dressed junction. *Phys. Rev. A,* 56, 3245-3254, ISSN 1050-2947.

Rayleigh, J. W. S. (1888). On the remarkable phenomenon of crystalline reflexion described by Prof. Stokes. *Phil. Mag.,* 26, 256–265, ISSN 1478-6443.

Rosa, E. De La; Diaz-Torres, L. A.; Salas, P.; Arrendondo, A.; Montoya, J. A. C. & Rodriguez, A. (2005). Low temperature synthesis and structural characterization of nanocrystalline YAG prepared by a modified sol–gel method. *Opt. Mater.,* 27, 1793-1799, ISSN 0925-3467.

Sajeev, J. (1987). Strong localization of photons in certain disordered dielectric superlattices. *Phys. Rev. Lett.,* 58, 2486-2489, ISSN 0031-9007.

Shalaev, V. M. & Kawata, S. (2007). Nanophotonics with surface plasmons *(Advances in Nano-optics and Nano-photonics),* 1-340, Elsevier Science, ISBN 0444528385, UK.

Sharma, A.; Dokhanian, M;. Kassu, A. & Parekh Atul N. (2005). Photoinduced grating formation in azo-dye-labeled phospholipid thin films by 244-nm light. *Opt. Lett.,* 30(5), 501-503, ISSN 0146-9592.

Shen, Y.; Friend, C. S.; Jiang, Y.; Jakubczyk, D.; Swiatkiewicz, J. & Prasad, P. N. (2000). Nanophotonics: Interactions, Materials and Applications. *J. Phys. Chem. B,* 104, 7577-7587, ISSN 1089-5647.

Sonnichsen, C.; Reinhard, B. M.; Liphardt, J. & Alivisatos, A. P. (2005). A molecular ruler based on plasmon coupling of single gold and silver nanoparticles. *Nat. Biotechnol.,* 23(6), 741-745, ISSN 1087-0156.

Stockman, M. I.; Kling, M. F.; Kleineberg, U. & Krausz, F. (2007). Attosecond Nanoplasmonic Field Microscope. *Nature* Photonics, 1, 539-542, ISSN 1749-4885.

Stucky Galen D. & Mac Dougall James, E. (1990). Quantum Confinement and Host/Guest Chemistry: Probing a New Dimension. *Science,* 247(4943), 669-678, ISSN 0036-8075.

Valentine, J.; Li, J.; Zentgraf, T.; Bartal G. & Zhang, X. (2008). Three-dimensional optical metamaterial with a negative refractive index. *Nature,* 455, 376-380, ISSN 0028-0836.

Verhagen, E.; Spasenović, M.; Polman, A. & Kuipers, L. (2009). Localization in Correlated Bilayer Structures: From Photonic Crystals to Metamaterials and Semiconductor Superlattices. *Phys. Rev. Lett.*, 102, 203904(1-4), ISSN 0031-9007.

Veronis, G. & Fan, S. (2007). Theoretical investigation of compact couplers between dielectric slab waveguides and two-dimensional metal-dielectric-metal plasmonic waveguides. *Opt. Express,* 15, 1211–1221, ISSN 1094-4087.

Waele, R.; de Koenderink, A. F. & Polman, A. (2007). Tunable Nanoscale Localization of Energy on Plasmon Particle Arrays. *Nano Lett.,* 7(7), 2004-2008, ISSN 1530-6984.

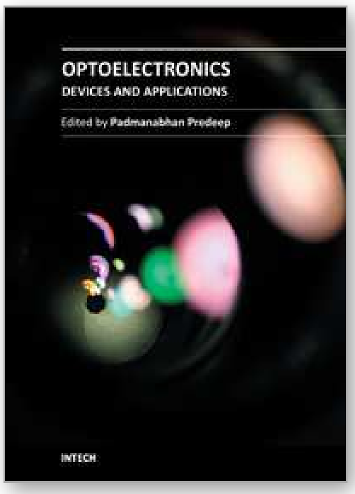
Walters, R. J.; van Loon, R. V. A.; Brunets, I.; Schmitz J. & Polman, A. A. (2010). Silicon-based electrical source of surface plasmon polaritons. *Nature Mater.,* 9(1), 21–25, ISSN 1476-1122.

Xing-huang, Y; Song-sheng, Z.; Rui-min, Y.; Jing, C;. Zhi-wei, X.; Chun-jia, L. & Xue-tao L. (2008). Preparation of YAG:Ce3+ phosphor by sol-gel low temperature combustion method and its luminescent properties. *Trans. Nonferrous Met. Soc. China,* 18, 648-653, ISSN 1003-6326.

Yablonovitch, E. (1987). Inhibited Spontaneous Emission in Solid-State Physics and Electronics. *Phys. Rev. Lett.,* 58, 2059-2062, ISSN 0031-9007.

Zhiyong, F.; Ruebusch, D. J.; Rathore, A. A.; Kapadia, R.; Ergen, O.; Leu, P. W. & Javey, A. (2009). Challenges and Prospects of Nanopillar-Based Solar Cells. *Nano. Res.,* 2, 829-843, ISSN 1998-0124.

Zouhdi, S.; Sihvola, A. & Vinogradov, A. P. (2009). *Metamaterials and Plasmonics: Fundamentals, Modeling, Applications*. Springer, ISBN 978-1-4020-9405-7, Germany.



Optoelectronics - Devices and Applications

Edited by Prof. P. Predeep

ISBN 978-953-307-576-1

Hard cover, 630 pages

Publisher InTech

Published online 03, October, 2011

Published in print edition October, 2011

Optoelectronics - Devices and Applications is the second part of an edited anthology on the multifaced areas of optoelectronics by a selected group of authors including promising novices to experts in the field. Photonics and optoelectronics are making an impact multiple times as the semiconductor revolution made on the quality of our life. In telecommunication, entertainment devices, computational techniques, clean energy harvesting, medical instrumentation, materials and device characterization and scores of other areas of R&D the science of optics and electronics get coupled by fine technology advances to make incredibly large strides. The technology of light has advanced to a stage where disciplines sans boundaries are finding it indispensable. New design concepts are fast emerging and being tested and applications developed in an unimaginable pace and speed. The wide spectrum of topics related to optoelectronics and photonics presented here is sure to make this collection of essays extremely useful to students and other stake holders in the field such as researchers and device designers.