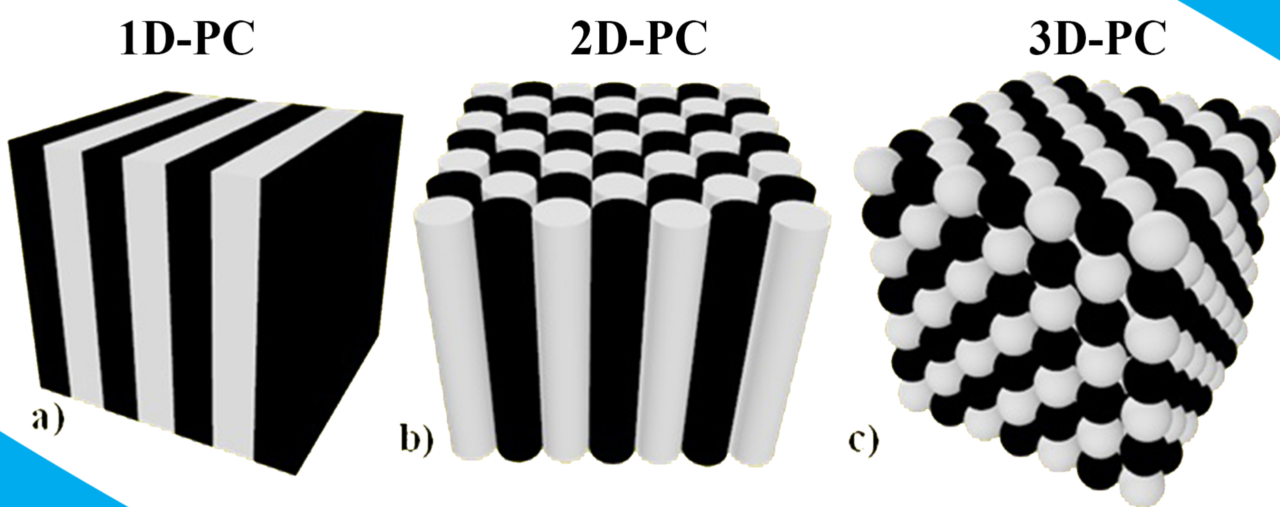
PHOTONIC MATERIALS:
RECENT ADVANCES AND EMERGING APPLICATIONS



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Photonic Materials: Recent Advances and Emerging Applications

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Photonic Materials: Recent Advances and Emerging Applications

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FOREWORD

I feel immense pleasure to write the foreword to the book, titled "Photonic materials: recent advances and emerging applications" edited by Dr. Aavishkar Katti and Dr. Yogesh Sharma. One of the editors, Dr. Katti is already known in the science community as he has authored a research monograph "Optical Spatial Solitons in Photorefractive Materials" on the photorefractive solitons and their various applications, which is published by Springer, Singapore. He is an expert in photorefractive materials and non-linear dynamics. The other editor, Dr. Sharma has been deeply involved in research on band gap engineering in magnetic photonic crystals. Both editors are well known to me as they have obtained their doctoral degrees from Banaras Hindu University.

This book describes current and cutting-edge research in the diverse area of photonics. There are fourteen chapters in the book covering theoretical, computational, and experimental research in photonic crystals, nonlinear optical materials, solar cells, semiconductor heterostructures, nano photonics, graphene-based photonics, and silicon photonics among other topics. Near the beginning, the chapters discuss optical logic gates, power splitter, polarizer, all-optical XOR gate, and optical properties of one-dimensional layered structure containing germanium. This optical XOR gate would replace the XOR gate based on semiconductors in the near future. The effect of the photovoltaic field on phase shift grating formed by nonlinear photorefractive materials is well described in one of the chapters.

When you will further delve deeper into the book, you will find chapters based on graphene plasmonics, third-generation solar cells and the use of graphene in solar cells. Solar cells are always looked at as an alternative to conventional energy sources since they are used for energy tapping through the Sun. The use of graphene for increasing the efficiency of solar cells has been investigated. Nowadays, nanophotonics has aroused the interest of the scientific research community. A few chapters focus on the properties and applications of optical materials used for nanophotonics. Recent research on fiber Bragg gratings has been beautifully captured in subsequent chapters while novel materials have been investigated in the next chapters. The applications of mono chalcogenides, transition metal dichalcogenides, and MXenes from fibre laser have been discussed. Some smart materials in photonics have also been reviewed. Lastly, the book includes Monte Carlo, stochastic collocation, and polynomial chaos expansion techniques for modelling of photonic integrated circuits.

This book is useful for beginners and advanced researchers in differentfields of theoretical or experimental optics and photonics, and material science. Graduates in physical sciences who are interested to pursue research in photonics will be highly benefitted from this book. I wish the book all the success and hope that it is useful for its target audience.

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PREFACE

Is photonics the new electronics?

If we compare the basic elements in electronics *viz*. the electron with the basic unit in photonics such as photon, soliton and plasmon, we find an uncanny similarity with device applications. This is reinforced if we go on further and compare other elements like electrical cables and optical fibres or plasmonic waveguides, electrical generators and lasers or masers, electric circuits and optical circuits and finally conventional transistors and optical transistors. It can be clearly inferred that photonics has clear analogues for all tools of electronics. It is due to these similarities that the photonic community believes that photonic devices will be able to replace electronic devices entirely.

In fact, even now, photonic devices are ubiquitous in fields like, biomedicine, where lasers are used to treat many diseases; aerospace technology, dealing with laser altimeters, laser radars, *etc*.; in engineering, where photonics is central to manufacturing MEMS and lasers are used for photonic devices, *etc*.; in information technology for data storage, optical switching, and data transmission using optical fibers among many other applications of practical importance. Such photonic devices encompass a diverse variety of materials like photonic crystals, nonlinear optical crystals like photorefractive crystals and liquid crystals, optical metamaterials, semiconductor laser materials, electro-optic and magneto-optic materials, photonic polymers, and photonic crystal fibers among many others.

In the present book, we present the latest trends and research in the broad field of photonics and photonic materials applications. The chapters are categorized as follows:

We shall first consider **Photonic Crystals. Chapter 1** summarizes recent developments in the field of photonic crystals by presenting the utmost frequent and necessary optical devices established based on PCs such as optical logic gates, optical power splitters, polarization splitters, sensing devices, and lasers. In comparison to conventional photonic devices, these devices have greater efficiency and a small footprint. In **Chapter 2**, a novel design for an all-optical XOR gate using 2D photonic crystals has been proposed and investigated. Initially, the XOR gate is designed and simulated by using the FDTD method. The proposed XOR logic is achieved without nano-resonators and then with nanoresonators to get enhanced performance metrics in the form of high contrast ratio. **Chapter 3** investigates and studies the effect of hydrostatic pressure on the reflectance and transmittance properties of the one-dimensional PC containing germanium (Ge). They use the transfer matrix method to calculate the transmittance and reflectance spectra.

Plasmonics is an emerging and fast-growing branch of science and technology that focuses on the coupling of light to the free electron density in metals, resulting in strong electromagnetic field enhancement due to the confinement of light into sub-wavelength dimensions beyond the diffraction limit. **Chapter 4** provides a comprehensive description of the theoretical approaches adopted to investigate the dispersion relation of graphene surface plasmons, types of graphene surface plasmons and their interactions with photons, phonons and electrons, experimental techniques to detect surface plasmons, the behaviour of surface plasmons in graphene nanostructures and the recent applications of graphene-based plasmonics.

Renewable energy is the future in a power-hungry world. **Solar Cells and Materials** are hence forth going to play a vital role in the energy sector. In **Chapter 5**, the third generation solar cells, in regard to materials, production, fabrication process, energy payback time, efficiency and applications have been critically analyzed. **Chapter 6** gives a brief overview of the recent research work on graphene in solar cell applications. It is notable that graphene has been used in heterojunction solar cells, GaAs solar cells, dye-sensitized solar cells, Perovskite solar cells, polymer solar cells, and organic solar cells and hence such a review will be useful for further research on graphene-based solar cells to achieve higher efficiency.

Nanophotonics is a component of the broad field of nanotechnology which studies the characteristics of light on nanometer scales. It can also be said to be a study of interactions of objects of nanometer dimensions with light. **Chapter 7** and **Chapter 8** focus on the recent developments in nanophotonics. The various materials used for nanophotonics, their properties and different applications have been elucidated quite comprehensively. **Chapter 9** investigates the electro-optic characteristics of a heterogeneous nanostructure for graded fibre optic cables based on shortwave infrared light communication systems under several number of nanoscale well-thickness layers.

Some **novel photonic materials** are considered next. **2D materials** are believed to be the future solution to various photonics and opto-electronic technologies including fiber laser. In **Chapter 10**, the application of monochalcogenides, transition metal dichalcogenides and MXenes is reviewed from the viewpoint of fiber laser technology. It covers the fundamental knowledge about these materials, the operating principle of Q-switching and mode-locking, and the configuration of 2D materials as saturable absorbers. The utilization of these materials as saturable absorbers in a wide range of fiber laser systems including Ytterbium-, Erbium- and Thulium-doped fiber laser is also discussed. **Smart materials** are those materials whose properties are changed upon application of an external stimulus. Devices using smart materials might replace more conventional technologies in a variety of fields. Smart Materials are attractive due to their light weight, sensing capability, lower component size, and complexity combined with design flexibility, functionality and reliability.

Bragg Fibers have tremendous practical applications hence spanning a large body of research. In **Chapter 11**, the propagation and dispersion properties of hollow-core Bragg fibre waveguides for both high and low refractive index contrasts of cladding materials are explored and compared. In **Chapter 12**, attractive research is presented to review the biological motivation behind the development of multilayer photonic nanostructure and various types of fuel adulteration detection optical sensors using various sensors-based techniques and compare with the Bragg Metal-Polymer nanocomposite optical sensor.

Silicon photonics is an area that relates to the investigation of photonic systems using silicon as an optical medium. Silicon photonics allows for high yield and complex integration with large processing, packaging, and testing availability. **Chapter 13** analyzes different approaches to modeling fabrication variations in photonic integrated circuits, such as Monte Carlo, Stochastic Collocation, and Polynomial Chaos Expansion.

Finally, **Chapter 14** gives a comprehensive review of different types of smart materials, their preparation, characteristics and applications.

In summary, we would like to state that the book tries to give a snapshot of current exciting research going on in the field of photonics incorporating different types of photonic materials. Photonics and photonic materials are a veritable ocean of which this is a humble attempt to sample a drop. We hope that this piques the interest of new researchers across the world and that they are encouraged to pursue research work in this fascinating field of photonics. In addition, we are hopeful that the book proves useful for scientists, university professors and industry professionals with a keen interest in photonics.

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CHAPTER 1

Photonic Crystal Instruments

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Abstract: Photonic crystals (hereafter represented as PCs), a synthetic dielectric formation that employs periodic and random changes in the refractive index to control the transmission of light, were presented by Yablonovitch and John in 1987. The capability to change the transmission of the electromagnetic wave in these formations on a miniature scale is used by photonic devices built on PCs. Electromagnetic waves scatter within the PC, and destructive intrusion happens at particular wavelengths, resulting in a photonic bandgap like the energy bandgap of electron waves in a semiconductor (hereafter denoted as SC). Because of the possibility of constructing a photonic bandgap, it may be feasible to influence light transmission. Instruments with tiny footprints are also feasible. In recent years, several fascinating PC-based devices, such as sharp bent waveguides (henceforth denoted as W/G), μ-resonator cavities, and Y-branches, have been demonstrated. These remarkable properties have the potential to result in the growth of a dense integrated circuit. Though PC technology is still in its infancy, and more study is needed in this field, this chapter summarizes recent developments in this sector by presenting the utmost frequent and necessary optical devices established on PCs such as optical logic gates, optical power splitters, polarization splitters, sensing devices, and lasers. In comparison to conventional photonic devices, these devices have greater efficiency and a small footprint.

Keywords: Photonic crystal, Sensor, Optical logic gate, Laser, Polarization splitter, Polarization-maintaining devices.

INTRODUCTION

The discovery of PCs in 1987, as described by Yablonovitch [1] and John [2], has flickered a great deal of curiosity. Electromagnetic waves scatter inside the PC, and for specific wavelength ranges, destructive interference occurs, ensuring the formation of a photonic bandgap, which is analogous to the energy bandgap of electron waves in an SC. It may be feasible to regulate light transmission because

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of the probability of creating a photonic bandgap. Light steering, negative refraction, and self-collimation are just a few of the distinguished utilizations where PCs are used. PCs show how to get great performance in sensing applications with a compelling resolution. Several photonic formation proposals established on various platforms have been extensively investigated and used in detection utilities. PCs demonstrate strong optical confinement to a tiny volume, allowing the identification of biochemical species classified on the nm scale. PC W/Gs have recently been investigated for use in microfluidic [3] and biochemical sensing [4].

Fabrication methods include molecular beam epitaxy, chemical vapour deposition, metal-organic chemical vapour deposition, and holographic ultra-violet beam exposure to photosensitive materials. In two coordinate axes of 2D-photonic bandgaps, the periodicity may be detected, while homogeneity can be found on the third axes. These kinds of structures can be made using dry reactive ion etching (RIE) or wet electrochemical etching. The first technique has a shallow etching depth and allows for nanometer-level precision in the hole size. Wet electrochemical etching has the potential to produce deep trenches, making the technique suitable for manufacturing assemblies with a high aspect ratio, however, the dimension of the etched cavities is unpredictable.

1D-PC formation is composed of a regular variation of the refractive index (RI) in the path of light transmission, but it offers a regular medium in the other two routes [5]. The RI of 2D-PCs varies in two directions but does not alter in the third. This may be shown by making trenches in a medium with a high RI, such as silicon [6]. 3D-PC formations may be created by changing the RI in all three spatial directions, such as a stack of spheres made of a dielectric medium positioned in the air [7]. Light transmission in a periodic formation, like electron transmission, may be investigated using a regular arrangement of atoms. The PCs are also frequently mentioned in principles like the Bloch theorem and Brillouin zones. Fig. (**1**) shows a graphic of the 1D, 2D, and 3D PC formations.

Because of their narrow lattice constant, 1D-PCs, also identified as multilayers, deficient of a broad photonic bandgap, and 3D-PC manufacturing is exceedingly challenging. However, 2D-PCs feature a complete photonic bandgap and are easier to manufacture than 3D-PCs. Consequently, scientists find them more attractive. 2D-PCs are composed of air-holes in a dielectric substratum or cylindrical dielectric rods engrossed in air. The PC's photonic bandgap may be changed by adjusting the lattice constant, the radius of the rods, and the RI of the dielectric medium. One of the best alternatives for producing a tunable filter for dense wavelength division multiplexing (DWDM) systems is resonant cavities. Cavity structures with an extraordinary Q-factor filter the chosen band of light with an appropriate bandwidth in DWDM systems. A tunable filtering element can also be created by modifying the formation of these cavities.

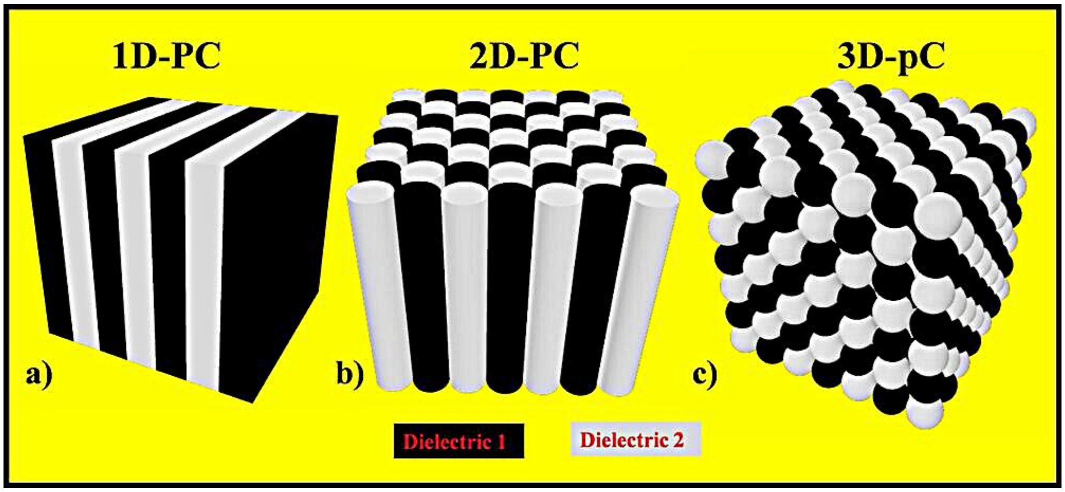

Fig. (1). Graphical representation of, **a**) 1D-PC, **b**) 2D-PC, **c**) 3D-PC. Dielectric 1 and dielectric 2 represents the high RI and low RI medium, respectively.

When the light is incident on PC, it is reflected from each interface. Under the right circumstances, these reflected waves will interact constructively, according to the Bragg condition. The Bragg formula with modest modifications for PCs is given by [8]:

$$m\lambda = 2n_{eff}d \quad \textbf{(1)}$$

Where m is the diffraction order, λ is the wavelength of the reflected light, n_{eff} is the effective refractive index of the regular formation, and d is the crystal's lattice period in the path of light transmission. When this stipulation is satisfied, an extraordinary reflection for the specified spectrum is seen. To show the Bragg reflection in the 400 nm to 700 nm band, the PCs require a sub-micrometre period (Λ). When light passes through the PC, a specific spectrum is reflected, which is reliant on Λ and n_{eff}. The photonic stopband is the spectrum range with the highest reflection (means no transmission). The photonic bandgap, instead, shows the spectrum range that is not acceptable to flow into the assembly, ensuing an extraordinary reflection.

The chapter is systematized in the following way. In the first section, the operational mechanism of the novel sensing instruments based on PCs is discussed and recent developments in the sensing area are presented.

CHAPTER 2

All-optical Logic Gate Using Photonic Crystals for Ultra-Fast Telecommunication Applications

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Abstract: Most major high-speed applications, such as communications, environmental monitoring, transportation, smart homes, industries and gadgets are enabled by recent photonic technology. Basic all-optical logic gates are used in the development of image sensors, ultra-fast optical devices, and positioning equipment in high-speed applications. Among different technologies proposed for all-optical implementation, Semiconductor Optical Amplifiers (SOA) have been widely adopted. They have attractive features such as wide gain bandwidth, low power consumption, compactness and strong non-linearity. SOA still has a limitation that its spontaneous emission noise restricts the performance. The semiconductor optical amplifiers with quantum dots exhibit higher saturation output power, lower current density threshold, wider gain bandwidth, and low noise figure than conventional SOA. Quantum Dot Semiconductor Optical Amplifiers (QDSOAs) also have limitations like large size, high power consumption and spontaneous emission of noise. Photonic Crystal (PhC) is an artificial material that is suitable to overcome all drawbacks of SOA and QDSOA due to its simple structure and compactness, high speed, low power consumption, and low loss. PhC-based structures allow propagation of light in a controlled manner with its periodic crystal arrangements having dissimilar diffraction index. PhCs are considered to be a suitable structure for designing all-optical devices with compactness. In this chapter, an all-optical XOR is designed. Initially, the XOR gate is designed and simulated by using the FDTD method. The proposed XOR logic is achieved without nano-resonators and then with nanoresonators to get enhanced performance metrics in the form of high contrast ratio. The contrast ratio is 260 dB for the XOR gate with a delay time of 0.19 ps. The proposed XOR logic gate has potential practical applications for high speed applications of telecommunication systems.

Keywords: Finite Difference Time Domain (FDTD) Method, Nanoresonator, Photonic Crystal (PhC), Plane wave expansion (PWE) Method, XOR Gate.

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INTRODUCTION

In a communication network, the current electronic technologies have serious limitations when large amounts of information need to be transmitted. The current electronic technology results in a limited amount of communication speed limit and computation time. Thus, to overcome this problem, all-optical logic gates are used.

Ultra-compact all-optical logic gates have become attractive devices for real-time optical processing and communications. All-optical logic gates are designed to avoid complications and speed limitations due to the need for optic-electric-optic conversion [1]. Thus, numerous technologies have been described to design and develop all-optical devices.

PhC devices are nanostructured optical media that can guide, limit and control the light propagation in the waveguide. Such nanostructures are constructed and manufactured to be used in future generation photonic circuits. Conventional photonic devices such as SOA cannot control the intended optical modes in small-scale circuits, because of the limiting factors such as total internal reflection and high loss in refraction. There has been explicit attention paid to PhC structures due to the fabricating feasibility of such material with the silicon and also because of the superior performance metrics such as lesser loss and higher light confining capability of input signals [2, 3]. A class of PhCs in two dimensions have nurtured a rapidly increasing interest over numerous applications with novel phenomena such as strong light confinement, slow light, spatial dispersion, and filtering [2 - 5].

The photonic bandgap (PBG) is formed in the PhC structure because of the periodic interaction within the structure. The frequency signals in the PBG span cannot propagate within the structure. By introducing a defect within the structure, the mode of light can be localized and limited in the lattice. This can let the PhC structures a strong capability to control the modes, limit and guide the input light and has improved the use of such structures in producing optical elements. The possibility of limiting optical modes is increased by extending the PhCs into two- or three-dimensional structures.

Currently, PhC based logic gates have become an attractive waveguiding medium to create all-optical devices [2, 4]. By utilizing the PhC structures, the optical logic gates dimension can be reduced to the order of the wavelength of light. Also, these devices lead to increased switching speed with the microwatts power consumption and its response time over the output in the order of lesser than a few picoseconds. Digital data can be transmitted at the speed of light to an electronic processor by an optical fiber. However, for electrical logic gates, the maximum switching speed is equal to 2×10^5 Hz (50 ps) for 0.5mW average switching power. The switching speed of logic gates made up of semiconductor material is limited by interlinking capacitances and p-n junction, whereas switching speed in an optical logic gate is limited only by light speed propagating through it.

Periodic dielectrics [6] or magnetic structures demonstrate a photonic bandgap in a PhC arrangement. An array of light wavelengths that cannot pass through the PhC is called Photonic Band Gap [7]. The propagation of electromagnetic waves within certain frequency bands is forbidden, the principle is that the electromagnetic waves cannot propagate through the periodic structures resulting in various optical effects. Light waves with frequencies lying within the bandgap will get reflected by the PhC. PhCs are nanostructures fabricated by means of the interrupted arrangement of different refractive index materials. PhC can have a period of single (1D), dual (2D) or full three (3D) dimensions. 1D PhCs are an alternating sequence of layers with different dielectric constants. 2D PhCs consist of periodic rods in a dielectric medium. 3D PhCs having a periodicity in the refractive index in all three dimensions are very difficult to fabricate, but can have huge potential in areas of optical computation.

RELATED WORKS

PhCs extend an adaptable method for the propagation of light and controlling emission [8] by changing the lattice constant value of the crystal structure. A photonic structure is a regularly repeating structure consisting of two materials or more of different dielectric constants. There have been proposed systems designing an all-optical logic gate using the 2D PhCs. Fariborz Parandina [9] designed structures of NOT, XOR, and NOR with a very low power transfer delay of 0.1 ps and a contrast ratio of about 30dB. Golnaz Tavakolia [10] realized a structure of XOR and XNOR cascading two resonant rings. The delay time for the XNOR and XOR logics is 2.5 and 1.5 ps, respectively, the working bit rates for the XNOR and XOR logics are 400 and 666 Gbit/s. Ahmad Mohebzadeh-Bahabady [11] designed a structure for NOT and XOR gate comprising three waveguides and a nanoresonator. The response time and contrast ratio (CR) for the XOR logic gate were found to be 0.466ps and 19.95 dB, respectively. Sandip Swarnakar designed an XOR gate using Photonic Crystal Ring Resonator [12]. The square lattice PhC is made up of Silicon in Silica and the contrast ratio is calculated to be 8.37 dB.

In this chapter, the all-optical logic XOR gate in a 2D PhC is proposed. The interference method is used to obtain the logic effect. The simulation of the proposed device is carried out using the Finite Difference Time Domain (FDTD) method of Rsoft Photonics CAD.

CHAPTER 3

Pressure Dependent Reflectance and Transmittance Properties in 1D- Photonic Crystal Containing Germanium (Ge)

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Abstract: In this work, we theoretically investigate and study the effect of hydrostatic pressure on the reflectance and transmittance properties of the one-dimensional PC (1D PC) containing germanium (Ge). In the present study, we first take a 1D PC structure composed of alternate layers of germanium (Ge) and air having a finite number of layers. In the second case, we take the same structure by breaking its periodicity such that each part of it acts as the mirror image of each other. The Refractive index of germanium varies under the applied pressure, therefore both reflection bands and transmission modes change with the applied pressure. In order to calculate transmittance and reflectance spectra of the proposed PC, the transfer matrix method (TMM) has been used. It has been observed that by increasing the hydrostatic pressure, the width of the reflection band decreases and the position of reflection bands shifts towards the lower side of wavelength. Further, the transmission modes of the considered PC structure are blue shifted with the increase in applied hydrostatic pressure and show high sensitivity with it.

Keywords : Defect Mode, Photonic Crystal, Photonic Bandgap Material, Pressure Sensor, Reflectance/Transmittance Spectra, Transfer Matrix Method.

INTRODUCTION

During the last few years, a new class of optical material called Photonic crystal has gained much attention and developed considerable interest among the researcher and scientific community. Photonic crystals (PCs) are artificial structures with periodic variation in dielectric constant on the length scale comparable to optical wavelength and have the capability to manipulate and control the propagation of electromagnetic waves [1 - 6]. Due to its peculiar

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optical properties, PC possesses many potential applications in the field of modern photonics and optoelectronics [7 - 11]. The most important property of Photonic crystal is the existence of photonic band gaps (PBGs) and confinement or localization of photons. The photonic bandgap is the range of frequencies or wavelengths in which propagation of the electromagnetic wave is forbidden through the PC [12 - 15].

Confinement of photon can be done inside the PBG by introducing the defect into the conventional PC. The defect inside the photonic crystal can be produced by breaking the spatial periodicity of the structure, which can be achieved by changing the thickness of the layer, inserting another material into the structure or removing a layer from normal PC structure [16 - 20]. When the frequency (or wavelength) of the incident photon is equal to equal to the defect state, the photon gets localized in the defect state and resonant transmission mode is generated inside the bandgap.

The wavelength of transmission mode can be tuned in two ways. The first one is based on changing the concentrations or ingredients of constituents' materials of Photonic crystals and the second one is based on controlling the refractive indices of the materials. The Refractive index of the defect layer can be controlled by changing the operating temperature, by applying an external electric and/ or magnetic field, by applying the hydrostatic pressure or by optical illuminations and leads to various photonic devices [21 - 26]. Further, the refractive index and hence the defect mode can also be tuned by applying the hydrostatic pressure on the PC [27, 28].

In this work, we theoretically investigate and study the effect of hydrostatic pressure on the reflectance properties of the one-dimensional PC (1D PC) containing the semiconductor layer. Also, we study the tunability of transmission modes in defective 1D PC just by breaking the periodicity of the structure without using any external defect layer. In our investigation, we use 1D PC, because the production of 1D PC is more feasible at any wavelength scale and its analytical and numerical calculations are comparatively simple. A great deal of research work has been carried out on 1D PC, both theoretically and experimentally, due to its simple structure, high reliability and easy fabrication process and integration.

In the present study, we first take a 1D PC structure composed of alternate layers of germanium (Ge) and air having finite layers. In the second case, we take the structure by breaking its periodicity such that each part is the mirror image of the other. Such type of PC is called a conjugate PC and a defect mode is generated within the photonic bandgap at the interface. Since the refractive index of germanium varies under the applied pressure [29, 30], therefore both reflection bands and transmission modes change with the applied pressure.

The optoelectronic devices whose properties can be manipulated by varying the refractive index are much more applicable because of the tunability and flexibility of the devices like narrow transmission filters and optical sensors.

THEORETICAL MODEL

The schematic diagrams of 1D PC are illustrated in Figs. (**1a - b**). In Figs. (**1a** and **b**), we represent the high (Ge) and low (air) refractive index materials having refractive indices n_A, n_B and thicknesses d_A and d_B respectively. The proposed PCs are represented as air/$(AB)^N$A/air and air/$(AB)^{N/2}(BA)^{N/2}$/air, respectively. $d = d_A+d_B$ represents the period of the structure and N number of periods of each structure. In order to calculate the reflectance and transmittance spectra of the proposed PC, we use the transfer matrix method (TMM) [31] which is a very effective technique to study the transmission and reflection properties of finite PCs.

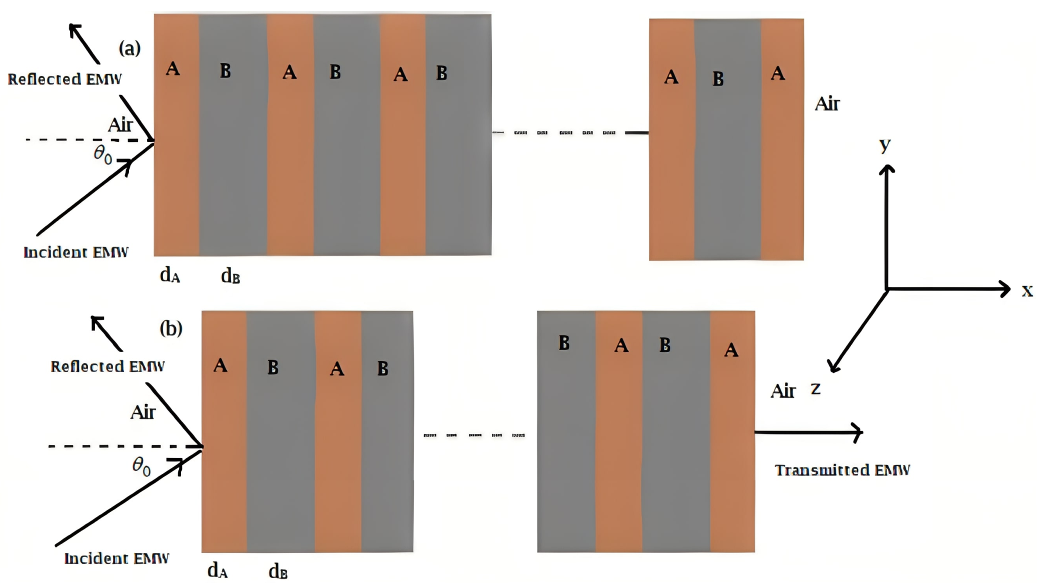

Fig. 1 (a-d). Schematic representation of proposed 1D-PC structure.

The hydrostatic pressure (P) dependent refractive index of germanium (Ge) is given as [29, 30]

$$n_A = \sqrt{15.94 - 0.36P + 0.014P^2} \quad \textbf{(1)}$$

Variation in the refractive index of germanium with hydrostatic pressure ranging

CHAPTER 4

Recent Advances in Graphene Based Plasmonics

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Abstract: Plasmonics is an emerging and fast-growing branch of science and technology that focuses on the coupling of light to the free electron density in metals, resulting in strong electromagnetic field enhancement due to confinement of light into sub-wavelength dimensions beyond the diffraction limit. The development of novel photonic and optoelectronic devices based on metal-based plasmonics is however plagued by the high loss at optical frequencies, originating partly from inter-band electronic transitions and lack of electrical tunability, practically limiting their potential applications in the terahertz (THz) and mid-IR spectrum range. The recent successful exfoliation of graphene from graphite has rendered a breakthrough in the realm of plasmonics due to its phenomenal properties such as exceptionally tight light confinement, extremely long plasmon lifetime, high carrier mobility leading to a relatively low level of losses, strong optical nonlinearity and electrostatically as well as chemically tunable response. These versatile features of graphene can effectively address the challenges faced by metals, and hence the physics and potential applications of graphene-based plasmonics have triggered increasing attention of industry, academic and research fraternity in recent years. This chapter provides a comprehensive description of the theoretical approaches adopted to investigate the dispersion relation of graphene surface plasmons, types of graphene surface plasmons and their interactions with photons, phonons and electrons, experimental techniques to detect surface plasmons, the behaviour of surface plasmons in graphene nanostructures and the recent applications of graphene-based plasmonics.

Keywords: Graphene, Graphene Nanostructures, Mid-infrared Photonics, Plasmonics, Quasi-Particles, Tunability, Terahertz Photonics.

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INTRODUCTION

A serious setback to technological progress in recent years is critically associated with the almost static growth of microprocessor performance. A cutting-edge solution to circumvent this persistent issue is to switch from the conventional electronic to the photonic mode which can have a pioneering impact on next generation computational and communication systems.

Among all the photonics related research domains, the field of plasmonics offers the most promising option to attain this goal. Plasmonics involves the study of light-matter interaction at the nano-scale limit. It exploits the phenomenon of coherent and collective oscillation of charge carriers excited by an electromagnetic field [1, 2] at the boundary between two media having a positive and negative magnitude of permittivity (*e.g.*, interface between metal and dielectric), termed as surface plasmon resonance (SPR), for a varied range of nano-photonic applications [3, 4]. Such free electron oscillations propagating on the surface of continuous thin films are designated as surface plasmon polariton (SPP), while those confined to nano-structures are termed as localized surface plasmon resonance (LSPR). Plasmons can also be induced by electron beams in the bulk of large materials, denominated as bulk plasmons, which evanesce severely due to heavy energy loss. The excitation of SPP and LSPR at characteristic frequencies results in a strong local electromagnetic field enhancement due to confinement of light into sub-wavelength dimensions, allowing the modulation of light beyond the diffraction limit. This appealing feature of SPR has attracted immense scientific interest in plasmonic based research over the past few years.

The dawning age of surface plasmons can be tracked down to the year 1902 when Wood [5] observed an irregular distribution of light intensity reflected by a metallic grating, termed as Wood anomaly. In 1904, Maxwell-Garnett [6] proposed a theory based on an effective dielectric constant to justify the colours emitted by glasses having small metallic particles. The Maxwell-Garnett theory was followed by Mie [7] theory in 1908, which attempted to explain the colour of metallic colloidal particles based on light scattering and absorption properties of an arbitrary sized spherical particle. A plausible explanation of Wood's anomalies, theoretically proposed by Fano [8] in 1941, suggested that quasi-stationary (Sommerfeld's type) electromagnetic waves with substantial tangential momentum on the surface of metals was responsible for the anomalous distribution of light reflected by a metallic grating which could not be elucidated by Rayleigh's approximation [9]. A comprehensive understanding of the theory of plasma oscillations in metals was realized in 1952 when Bohm and Pines [10 - 13] propounded a quantum-mechanical theory incorporating long-range electron correlations to explain the correlation between the discrete and collective behaviour of the free electrons. They showed that the free electrons oscillate collectively for distances d > λ_D, where λ_D is the Debye length; while for d < λ_D, it could be approximated as an ensemble of almost free discrete particles. This theory could conclusively explain the experimental observation of energy loss (in keV) of electrons in metallic films by Ruthemann and Lang [14, 15]. In 1957, Ritchie [16] computed the dispersion relations of SPPs in metallic films to predict that when an electron propagates in thin films, anomalous energy (depending on the thickness of films) is lost both at and below the resonant frequency of plasmon. The predictions of Ritchie was experimentally corroborated by Powell and Swan [17] from the measurements of electron energy loss spectra of aluminium foils. The next significant development in this field was achieved in the era of 70s by the seminal works of Teng and Stern [18], experimental demonstrations employing the attenuated total reflection (ATR) method by Otto [19], and also Kretschmann and Raether [20], followed by the discovery of the surface-enhanced Raman scattering by Fleischmann *et al.* [21]. From this time forth, several outstanding researchers have gradually achieved significant developments in the domain of surface plasmons.

According to Maxwell's electromagnetic theory [1, 2, 22], the electric field of SPPs traversing along the boundary of a dielectric and a semi-infinite metallic medium is

$$E_j = \left(E_x^j, 0, E_z^j\right) exp\{i(k_{SPP}x - \omega t)\} exp\left(-\alpha_j |z|\right) \tag{1}$$

where, k_{SPP} and ω designate the wave-vector and frequency of SPPs, the superscript $j = d$ and $j = m$ represents the dielectric and metal, respectively, while α_j is termed as the decay constant.

The y-component of the magnetic field satisfies the same condition, implying that surface plasmon polaritons can be excited only by polarized transverse magnetic (TM) field.

The amplitude of the electromagnetic field associated with SPPs decreases exponentially along with the normal interface between metallic medium and dielectric surface. The decay constants α_d and α_m for the dielectric surface and metal obey the relationship as shown below:

$$\alpha_d = \frac{\omega}{c}\left[\frac{{\varepsilon_d}^2}{\varepsilon_d + \varepsilon_m}\right]^{\frac{1}{2}} \quad \text{and} \quad \alpha_m = \frac{\omega}{c}\left[\frac{{\varepsilon_m}^2}{\varepsilon_d + \varepsilon_m}\right]^{\frac{1}{2}} \tag{2}$$

CHAPTER 5

Third Generation Solar Cells - Promising Devices to Meet the Future Energy Needs

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Abstract: Energy is the basic input for the improvement of the social status of human beings and the development of a nation. At present, we are observing a shift in the use of energy from non-renewable to the renewable energy due to exhausting natural resources of non-renewable energy and other environmental and climatic concerns. Solar energy resource is an inexhaustible source of energy. The development of first generation solar cells using silicon material in the middle of the nineteenth century introduced a new era in the renewable energy transformation process when the first solar cells were flown on the fourth satellite, the Vanguard-I in 1958. But despite abundant material resources, high stability and good performance, this technology could not fulfill the energy need except a fraction due to very long payback time. The second generation solar cells are also not very encouraging due to the scarcity of materials and their toxic nature. The third generation solar cells, due to extremely low energy payback time and unlimited availability of material are promising devices to contribute significantly in solar energy conversion, despite limitations of poor stability and low efficiency. The present chapter critically analyses the third generation solar cells, in regard to materials, production, fabrication process, energy payback time, efficiency and applications.

Keywords: Efficiency, Energy Payback Time and Applications, Renewable Energy, Solar Cells.

INTRODUCTION

Energy is the basic input to the national economy, both agricultural and industrial, apart from being an instrument for improving the quality of life. The development of any nation and society as a whole depends on the energy resources available and affordable technologies for usable energy conversion. The energy demand is increasing. The question is, how we are going to meet the growing energy demands of the future and what is the right choice for utilizing the resource base. The need of the time is to develop promising new technologies and even new

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physical and chemical processes for the establishment and operation of efficient systems to generate, accumulate, transform and transport energy into its various forms [1]. Decreasing trends in non-renewable energy resources and their negative social, health, and environmental impacts on account of unsustainable patterns of energy extraction and use are apparent [2, 3]. The significant global warming due to the emission of greenhouse gases and climate change put a threat to the sustainability and existence of entire species on the globe. The currently available data on non-renewable energy resources indicate that to meet the future energy demand, large-scale alternative methods of producing the vast quantities of energy will be needed to sustain and enhance our standard of living [4, 5]. We are fortunate enough that nature has provided us with alternative sources of energy, such as wind, geothermal, biomass, and solar energy.

Among these energy resources, solar is the most promising because every hour the energy absorbed by Earth's atmosphere from the sun is sufficient to satisfy global energy needs for a year. Solar power is a renewable resource that is available everywhere in the world but in varying degrees depending on the geographical status of a country and for India, solar power is the best choice. Among the advantages are; inexhaustible source of power (as long as the sun shines), a sustainable and environmentally friendly method of producing energy, small and highly modular, no fuel costs and relatively low operation and maintenance costs.

The first photovoltaic effect was discovered by Becquerel in 1839 and since then, solar energy has been of research interest in the scientific community. In 1877, the photovoltaic effect was observed in solidified Selenium [6]. In 1883, Charles Fritts developed the first Selenium solar cell based on a thin layer of gold, which has a power conversion efficiency of less than 1%. Since then, research has exploded to find the most efficient and cost-effective solar cells. Due to the design and synthesis of the novel compounds, understanding and controlling the film morphology and elucidating the device mechanism, the PV cell technologies are improving and are usually classified into three generations.

The **first generation** solar cells are mainly based on silicon wafers and typically demonstrate the performance of about 15-25%. Good performance and high stability are the main advantages, while very large payback time, rigidity and large energy requirement in their production are the main disadvantages [7].

The **second-generation** solar cells are based on inorganic semiconducting materials with higher absorption coefficients like amorphous silicon, polycrystalline semiconductors, Copper Indium Gallium Selenide (CIGS) and Cadmium Telluride (CdTe). They demonstrate the typical performance of about

10-15%. They are thin film solar cells since they use direct bandgap materials and can be made much thinner than first generation solar cells. However, the production of these solar cells requires a large amount of energy to go through the vacuum processes and high-temperature treatments. Also, the materials used in these cells are scarce elements and this is a limiting factor in both the price and their commercialization [7, 8].

The **third-generation** solar cells are a mix of many types of solar cell technologies mostly processed from solution. These include; organic solar cells, perovskite solar cells, dye-sensitized solar cells, multi-junction solar cells, and quantum dot solar cells. The experimental multi-junction solar cells hold the world record in solar cell performance, plus novel devices in general. A new class of thin film solar cells currently under investigation are perovskite solar cells which show huge potential with record efficiencies beyond 20% on a very small area.

The present book chapter critically analyses the third generation solar cells, in regard to materials, production, fabrication process, energy payback time, efficiency and applications. The main focus will be kept on low cost PV technology, which is getting a lot of attention from academic researchers and there is adequate industrial interest too. This article will also provide you with enough motivation that there is a need for low cost PV technology and the development of solar cells to meet the future energy demands.

Basic Parameters

To understand the power production capability of solar cells, it becomes essential to learn about their I-V characteristics. I-V Characteristics determine the parameters like open circuit voltage, short circuit current, fill factor, power conversion efficiency and external quantum efficiency. The rating of the solar panel is determined by these parameters which are illustrated in Fig. (**1**) and briefly described below.

The current equation of a solar cell, when illuminated by light, is given by;

$$I = I_o \left[exp\left(\frac{qV}{nkT}\right) - 1\right] - I_L \quad \textbf{(1)}$$

where I_L is the light generated current. It is the photocurrent when the external voltage is zero. It has the effect of shifting the I-V curve down.

The Power Conversion Efficiency (PCE) is related to the short-circuit current density (J_{sc}) and the open circuit voltage (V_{oc}) by:

CHAPTER 6

Recent Advances of Graphene in Solar Cell Applications

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Abstract: There has been incredible progress so far in graphene (Gr)-based solar cells and this is going to continue well into the future. Therefore, it is important to get an idea of the recent progress of graphene-based solar cells in the last decades. In this chapter, a brief overview of the recent research on Gr in solar cell applications has been outlined. It is prominent that Gr has been used in heterojunction solar cells, GaAs solar cells, Dye-sensitized Solar cells (DSSC), Perovskite solar cells, Polymer solar cells, and organic solar cells. In these solar cells, Gr has been utilized either as an absorber layer, hole transport layer, or electron transport layer. However, Gr has been used in the form of thin film, flakes, or quantum dot form. About 25% output efficiency has been observed in Gr-based solar cells so far. This chapter gives an overview of the Gr-based solar cell with efficiencies to further continue the research on Gr-based solar cells to achieve higher efficiency.

Keywords: Absorber Layer, DSSC, Electron transport Layer, Heterojunction, Hole transport Layer, Perovskite, TCE.

INTRODUCTION

With the rise of the world population by 0.7% per year and the development of industries, the consumption of energy increases gradually. As a result of this, the conventional and non-renewable energy sources (*i.e.* fossil fuels) diminish day by day. Alternatively, the burning of fossil fuels adversely affects the environment by releasing greenhouse gases. Considering the energy crisis and the crucial impact on our environment, human begins to think of alternative, renewable, low cost, and environment-friendly energy sources that are capable of fulfilling the higher energy demand in the future. Solar energy is one of the renewable and freely available energy sources [1 - 3].

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Since the discovery of energy generation from sunlight by Edmund Becquerel in 1839 [4], the Photovoltaic (PV) solar cell technology opened the era for energy generation. Solar cells are the devices that converted sunlight directly into electricity. At present time, silicon-based solar cells have captured 80% market share as silicon is abundant and easily available [5]. Besides, the performance of this silicon-based solar cell is reliable. Moreover, III-V material-based solar cells have also shown their efficiency about 32.8% [6]. Beyond these, the comparatively new and promising Perovskite and Dye-based solar cells have compatibility in terms of their efficiency, low cost, and easy fabrication process [7 - 8]. Although these conventional solar cells are highly efficient, yet some drawbacks limit their application extensively. For example, the process cost of silicon [9] and III-V materials is very high [10]. The Perovskite materials are unstable [11] and the materials used in conventional dye-based solar cells are not cost-effective [8]. Therefore, to overcome these challenges we have to realize such a material that can be easily integrated with the mature and well-established solar cell technology to overcome these difficulties. Over the last few years, two-dimensional graphene (Gr) has emerged as a potential material for solar cell application. Graphene is an allotrope of carbon consisting of carbon (C) atoms arranged in a honeycomb structure [12]. Fig. (**1**) illustrates the structure of 2D-Gr.

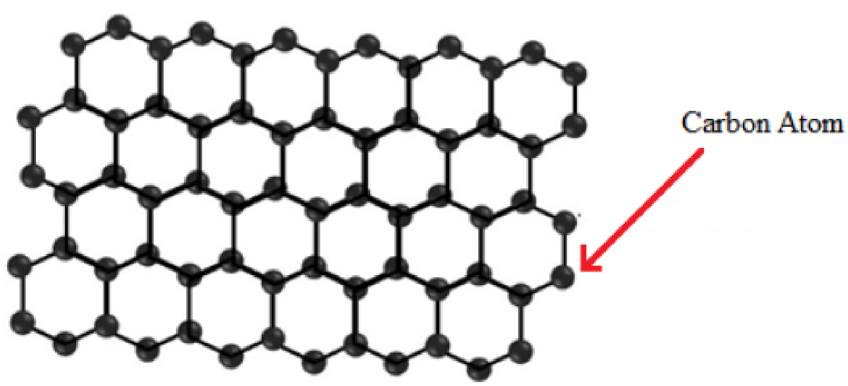

Fig. (1). Molecular structure of 2D-Graphene.The Carbon atoms are arranged in a honeycomb structure.

In 2004, Andre Geim and Kostya Novoselov [13], for the first time demonstrated the 2D-Gr exfoliated from highly oriented pyrolytic graphite. After the discovery of Gr, from near and far in 2010, research had been started on the potential application of Gr on solar cells due to its exciting and interesting optoelectronic properties. Gr exhibits semi-metallic behavior and many interesting properties such as more than 90% optical transparency, sheet resistance as low as 10 Ω/sq, and charge carrier mobility of 10^5 cm^2/Vs and tunable bandgap as well as work function. These properties ensure the applicability of Gr in solar cells [14].

APPLICATION OF GR IN VARIOUS TYPES OF SOLAR CELLS

Gr in Heterojunction Silicon Solar Cell

The first generation heterojunction solar cells are composed of n-type silicon and p-type silicon. Although these solar cells are highly efficient yet the processing cost is very high. To reduce its cost, the research on the application of Gr in Si solar cells has been started.

Gr is a semi-metallic material with a zero bandgap. Therefore, most of the research from 2010 to 2020 has been carried out on the Gr/Si schlocky junction solar cells. Here, Gr has been used as an emitter layer. However, Gr has also been used as a Transparent conducting electrode (TCE). So far maximum output efficiency (η) of 15% has been reported as per our knowledge. To achieve this efficiency, the study on the effect of doping on Gr and anti-reflecting coating on Gr/Si structure has also been carried out during the past years. In Table **1**, research progress on Gr/Si-based solar cells from 2010 to 2020 has been listed.

Table 1. Research Progress of Gr/Si solar cell.

Year	Structure	Gr layer (layer=L)	η (%)	Ref.
2010	Al/Gr/p-cSi/Al	1-4 L, CVD grown	0.01	[15]
2010	Au/Gr/n-Si/ (Ti/Pd/Ag)	> 3L,CVD grown	1.5	[16]
2011	Gr/n-SiNW/(Ti/Pd/Ag)	Multilayer, CVD grown, Treated with $SOCl_2$	2.86	[17]
2011	Ag /Gr/nSiNW/Ag	1L, CVD grown	2.15	[18]
2012	G/n-Si/ (Ti/Pd/Ag)	3-5 L, CVD grown, Boron doped	3.4	[19]
2012	(Ag/Ti)/Gr/n-Si(Pillar-array) /(Ti/Pd/Au)	1L, CVD grown, Treated with HNO_3	4.35	[20]
2012	Ag/Gr/P(VDF-TrFE)/GO/n-Si/(In-Ga)	1L, LPCVD grown	4.14	[21]
2012	Ag/Ti)/Gr/n-Si(Pillar-array) /(Ti/Pd/Au)	2~3 L, CVD grown, Treated with HNO_3	7.72	[22]
2012	(Au/Cr)/Gr/n-Si/---	1L,CVD grown, TFSA amide doped	8.6	[23]
2013	---/Gr/n-Si/(Ti/Au)	1-5 L, CVD grown, Treated with HNO_3	9.63	[24]
2013	----/Ag/Gr/Si/--- (TiO_2 coating)	1L, CVD grown, Treated with HNO_3	14.5	[25]
2013	Ag wire/Gr/n-Si/(cu foil+ silver paste)	3L, CVD grown, Treated with $SOCl_2$	5.95	[26]
2013	--/Gr/n-Si/(Ti/Au)	4-7L, CVD grown, Treated with $SOCl_2$	9.27	[27]

CHAPTER 7

A Review on the Materials and Applications of Nanophotonics

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Abstract: Recent developments in nanotechnology have resulted in significant technical improvements in devices based on light's interaction with nanomaterials. As a result, nanophotonics has seen a significant increase in attention among researchers. The significance of low energy consuming information processing at high rates of speed has pushed the use of light for information transmission and processing forward. Nanophotonics hence introduces ways of integrating a wide range of systems that can produce, regulate, amplify and process light waves that are at superfast accelerations, as energy demands and interaction time decrease with a decrease in the particle dimensions of the nanomaterials. Nanophotonics, also known as nano-optics, is a branch of nanotechnology that studies characteristics of light at nanoscale dimensions and the interrelationships of nano-scale materials with light. Nanophotonics is a subfield of nanotechnology and a discipline of optoelectronics. On a dimension considerably smaller than the wavelength of light, it presents new opportunities for exploring concepts of interaction between the propagating light and matter. Fundamental properties of nanomaterial-light interactions, such as nanometer photon confinement and change in optical, chemical and physical properties of the material in nanorange, continue to provide numerous possibilities for real-life applications. The optical characteristics of materials can hence be enhanced by these materials having dimensions smaller than the wavelength of light. Electromagnetic waves are diffracted and dispersed if the material has dimensions in the range of the light wavelength or a portion of the wavelength, and the numerous waves produced interfere with each other. Controlling the spatial distribution of light, as well as its phase, polarization, and spectral distribution may be accomplished by understanding such materials. Moreover, materials with lower dimensions can be used to make extremely condensed sophisticated systems in a variety of industries, including information technology, optical interactions, photovoltaic energy, image processing, medical and surveillance. This chapter reviews the various materials used for nanophotonics and their properties as well as their nanophotonics application.

Keywords: Nanophotonics, Nanotechnology, Photonic Devices.

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INTRODUCTION

There has been a huge influx and range of photonics technologies throughout the last five to ten years. This is responsible for the recent improvements in computerized development tools including subsequent affordability, as well as the advent of novel nanotechnology approaches and the implementation of innovative morphological and electrical analytical techniques. The emergence of sub-micrometre and nanometer technologies having proportions with the range of wavelength of light is at the leading edge of these advancements [1]. Nanoscience and nanotechnology refer to the science and engineering associated with the matter at the nanometric scale, such as atomic, molecular or macromolecular structures. Photonics is the science and engineering associated with the generation, control and detection of photons [2].

Photonics and electronics are analogous fields of science as within photonic applications, photons fulfill the same function electrons do within electric circuits. Likewise, as transistors were one of the turning points in electronics, lasers were the same with respect to photonics. Nanophotonics is therefore the field concerned with optical phenomena and materials in which the length-scale is smaller than the wavelength of optical radiation [1, 2].

Light-matter interactions occur at the nanoscale, at which the length scale is equal to or smaller than the wavelength of radiation. It poses challenges to fundamental science while also opening the door to technological innovations. It encompasses the investigation of novel optical interactions, materials, manufacturing techniques, and models, as well as the exploration of organic and inorganic, or chemically manufactured structures such as holey fibers, photonic crystals, sub-wavelength structures, quantum dots, and plasmonics. Researchers could perhaps start modifying and influencing photon interactions at nano-scale as required for specific applications by studying how they function, which may lead to ideas such as a novel approach to diagnose and cure cancer or optical quantum computers. During the next 10 years, nanophotonic approaches guarantee dramatic decreases in energy required for systems, more intensively comprehensive technologies with reduced power consumption, better accuracy for image processing and morphogenesis, and control technologies with higher accuracy and precision [3].

Developments in morphological characterization techniques including atomic force microscopy, nano-secondary ion mass spectrometry, scanning electron microscopes and transmission electron microscopes have been aided by the growth in nanophotonics. The capacity to link the dimensions, elemental composition and morphology of nanostructures to observable optical characteristics has been greatly aided by these devices.

Optoelectronic devices, bioinformatics, photonics, and nanotechnology are all significant surge topics in nanophotonics. Increasing proficiency in combining nanomaterials and optoelectronics has lately proven to be crucial, resulting in the emergence of frontiers that challenge basic research.

The fundamental aspects of nanophotonics are the three types of confinement which have also been summarized in Fig. (**1**).

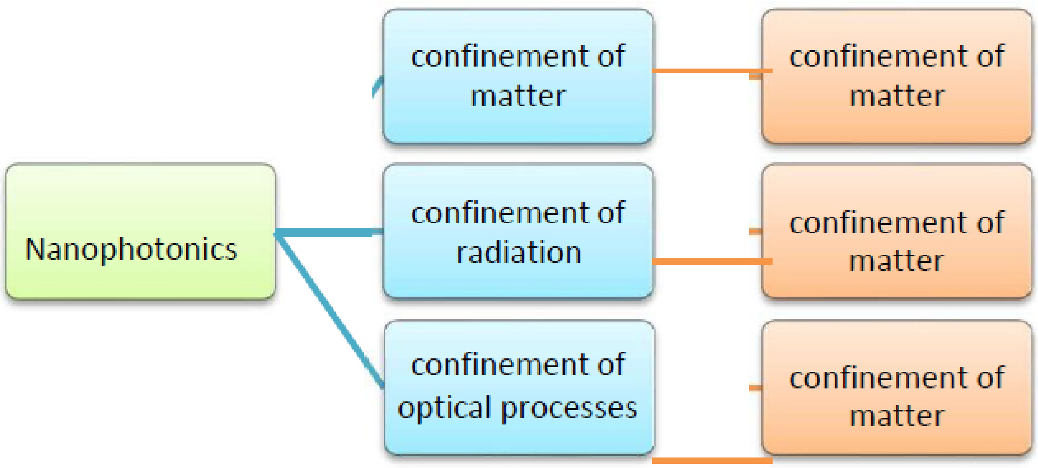

Fig. (1). Key confinements in nanophotonics [4].

- Nanoscale confinement of matter – Physical structures have their dimensions limited to the nanometric scale *via* specialized synthesis techniques, such as photolithography and chemical vapour deposition. These physical constraints alter the optical properties of materials by varying the bandgap, optical resonance and excitation phenomena, influencing light-matter interactions to this scale.
- Nanoscale confinement of radiation – Confining light to nanometer-sized dimensions far less than the wavelength of light, for example *via* the use of the near-field optical transmission model.
- Nanoscale confinement of optical processes – Control of the spatial confinement of photochemical and photophysical processes to allow for nanofabrication techniques [4].

As photons traverse space at the speed of light, photonics presents us with the opportunity to significantly increase the efficiency and speed of current technologies.

CHAPTER 8

Revolutionary Future Using the Ultimate Potential of Nanophotonics

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Abstract: As the world is modernizing, it is noteworthy to mention photonics and its categorization based on size. Despite the components of light being invisible to the human eye, nature never ceases to amaze us with its idiosyncratic phenomenon. Furthermore, the manipulation of the matter is confined to the nanoscale as a part of the progression. Adding nanotechnology to photonics emerges out as nanophotonics which is the cutting-edge tech of the twenty-first century. Human beings have acclimated to the concept of photonics, furthermore, nanophotonics is the science of miniaturization study, potentially helping the technology to modify itself into the sophistication of the equipment and thereby be of assistance in various disciplines of science and technology. One can illustrate nanophotonics by considering the fabrication processes of nanomaterials. In variegated applications, these nanoscale processes will refine and produce structures with high precision and accuracy. Meanwhile, groundbreaking inventions and discoveries have been going around, from communications to data processing, from detecting diseases to treating diseases at the outset. As one stresses on the idea of nanophotonics, it never reaches a dead-end, however, this explains how vast the universe and each of the components co-existing are infinitesimally beyond humans' reach. Nevertheless, nanophotonics and its applications bring about remarkable multidisciplinary challenges which require proficient and well-cultivated researchers. Despite the fact it has several advantages, it carries its downside, which requires a detailed analysis of any matter. Using state-of-the-art technology, one can constrict light into a nanometer scale using different principle methodologies such as surface plasmons, metal optics, near field optics, and metamaterials. The distinctive optical properties of nanophotonics call out specific applications in the electronics field such as interaction chips, tiny devices, transistor filaments, *etc*. When compared to conventional electronic integrated circuits, the pace at which data using nanophotonic devices is sent is exceptionally fast, accurate, and has a better signal processing capability. As a result of the integration of nanotechnology with photonic circuit technology, high-speed data processing with an average processing speed on the order of terabits per second is possible. Furthermore, nano-integrated photonics technology is capable of comprehensive data storage and processing, which inevitably lays the groundwork for the fabrication, quantification, control, and functional requirements of novel optical science and technology. The maj-

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ority of applications include nanolithography, near-field scanning optical microscopy, nanotube nanomotors, and others. This explains about the working principle, different materials utilized, and several other applications for a better understanding.

Keywords: Metal Optics, Near Field Optics, Metamaterials, NEMS, Surface Plasmons.

INTRODUCTION

Nanotechnology merged with photonics, called nanophotonics includes a broad range of recursive physical phenomena, including light-matter dynamics that are well below diffraction boundaries, and has paved the way for novel applications in light absorption, sensing applications, luminescence, optical switching, and media transmission technological advancements [1 - 6]. Growing competence in merging nanotechnology and photonics has recently emerged as a fundamental, emergent frontier, challenging basic experiments and prospects for innovations in our daily lives, and playing a vital role in several optical components [1 - 6].

It presents analytical research on photonic interaction with matter at infinitesimally small sizes, known as nanostructures, in order to build nanoscale devices and equipment to process, develop, lose momentum, influence, and/or control photons by understanding their behaviour when interacting with or otherwise passing through matter [1 - 6]. This multifaceted discipline has also influenced the industry, encouraging researchers to develop new frontiers in designing, applied science, chemistry, physical science, basic materials science, and biomedical technology [1 - 6].

Before understanding how photonics function and their application, it's important to brief about the similarities and differences between Photons and Electrons.

Photons and Electrons: Similarities and Differences

Photons and electrons are fundamental components in the language of physics, which display the same behaviour as particles and waves. In terms of Classical physics, photons are described as electromagnetic waves, which carry energy, and electrons as the basic charged particle (lowest mass) of matter. On the contrary, a quantum description indicates that photons and electrons may be processed directly analogously and have many comparable properties [1].

In most contexts, the electrons are marked by substantially greater dynamic values than photons of equal energies (derived from orders of magnitude more rest mass than the relative mass of a photon given by $m = \frac{h}{c^2}$ [1]. Therefore, there is a better solution for electron microscopy (in which the electron power and momentum are regulated using the accelerated high volume value) over optical (photon) microscopy because the final microscope resolution is restricted to the wavelength by the phenomenon of diffraction [1]. The wavelength of the photons can be given the equation as:

$$\lambda = \frac{h}{p} = \frac{2\pi c}{\omega} \quad \textbf{(1)}$$

The conduction electrons travelling in a solid have momentum values that are relatively high compared to photons, and hence the feature-specific lengths are shorter than the wavelengths of light. A significant consequence of this characteristic is that photons have 'size' or 'containment' effects on greater sizes than electrons [1]. The eigenvalue equation of the photons can be given as:

$$\left[\nabla \times \left(\frac{1}{\varepsilon(r)} \nabla \times \boldsymbol{E}\right)\right] = \left(\frac{\omega}{c}\right)^2 \boldsymbol{E} \quad \textbf{(2)}$$

And, the free space propagation of photons is given by:

$$E = \frac{1}{2} E_0 \left(e^{-i(k\,.\,r\,-\,\omega t)} + e^{i(k\,.\,r -\,\omega t)}\right) \quad \textbf{(3)}$$

where k is the wave vector, a real quantity.

Photons and Electrons: The Constriction in Various Facets

The spread of photons and electrons can be dimensionally restricted by employing regions with diverse interaction possibilities to reflect or redirect these particles, therefore restricting their spread to a certain route or a certain group of them [1]. In the case of photons, trapping light in a high refractive area or high surface reflectivity can introduce configuration. This secluding area might be a cavity resonator or a waveguide.

Considering a thin film, a high refractive index layer carries out the propagation of light, provided the light-guided layer has a high refractive index (n_1). The graphic displays the traditional optical image via a ray path, which describes light directing (trapping). For a flat waveguide, the containment is in the vertical position only (x-direction). The light propagates in the z-direction, whereas in the case of a fiber or a channel guide, the path is followed in the x and y directions.

CHAPTER 9

A Simulative Study on Electro-Optic Characteristics of InAlGaAs/InP for Fiber Optic-based Communications under Nanoscale Well Thickness Layers

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Abstract: The paramount goal of this fundamental explanatory book chapter has been to investigate a simulative study on EO (Electro-Optic) characteristics of InAlGAs/InP heterogeneous nanostructure for GFOCs (Graded Fiber Optic Cables) based SIL (Shortwave Infrared Light) communication systems under several numbers of NWTLs (Nanoscale Well Thickness Layers) in the photonic material based emerging nanotechnological sciences. The energy values in eV of C-V (Conduction-Valence) band offsets with SN (Step Normalized) width and the maximum value of quasi-Fermi energies in eV with various NWTLs have been illustrated graphically under the exploratory simulation in this chapter. Under this simulative investigation, the computational performances of SIL gain amplification with photon's wavelength and values of carrier concentration per unit volume for several NWTLs have been properly calculated. Next, other various critical parameters such as modal confinement SIL gain amplification and A-G (Anti-Guiding) parameter with values of current per unit area of the cross-section for various values of NWTLs have been calculated cumulatively. Moreover, the performances of differential SIL gain amplification with carrier densities per cubic cm for various NWTLs have been illustrated. It has been distinguished by SIL gain spectra that the peaks of SIL gain spectra are enhanced with a decrease in the value of NWTLs and have been shifted towards the low value of the wavelength of lasing due to enhancement in energy separation values between quasi-Fermi energy levels. In the exploratory investigation through the results, the crest values of SIL gain amplification are ~ 6100/cm and ~ 5100/cm at the photon wavelengths ~ 1332 nm and 1553 nm respectively for 4 nm and 6 nm values of NWTLs. The SIL of maximum intensity emitted by the proposed heterogeneous junction based nanostructure of wavelengths ~ 1332 nm and 1553 nm has been largely utilized in the GFOCs-based SIL communication systems through the process of TIRs (Total Internal Reflections) with no attenuation loss of SIL signals in dB/km because of diminished net dispersions, scattering and net absorptions in the photonic material.

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Keywords: A-G Parameter, C-V Energy Band Offsets, Differential SIL Gain Amplification, GFOCs, InAlGaAs, InP, Modal Confinement SIL Gain Amplification, Net SIL Gain Amplification, NWTLs, SIL Signal Loss, TIRs.

INTRODUCTION

It has been noticed that, since the last few years, the GFOCs (Graded Fiber Optic Cables) based SIL (Shortwave Infrared Light) communication systems and heterogeneous junction inspired nanostructures have made a critical contribution to nano-optoelectronics and photonics nanosystems due to their unidirectional nature of propagating light. The nanophotonic materials based on a heterointerface nanostructure (such as AlGaInAs, AlGaInN, AlAsInP and GaAsAl, GaAs, *etc.*) inspired emerging technologies and have tremendous applications in various fields such as in medical research area, industrial field, area of remote sensing, aerospace field, SIL emitters, SIL lasers, SIL detectors, and SIL communications by GFOCs nanosystems *etc.* In emerging nanotechnological based photonics, the various EO characteristics of III-V photonic materials based on nanoheterointerface structures [1 - 7] have been simulated and investigated experimentally and theoretically by researchers in recent times. The photonic material InAlGaAs/InP based heterointerface nanostructure plays an important role in the SIL emitters due to their high temperature tolerance performances. This is because such type of photonic material has higher energy values of CBOs (Conduction Band Offsets) than VBOs (Valence Band Offsets) so electrons have been confined properly resulting in minimal leakage due to vaporization. This III-V group InAlGaAs/InP photonic material-based heterointerface nanostructure has been utilized in SIL applications because firstly, the emitted SIL is safe to our eyes and secondly, loss effects like dispersion and scattering are negligible in the lasing process. The EO properties [8 - 10] of MQL (Multi Quantum-well Laser), BTL (Bipolar Transistor Laser) and JDL (Junction Diode Laser) based on III-V photonic material AlGaInAs-InP have been investigated recently by several authors. In this chapter, the fundamental EO characteristics of InAlGAs/InP heterogeneous junction-based nanostructure for GFOCs based SIL communication systems under several numbers of NWTLs have been investigated by the computing process. The energy values in eV of C-V band offsets with SN width and the maximum value of quasi-Fermi energies in eV with various NWTLs have been illustrated graphically under the exploratory simulation in this chapter. Under this simulative investigation, the computational performances of SIL gain amplification with photon’s wavelength and values of carrier concentration per unit volume for several NWTLs have been properly calculated. Next, other various critical parameters, such as modal confinement SIL gain amplification and A-G parameter with values of current per unit area of the cross section for various values of NWTLs have been calculated cumulatively.

Moreover, the performances of differential SIL gain amplification with carrier densities per cubic cm for various NWTLs have been illustrated. It has been distinguished by SIL gain spectra that the peaks of SIL gain spectra are enhanced and diminished as per the value of NWTLs and have been shifted towards the low value of the wavelength of lasing due to enhancement in energy separation values between quasi-Fermi energy levels. It can be seen that the crest values of SIL gain amplification have been found to be ~ 6100/cm and ~ 5100/cm at the photon wavelengths ~ 1332 nm and ~ 1553 nm respectively for 4 nm and 6 nm values of NWTLs. The SIL of maximum intensity emitted by the proposed heterogeneous junction based on the nanostructure of wavelengths ~ 1332 nm and ~ 1553 nm has been largely utilized in GFOCs-based SIL communication systems through the process of TIRs with no attenuation loss of SIL signals in dB/km because of diminished net dispersion, scattering and net absorption in the nanophotonic materials.

SIMULATED HETEROINTERFACE NANOSTRUCTURE, AND THEORETICAL DETAILS

Taking into account the dimensional performances of nanoscale order, the simulative type heterogeneous interface-based structure has been proposed by computing-based nanotechnologies. The proposed heterogeneous interface-based nanostructure is a simulative structure. This simulative structure has a total of five RNLs (Refractive-index Nanoscale Layers) in which one QNL (Quantum-well Nanoscale Layer) is sandwiched between two RNBLs (Refractive-index Nanoscale Barrier Layers) hence this simulated system is enveloped by two RNCLs (Refractive-index Nanoscale Cladding Layers), such that the whole system is grown simulative on the substrate of InP layer. The entire details of compositional and dimensional parameters have been illustrated in Table 1.

Table 1. The details of parameters of the simulative proposed heterogeneous interface-based nanostructure.

Five types of specified RNLs	The percentage value of x and y for specified RNLs (In1---yAlyGaxAs)	Values of thickness of specified RNLs in (nm)	Values of Photon's wavelength in (nm)	Energies values of BOs in (eV)
RNCL (C.B.)	0%, 48%	10	0837	0.2354
RNBL (C.B.)	34%, 25%	5	1035	0.1525
QNL	21%, 08%	6	1554	0.0514, - 0.0514
RNBL (V.B.)	34%, 25%	5	1035	- 0.1525
RNCL (V.B.)	0%, 48%	10	0837	-0.2354

CHAPTER 10

Two-Dimensional Materials for Advancement of Fiber Laser Technologies

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Abstract: Two-dimensional (2D) materials such as graphene, chalcogenides, topological insulators, black phosphorus, and MXenes have of late become the focus of intense research efforts due to the excellent and unique optoelectrical properties these materials possess. This is due to the unique properties these materials possess, such as tunable bandgaps, high mobility in the energy bandgap, third-order nonlinearity, and nonlinear absorption that can be tailored to suit the specific needs of different optical applications. These properties have allowed for the development of fiber optic-based pulsed laser systems with better integration and flexibility capabilities as well as improved performance as compared to their bulk counterparts. In this chapter, the development of optical fiber pulsed lasers that incorporate selected 2D materials, particularly 2D chalcogenides that encompass metal monochalcogenides (MMs), and traditional metal dichalcogenides (TMDs) and MXenes is reviewed. This chapter will cover the fundamental aspects of the aforementioned materials, the operating principles of Q-switching and mode-locking, and the configuration of these 2D materials as saturable absorbers (SAs). The main section of this chapter will focus on the current status of the development of Q-switched and mode-locked optical fiber laser systems using 2D material-based SAs. Finally, the chapter will explore the perspectives and challenges on the future of the potential applications of these 2D materials in pulsed optical systems.

Keywords: Fiber Lasers, Nonlinear Optics, Optical Systems, Two-Dimensional Materials.

INTRODUCTION

In recent decades, optical fibre laser technologies have expanded rapidly into a commercial business worth more than $800M/year and an annual growth rate of approximately 13%, which is the highest among the various laser technologies [1]. This record represents the remarkable achievement of fiber laser technologies

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and was driven mainly by the flexibility, compactness and alignment-free properties afforded by optical fibers and systems developed using optical fibers. Of the many types of fiber laser technologies, pulsed fiber laser technologies, in particular, have proven to be very useful for a variety of applications such as material processing [2, 3], skin treatment [4, 5] and medical applications [6, 7]. The efficient generation of pulses from fiber laser systems however required the use of use of an optical modulating optical modulating element known as saturable absorber (SA) which exhibited power dependent absorption properties. The SA could be obtained as either active or passive devices, but the latter was mostly preferable due to its simplicity and cost-effectiveness.

Currently, semiconductor saturable absorber mirrors (SESAMs) based on III–V semiconductors have been the primary choice for passive SA devices.

These devices have high performance and stability, but with the limitation of being complex and fragile and having a costly fabrication process. In addition, they also possess a relatively narrow tuning range dictated by the bandgap energy of the semiconductor absorber. These limitations have thus shown the need to develop a more cost-efficient, broadband saturable absorber for pulsed laser generation in fiber laser systems. While there were many efforts to develop a more cost-effective and viable SA, it was the discovery of graphene by Andre Geim and Konstantin Novoselov in 2004 that showed the potential of two-dimensional (2D) materials as SA devices [1]. 2D materials are highly suitable for fiber laser technologies due to the fiber compatibility which allow an alignment-free, all-fibre format. Furthermore, they offer easy integration into the fiber laser system as the SA can be formed by sandwiching the 2D material between two fibre connectors or drop-casting it onto the surfaces of a specially designed fiber.

By 2009, graphene had already been heavily utilized as an SA in fiber laser systems due to its easy fabrication procedure and unique optical properties. Nevertheless, single-layer graphene suffered from a low-modulation depth, which was insufficient for ultrafast laser generation. The stacking of few-layers graphene could enhance the modulation depth but at the same time it also increases its non-saturable loss. As a result of this, various 2D materials other than graphene have been studied and tested for pulsed fiber laser generation. These new emerging 2D materials include chalcogenides [8 - 12], topological insulators (TIs) [13], black phosphorus (BP) [14 - 16] and MXenes [17 - 20]. These materials show distinct optical properties and are thus suitable to be used for the generation of a versatile pulsed fiber laser system.

Among these 2D materials, chalcogenides including metal monochalcogenides (MMs) and transition metal dichalcogenides (TMDs) as well as MXenes are currently attracting the greatest research interest in the field of fiber lasers. TMDs are particularly interesting for application as an SA in pulsed fiber laser systems due to their layer-dependent optical properties [21, 22] and ultrafast carrier dynamics [23 - 25]. On the other hand, MMs provide alternative structural features than that of TMDs, together with large material options. Alternatively, MXenes are widely explored due to their broadband nonlinear optical response and high optical nonlinearity [18, 26].

In this chapter, the development of fiber lasers based on MMs, TMDs and MXenes is reviewed. A discussion on the operating principle of these SAs for Q-switching and mode-locking in fiber laser system, the integration configuration of the saturable absorber and experimental setup for pulsed laser generation at different wavelength ranges is also presented. Lastly, the challenges and future perspective of the MMs, TMDs and MXenes saturable absorber for the advancement of fiber laser technologies are discussed.

2D Material-Based Saturable Absorbers for Fiber Lasers

It is well established that the pulsed fiber laser can be operated in both Q-switching and mode-locking modes. These pulsed lasers can then be classified further as active and passive systems, depending on the technique used to generate the pulses. An active pulsed laser is one that used several optical devices to generate pulses, such as electro-optic or acousto-optic modulators. This technique is very effective in controlling most of the parameters of the generated pulses; however, the resulting bulky setup, as well as high cost, became a major inhibitor for the widespread use of this approach. On the other hand, passive pulse lasers were usually realized by means of SAs, which overcome the issues of bulk and cost but at the same time offer less control on the output parameters of the pulses generated therein. However, in most real-world applications, the pros of this approach far outweigh its cons, and thus research efforts are now focused on the development of passively pulsed fiber lasers.

Like graphene, 2D materials exhibit interesting characteristics that make them highly desirable for photonics applications, such as strong light absorption. This is a unique behaviour of 2D materials and it is not exhibited by their bulk material counterparts [27]. Furthermore, 2D materials also demonstrate a great linear energy-momentum dispersion correlation which permits broad wavelength range coverage ranging from ultraviolet to far-infrared [28]. Layered 2D materials possess an excellent potential for incorporation into optoelectronic devices due to their good mechanical flexibility, strong intra-layer bonding and great robustness [29]. Fig. (**1**) shows some of the examples of 2D materials that have been used as SA materials for pulsed fiber laser generation.

CHAPTER 11

Optical Properties of Hollow-Core Bragg Fiber Waveguides

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Abstract: The propagation and dispersion properties of hollow-core Bragg fibre waveguides for both high and low refractive index contrasts of cladding materials are explored and compared in this chapter using two design wavelengths: 1550 nm in the near-infrared area and 632.8nm in the visible range. The boundary matching approach was used to build a relationship between the incoming and outgoing light waves employing the transfer matrix method. The observed photonic band gaps are somewhat substantial in high refractive index contrast cladding Bragg fibre waveguides, *i.e.* HRBFW, and low periodic cladding layers are required to achieve a perfect photonic bandgap. The spectrum range and spectral location of photonic band gaps in both HRBFW and low refractive index contrast cladding Bragg fibre waveguides, *i.e.* LRBFW, are substantially dependent on the angle of incidence of a light beam, *i.e.* the optical path of the incident light. The sensitivity of the Bragg fibre waveguide for sensing applications may be determined by measuring the thickness of the photonic bandgap or the spectral shift of the photonic bandgap. HRBFW seems to have a high sensitivity when considering the change in spectral bandwidth of photonic bandgap with core refractive index, which grows with increasing design wavelength. LRBFW has a much higher sensitivity than HRBFW when considering the LBE (Left band edge) and RBE (Right band edge), hence it is suggested for sensing applications. HRBFW directed a greater number of modes than LRBFW, according to the assessment of dispersion characteristics.

Keywords: Photonic nanostructures, Transfer matrix method, Hankel formalism, Sensitivity, Photonic Bandgap.

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INTRODUCTION AND MOTIVATION

Due to its advantageous features over traditional fibers, Bragg gratings and the fiber based on other photonic crystals, researchers have been enamoured with Bragg fiber waveguides during the last decade. The theoretical introduction of the Bragg fiber waveguide by Yeh *et al.* [1 - 3] was followed by the design and viability investigation for optical communications by various investigators, including Doran and Bluow in 1983 [4]. However, towards the turn of the twenty-first century, an experimental platform for such a waveguide was proven. In a nutshell, a Bragg fiber is a concentric circular cladding in length that surrounds a low index cylindrical dielectric or material free core in the middle.

These concentric circular claddings are designed by a periodic arrangement of two different bi-layer materials that are transparent in the visible and near-infrared region. The propagation mechanism of electromagnetic waves (EM waves) in Bragg waveguides is completely different from that of ordinary fiber waveguides based on total internal reflections. The thickness of the layers in the Bragg fiber waveguide is designed to accept the quarter-wave condition. Recurrent Bragg reflections from claddings propagate the EM wave in such waveguides, and total reflections are concentrated in the low index core and further move towards the end of the fiber. Birefringence effect, polarisation effect, dispersion non-linearity, material dispersion, distortion, and various losses due to confinement, modal dispersion and further unusual radiation [4 - 17], which happen often in various classic fibers, are virtually eliminated in such waveguides because of the material free core. In addition, the Bragg fiber waveguide's hollow or low index core makes it a strong contender for a range of other intriguing applications. Biosensors [18 - 25], chemical gas sensors [26], strain sensors [19, 27, 28], and other devices based on Bragg fiber waveguide have recently been created. In addition to these uses, narrowband transmission filters, optical de-multiplexers [28 - 32], temperature sensors [33], and other optoelectronic applications of these waveguides exist.

Researchers, on the other hand, have built and investigated the various characteristics of 1-D cylindrical photonic crystals, which are most similar to the design mechanism of Bragg fiber [34 - 36], due to their ease of production (just one step) [35]. Various types of Bragg fiber fabrication are also simple in this context. Researchers have recently been intrigued by the possibility of fabricating such fibers utilising solvent evaporation fiber rolling and drawing techniques [37, 38]. In the drawing approach, they first produced a bilayer preform, then used fiber drawing towers to draw it into length, which is already mentioned in the introduction part of the present chapter. High contrast Bragg fibers can be made with the help of this method in which polymer material is at the low index layer and chalcogenide or perovskite material is at the high index layer [39]. Further low contrast Bragg fiber where both low refractive index (R.I). material as well as high R.I. material are of the polymer film, can be fabricated by using the rolling technique [40]. Sensing and optoelectronic are important applications where we can use such fiber waveguides. Recently, due to very specific properties, these fiber waveguides have tremendous applications in high power laser transmission where the non-linear effects are significantly suppressed [41]. They are also promising in various applications such as strain, bio and chemical sensing [26, 39, 40, 42] bending and displacement sensing [40], narrowband transmission filter, optical de-multiplexers, *etc.* [29, 31, 43, 44]. The optical characteristics of high R.I. contrast and low R.I. contrast Bragg fibers are of concern to the contemporary investigator due to their recent popularity. Since, the photonic bandgap (PBG) mechanism is used to guide EM waves in such a fiber structure, the function of PBG in high and low R.I. contrast Bragg fibers has been investigated, optimised and compared in this chapter. By adjusting the incidence angle of light, the tunable PBG from such fiber structure can be obtained. The PBG is determined for the operational spectral mode, namely the widely utilised 632.8 & 1550 nm for which signal loss window is minimum. The main characteristic parameter, full width at half maximum (FWHM) of the output spectrum is also influenced by the Bragg fiber periodicity. As a result, two types of empty core Bragg fiber structures, HRBFW and LRBFW, have been examined in this chapter. The suggested fiber waveguide's propagation characteristics are studied using the transfer matrix approach. In addition, we have seen the PBG move in response to changes in the core refractive index, which is the biosensing mechanism's primary premise. Furthermore, dispersion analysis is critical for the practical implementation of such fiber waveguide structures. Through proposed HRBFW and LRBFW structures, dispersion analysis of fiber waveguide structure examines the optimization of core radius and cladding thickness, as well as their cutoff condition. In this chapter, we have used the transfer matrix method (TMM) and Hankel formalism (HF) to theoretically analyse the propagation parameters of the Bragg fiber and find the mathematical equation for the various propagation modes in the fiber structure.

THEORETICAL MODELLING OF THE PROPOSED STRUCTURE

The front view with all details along the length of the Bragg fiber is shown in Fig. (**1a**). In this front view, n_c and r_c shows the R.I. and empty core radius while n_H , n_L and d_H , d_L depict respectively, the R.I.'s and the respective thicknesses of high and less R.I. cladding layers forming the periodic structure. Further, $\Lambda=d_H+d_L$ is periodicity. Assuming that the electro-magnetic components can be represented by spatial-temporal factor of $U_{tz}=\exp[i(\omega t-\beta z)]$, β being the propagation constant. With the periodic arrangement, a concentric Bragg fiber must be disigned. In the

CHAPTER 12

Photonic Nanostructured Bragg Fuel Adulteration Sensor

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Abstract: The adulteration of liquid fuels has several far-reaching repercussions, including pollution and a rising energy crisis. Around the world, fossil fuels are widely utilized for transportation and energy generation. Fuel adulteration currently threatens a big number of customers. Adulteration of fossil fuels with other recognised hydrocarbons is a common occurrence. Adulterants are added to these base fuels in the form of additional low-cost hydrocarbons with similar compositions, leading the base to be altered and degraded. Adulteration is an unauthorised or illegal introduction of a lower-quality external substance into a higher-quality commodity, causing the latter to lose its original composition and qualities. The Opto-Microfluidics approach is a new field that uses a small sample to identify adulteration in food and fuel, resulting in high-resolution findings. Consumers will benefit from very sensitive detection of dangerous adulteration in any commodity thanks to opto-microfluidic lab-on-chip technologies. Using the metal-polymer nanocomposites' multilayer cylindrical nanostructure with a microfluidic channel, we develop a real-time and temperature-dependent prototype of the Bragg Opto-microfluidic sensor for effective tracking of contaminated fossil fuels. The purpose of this chapter is to examine the biological motivations for the development of multilayer photonic nanostructures and various types of fuel adulteration detection optical sensors using various sensor-based techniques, as well as to compare the Bragg Metal-Polymer nanocomposites optical sensor with other optical sensors. This chapter is devoted entirely to the use of the theoretical model's Kay, Eykman, Dale-Gladstone, Newton, and Lorentz-Lorenz, as well as Hankel formalism and the transfer matrix method for cylindrical symmetry.

Keywords: Photonic nanostructures, Fossil fuel and energy, Adulteration sensor, Transfer matrix method, Hankel formalism.

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INTRODUCTION

The structure, content, and optical presence of biological photonic systems might serve as a source of stimulation for creating innovative artificial photonic elements [1 - 3]. Natural photonics research can occasionally lead to specific optical technology design templates [4 - 9]. After uncovering a hierarchical photonic nanostructure, Margaritaria nobilis fruit's seed coat, they constructed novel photonic nanostructured fibres. Light interference inside a concentrically-layered architecture found in the individual cells in the seed's outer tissue layers causes the fruit's hue. Regularity of nano-cylindrical symmetry, which leads to selective wavelength dispersion of light in an extensive range of directions; and regularity of nano-cylindrical symmetry, which leads to selective wavelength dispersion of light in an extensive range of directions are two technologically exploited properties for light and colour handling in the natural structure.

This lays the groundwork for a new soft, biologically inspired nanostructured photonic fibre with spectrum filtering capabilities and colour brightness similar to a flat Bragg stack, as well as a vast angular spatial range offered by the nanoscale bend.

Because of the elastic and transparent synthetic materials, the multilayer interference fibres have high reflectivity that is dynamically changed by a longitudinal mechanical strain. This type of soft photonic fibre is designed and manufactured in a biologically inspired manner, and it marks the transition to new fibre flexible fabrics and photonic materials. Nature's most gaudy hues, extraordinary transparency, brightest whites, or darkest blacks rely on the wavelength of visible light in the order, in a quasi-ordered or disordered structure with scattering element sizes or lattice constants [10 - 14]. By causing diffraction or interference, the wide structural range of biological structures has a significant impact on the spectral composition of transmitted and reflected light, ensuing in remarkable structural colours for many species [15, 16]. The plant Margaritaria nobilis has blue-green fruits, grown in the rain forestry of Middle and South America. The plant relies on birds to disperse the seeds, and the bright display may attract them [17 - 20]. The cells in the blue seed coat of the fruit are lengthy and mostly blue and green in colour. Various cell layers are placed on top of each other, each with a different planar location. A cross-section of a single cell tells that the whole inner volume is occupied by a periodically concentrated morphology. The presence of light on the fruit's surface causes blue light to reflect because the usual structure of each cell is disrupted. Under diffuse light, the colour blue varies as the angle of view increases. Instead, due to the superposition of microscopic curvature, the reflected structural colour over the wide angular gamma inside the layers of each seed coat tissue cell, as well as the overall macroscopic curvature of the fruit, is more noticeable in M. Nobilis. This idea is also used to design novel optical technology [6, 7, 9]. The photonic hierarchy in the seed coat of M. nobilis fruit is required for the production of striking blue and green colours. It encourages the use of a combination of nanoscopic regularity and overlaid microscopic curvature to build optically capable artificial photonic fibres.

While the artificial system is comparable to its natural counterpart in terms of optical interactions and dimensions, it evades many of the intricacies of natural structure, such as ellipticity and any fine structure inside the regular layers of the fruit cells, for its expedient set of characteristics for precise fiber-optic tuning, as shown below. This material system has previously been chosen in the framework of planar, flexible, multi-layer systems. The emphasis of exertions on a restricted group of materials and architectures that give light guiding in the fibre core over total internal reflection in the transparent region of silica glass has been an unforeseen side consequence of this accomplishment. In the previous ten years, things have changed. Though light-guiding still depends on total internal reflection, nanostructured fibres have been investigated, allowing for a wider range of fibre configurations [21 - 23]. Fibers with two-dimensional (2D) photonic-crystal structures [24] have been proven to direct light *via* the photonic bandgap [25 - 27] (PBG) effect. The vast range of outcomes achieved by these fibres has been very attractive for research considering the diverse applications [22 - 29]. Traditional materials, such as silica glasses or polymers, are used in these fibres, with the accumulation of air holes that may enclose fluids [30]. Optical transmission and related phenomena are limited by the presence of compressible domains and the usage of electrically insulating materials. The technique of employing a multi-material preform for fibre processing is established first, followed by the assortment criteria for well-matched material combinations.

Subsequently, we exhibit a fibre with alternating layers of an electrically insulating polymer and a semiconducting glass of predefined thicknesses that restrict light to a hollow core, resulting in a cylindrical omnidirectional mirror [31 - 35]. Because the index difference between layer materials is strong enough, the electromagnetic field cannot penetrate the solid layers, resulting in a fibre that is significantly more transparent than its basic elements. This structure is unique due to the scalable wavelength, meaning that the structure's period influences the wavelength of light transmitted down the fibre axis. As a result, by merely adjusting the lattice constant of the periodic multilayer structure, fibres that direct ultraviolet (UV), visible, near, or mid-infrared (NIR or MIR), light may be made using the same overall manufacturing process. The drawing of long lengths of fibre results in a huge surface area. This opens the door to the development of

CHAPTER 13

Modelling Fabrication Variability in Silicon Photonic Devices.

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Abstract: Silicon photonics allows for high yield and complex integration with large processing, packaging, and testing availability. Using silicon as a material leverages the use of the existing CMOS infrastructure with hybrid and epitaxial layer integration, allowing photonic system-on-chip. Although high refractive index contrast with sub-micrometer waveguide dimensions allows a dense integration, sensitivity to fabrication variations shows an increased effect. This sensitivity shows a cumulative effect on the optical properties of complex silicon photonic circuits such as lattice filters, and wavelength division multiplexers (WDM). This increases the demand for model fabrication variation at the design stage itself since the fabless users have no insights into the process specifications. As a result, reliability modelling of photonic circuits has shown significant interest in recent years. This is done by using efficient behavioural models at the circuit level and then applying random variations in the model parameters to assess the impact of these variations. In this chapter, different approaches to modelling fabrication variations in photonic integrated circuits, such as Monte Carlo (MC), Stochastic Collocation (SC), and Polynomial Chaos Expansion (PCE) are reviewed. These methods employ random distribution to the varying parameters with the correlation between different parameter sets fixed. Virtual Wafer-based MC (VW-MC) allows layout-aware variability analysis, where the placement of circuit components on the layout coordinates is exported to the circuit design for dependence analysis. Using these methods, mitigation strategies to counter the manufacturing variations such as thermal compensation, and tapered designs are quantitatively evaluated by appropriate yield analysis and design for manufacturability.

Keywords: CMOS, Lattice filters, Monte carlo simulation, Silicon photonics, Stochastic collocation, WDM.

INTRODUCTION

Silicon photonics integrates multiple optical operations on a single chip *via* CMOS fabrication thereby enabling low cost and high volume manufacturing.

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The high refractive index contrast (Si = 3.4757, SiO_2 = 1.5277 at 1550 nm) allows sub-micrometer waveguide size, small bend radius and dense packing on chip [1]. However, the high index contrast imposes restrictions on the dimensional variability (nanometer resolution) due to a small fabrication mismatch. The more complex the photonic circuit, the higher the effects of fabrication variability on its performance [2]. This eventually affects the overall yield of the chip design rendering wafer material to waste. The challenge of capturing the effects of this variability at the design stage to enable a pre-fabrication yield estimate is one of the primary areas of investigation in silicon photonics currently [3 - 7]. Taking the example of a silicon photonic transceiver, yield analysis would entail determining the percentage of chips that have modulators working with bit error rates (BER) below a threshold value [7].

The design for manufacturability (DFM) ensures that the high yield is done at three levels [4, 5]. It starts with the robust design of device elements (like waveguides, and directional couplers) of a photonic system. Secondly, optimization of the photonic circuit, by selecting the robust device components and ensuring proper routing at the schematic level. It should take into account the proper correlation between the device components requiring extensive models continuous in the variational parameter space. These models monitor and map the device variations while conserving its physical properties like passivity, stability, and causality [5]. Finally, the remaining imperfections are compensated using active compensation techniques.

In this chapter, we discuss all the three levels of silicon photonic- DFM. In Section II, sources of device variation and their effect, photonic device optimization methods are introduced. In Section III, the evaluation of photonic circuit performance and modelling for correlation is discussed. SC, PCE and layout-aware variability is analyzed for design under test.

PHOTONIC DEVICE LEVEL OPTIMIZATION

For any photonic circuit, the variation starts with the process conditions of individual elements such as optical waveguides, directional couplers, y-branches, *etc.* The process conditions include exposure dose, plasma density, slurry composition, mask alignment, and chemical, and mechanical polishing (CMP) for planarization [5]. These process steps are not exactly reproducible from die to die, wafer to wafer and one lot to another [6]. These processing steps affect the pattern density which can lead to geometrical variations such as in waveguide width, thickness, sidewall angle, doping profiles, *etc.* [7]. The effect of pattern density on the waveguide width with an intra-die correlation coefficient of 0.57 at optimum selected window size resolution of 69 um has already been demonstrated [7]. As far as the waveguide thickness is concerned, its variability is mainly attributed to silicon on insulator bonding [7]. To check these geometrical variations, we need measurement methods characterizing these variations. Atomic force microscopy, scanning electron microscope and other indirect methods are some of the common methods employed [5, 8]. Process control monitors with reflection optics are also commonly employed to monitor geometric variations during or after the fabrication. However, most of these methods are costly, time-consuming with the risk of damaging the device permanently [8]. Recently transmission spectrum based methods have been employed to extract the geometry of photonic devices using either the resonance shift method or the curve tracing method [7, 9]. A single circuit with a double MZI circuit has been proposed to monitor and extract multiple parameters of waveguides and directional couplers [7]. Once the exact statistical distribution of geometrical variations is known, the effect on optical properties will follow. For optical waveguides, effective index and group index and for directional couplers, coupling coefficient, splitting ratio vs wavelength are the figures of merit (FOM) [8]. This device FOM then affects the circuit FOM and photonic circuit yield analysis and thus taking the design for manufacturability (DFM) into consideration becomes a possibility.

Intuitively, this design of a single device component for a fixed FOM is mostly made by physics-based analytic models, practical know-how and intuition [9]. With complicated geometries required for optimum FOM values, the light matter interaction *via* numerical electromagnetic simulations gets complex [9]. For an efficient design process, an inverse design assisted by iterative optimization methods and deep neural networks (DNN) is being employed in the state of art designs [10]. The alternative optimization algorithms show satisfactory optimization results, however, the need for parameter sweeps makes it laborious since electromagnetic simulations tend to become time-consuming in that case. The relation between geometry and optical FOMs becomes like that of non-deterministic (NP) hard problems, which are not easy to define explicitly [10]. Iterative gradient free algorithms such as genetic algorithm (GA), particle swarm optimization (PSO) and direct binary search (DBS) have been extensively used to solve such NP hard problems in optical devices [11, 12]. Recently, gradient-based topology optimization (TO) for an irregular design structure based on silicon photonic devices has also been used [13].

Instead of the common iterative algorithm approach of taking key parameters and abstracting them, TO takes the entire design shape space as a bitmap [13]. After selecting the entire design space, all the pixels of this bitmap are iteratively updated towards the direction of gradient descent until the gradient resolves them to a non-assuming value. Very complicated device structures have been possible using this method. However, all the iterative optimization algorithms discussed

CHAPTER 14

Introduction of Smart Materials: The Art to Outrival Technology

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Abstract: Smart materials are the name given to materials that can alter their properties on the application of external stimuli. Devices using smart materials might replace more conventional technologies in a variety of fields. Smart materials are attractive due to their lightweight, sensing capability, lower component size, and complexity combined with design flexibility, functionality, and reliability. A smart material is an object which is susceptible to undergoing a material property change and shows a visual and tangible reaction to external stimuli. Proper execution of smart materials will provide a level of environmental robustness that is not easily achieved through conventional technologies as they are susceptible to the influences of nature. One concept which includes the futuristic application of smart materials is the utilization of smart materials in the transportation sector using shape-memory alloys and piezoelectricity. Although the applications of smart materials are far-reaching, a greater dependency on them is prevented by certain drawbacks that need to be addressed if utilization of smart materials is to be accomplished, such as system compatibility, availability, cost, delicateness, decreased performance over time, difficulties with integration and toxicity.

Keywords: Conductors, Insulators, Piezoelectric, Self-Healing, Smart Materials.

INTRODUCTION

Due to the advancements in the field of material science, the usage of new, high-quality, and low-cost materials in different fields of engineering can be observed. In the past century, materials have become more versatile and require the enhancement of various properties and features. Taking past advancements into account, it can be observed that researchers focused on composite materials, and currently, the upcoming revolutionary discovery is that of smart materials. Smart materials or responsive materials are futuristic materials that outperform traditional materials. Smart materials are beneficial due to their lightweight,

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component size, sensing capability, functionality, reliability, and complexity blended with design flexibility [1]. A smart material is an object receptive to undergoing a property change and shows a physically perceptible reaction to an internal or external stimulus [2]. Smart materials have the inherent and acquired ability to acknowledge a stimulus and to operate with respect to those stimuli by undergoing a pre-determined change in property.

Pressure, electric or magnetic fields, nuclear radiation, and temperature are a few examples of stimuli that bring about a change in smart materials. The visible changes in physical properties that could potentially occur are stiffness, structural changes, or damping. Material science is used to characterize and determine the functions of various engineering materials, which is then used to develop successful engineering technologies. The quality and functioning of these products rely heavily on the material used for manufacturing the product. In order to make products with exceptional properties, material science engineers turned to smart materials to produce engineering materials. They explored the possibilities of producing conductors and insulators using these smart materials.

In recent years, smart materials have been studied extensively for their applications in the aerospace, mechanical, and biomedical fields [3]. Smart materials or responsive materials can be classified as non-living systems which assimilate the functions of logic, sensing, control, and actuation [4]. It refers to any device that can sense a change within its environment, allowing for an optimal response by altering its geometry, mechanical, material, or electromagnetic properties [5, 6]. They may also be defined as structures consisting of distributed actuators, processing networks, and sensors [5]. This idea of smart devices arises from nature due to the response to stimuli capabilities present within all living organisms [6]. The material contains feedback functions in combination with the functions and properties of the material. Active responsive materials are defined as materials that can adjust their material or geometric attributes when under the influence of electric, magnetic, or a thermal field, as a result of which, they acquire an innate capacity for energy transduction [7]. They are capable of adapting based on the external stimulus on the material with an inherent intelligence [8]. These stimuli may refer to temperature, pressure, electric fields, chemicals, magnetic fields, or nuclear radiation and the corresponding physical changes can be shape, viscosity, damping, or stiffness. Piezoelectric materials are known for being used in strain sensors [9], accelerometers, stress waves emitters and receptors [10], actuators [11], pressure transducers [12], and vibration sensors [13, 14]. Table 1 summarizes the types of smart materials, properties, and applications.

Table 1. Types of smart materials, properties, and applications.

Type of Smart Material	Stimuli	Property Change	Applications
Piezoelectric Materials	Applied Mechanical Strain	Voltage produced	Tracking devices, keyboards, microphones, *etc.*
Shape Memory Alloys	Temperature Change	Return to original shape	Orthodontic wires, stents, bride structures, *etc.*
Magneto-restrictive Materials	Change in Magnetic Field	Give rise to a voltage	Ultrasonic cleaning devices, underwater sonar, *etc.*
Thermo-chromic Materials	Temperature Change	Colour change	Fashion, home furnishings, food storage, *etc.*
pH-Sensitive Materials	Change in acidity	Colour change	Drug delivery, cancer imagery, *etc.*
Photochromic Materials	Light	Colour change	Optical data storage, eyeglasses, *etc.*

Depending on the temperature, the occurrence of smart materials happens in two stable phases: the material goes from the Austenite phase to Twinned Martensite on cooling, which transforms to Detwinned Martensite when it undergoes applied stress. The material returns to the Austenite phase at high temperatures. During higher temperatures, smart materials exist as Austenite and at low temperatures, they exist as Martensite. Martensite materials are known to have two forms: twinned Martensite and detwinned Martensite. Smart materials remain at a thermodynamically stable phase at a fixed temperature. When temperature varies, smart materials transform between Austenite and Martensite phase, which gives rise to their special properties, like pseudoelasticity and shape memory effect [3].

The material will remain in the Austenite phase under room temperature when the Austenite finish temperature (A_f) is extremely low. In this phase range, it can be observed that the material gets converted to a detwinned Martensite phase when the external stress is applied. On the release of externally applied stress, the material goes back to the Austenite phase [3].

The most useful attribute of smart materials is that they possess the ability to carry out significant alteration of their properties in a restrained manner when exposed to stimuli. Built-in sensors, their control mechanism, and actuators are the components of a smart material that give it the ability to identify an external stimulus, fixedly react to that stimulus, and return to its actual state as soon as the external stimulus gets withdrawn [13]. Smart materials can be classified into various categories.

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Dr. Aavishkar Katti earned his Bachelors and Masters in Physics with a specialization in Lasers and Spectroscopy from University of Delhi (Delhi, India). He then completed his Ph.D in the field of theoretical nonlinear optics from the Banaras Hindu University (Varanasi, India). His doctoral research work was on Optical Solutions in Nonlinear Optical Materials. He has qualified the intensely competitive National Eligibility Test required for a teaching position in India. He joined as Assistant Professor in Department of Physics at Banasthali Vidyapith (Rajasthan, India) in 2017, where he was teaching till April 2021. He is now Assistant Professor at MIT World Peace University (Pune, India). His areas of interest include Nonlinear Optics and Nonlinear Dynamics. He has published in many reputed and indexed journals and has a track record of robust independent research. He has recently authored a research monograph on Optical Solutions which has been published by Springer Nature. Recently, he has been awarded with the Department of Science and Technology, Govt. of India's prestigious Core Research Grant (CRG) of more than 25 lakhs. He is a reviewer for many reputed journals in the field of optics and photonics. He has supervised many students for their Master's dissertation and for their doctorate.

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