



## Dielectric and Semiconducting Photonic Crystals: Optical Response, Absorption Mechanisms and Device Relevance

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### Abstract

Dielectric and semiconducting photonic crystals (PCs) constitute an important class of periodic optical media where the refractive index contrast and periodicity enable strong control over electromagnetic-wave propagation. In such structures, macroscopic optical properties can be effectively described using phenomenological parameters such as refractive index, dielectric permittivity, susceptibility and conductivity, particularly because the optical wavelength is typically much larger than the interatomic spacing. The optical response of dielectric/semiconductor multilayers is primarily governed by light–matter interaction through electronic polarization and absorption due to band-to-band transitions. While dielectrics generally exhibit dominant absorption in the ultraviolet region owing to large band gaps, semiconductors show significant absorption in the visible and near-infrared regime due to comparatively smaller band gaps. By applying Maxwell’s equations and boundary conditions at interfaces, key spectra such as transmittance, reflectance and absorption can be modeled, allowing systematic tuning of photonic band gaps and pass bands. These properties make dielectric–semiconductor PCs suitable for designing frequency-selective filters, reflectors and integrated photonic components, where controlled propagation and attenuation are essential for optical and optoelectronic applications.

**Keywords:** Dielectric photonic crystal; Semiconductor multilayer; Refractive index; Dielectric permittivity; Optical absorption; Band gap; Light–matter interaction; Maxwell boundary conditions

### Introduction

Dielectric and semiconducting photonic crystals represent periodic multilayer structures that exploit refractive-index modulation to tailor the propagation of electromagnetic waves. Unlike bulk materials, these engineered periodic media exhibit photonic band gaps and selective transmission bands, enabling precise frequency filtering and wave control. Since optical wavelengths are usually much larger than atomic spacings, the optical behavior of dielectric and semiconducting thin films can be described using macroscopic parameters such as refractive index (including its complex form), permittivity, susceptibility and conductivity. The interaction of light with these media is strongly influenced by electronic polarization and absorption processes. In dielectrics, large electronic band gaps typically shift absorption into the ultraviolet region, leading to high transparency in the visible range. In contrast, semiconductors possess smaller band gaps, making absorption significant in the visible and near-infrared regions through electron band transitions. Using Maxwell’s equations with appropriate boundary conditions at interfaces, the optical response transmittance, reflectance



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Impact Factor: 6.4

ISSN No: 3049-4176

and absorption can be modeled and optimized. Therefore, dielectric–semiconductor PCs form a foundational platform for photonic devices where spectral selectivity, low-loss propagation and controlled attenuation are required.

Introduction to optics behind photonics

The optics of the materials have been elaborated in this chapter and further, the optics of the photonic have been presented in detail, studying the optical properties of the periodic materials with the simple laws and the concepts of optics. Finally, detailed potential applications of the periodic structure of different materials have been given. The investigated properties of PCs for potential applications of photonics are discussed one by one.

## Optics

Through human vision, the beauty of nature is perceived as a result of the interaction of electromagnetic waves (EMWs), commonly known as light, with matter. When light undergoes processes such as scattering, reflection, refraction, diffraction and absorption, it becomes detectable by the human eye. The interaction of electromagnetic radiation particularly visible and infrared radiation with matter occurs in a relatively simple and well-understood manner, forming the basis of a classical branch of physics known as Optics. Consequently, optical instruments are employed to collect, analyze and interpret information carried by electromagnetic radiation during light–matter interaction. In a broader sense, optics is the scientific study of vision and the behavior of light. The interaction of light with materials is governed by intrinsic optical properties such as optical density and refractive index, which determine how electromagnetic waves propagate through different media. Thus, optics constitutes a major division of physics that focuses on understanding the characteristics and behavior of electromagnetic waves during their interaction with matter. Research in optics plays a crucial role in the design and development of optical instruments and devices. Electromagnetic radiation encompasses a wide spectrum that includes not only visible light and infrared radiation but also radio waves, microwaves and X-rays, all of which exhibit wavelike properties analogous to light [1]. Most optical phenomena can be satisfactorily explained using the classical electromagnetic theory of light, which provides a comprehensive framework for understanding light propagation and interaction mechanisms. In classical optics, wave behavior is broadly categorized into two principal approaches: (i) Geometrical Optics (Ray Optics) and (ii) Physical Optics (Wave Optics). These two frameworks form the foundation for analyzing optical phenomena and are discussed in detail in the following sections.

## Geometrical optics

The propagation of light can be effectively described within the framework of geometrical optics, in which light is represented as traveling along straight-line paths known as rays. When these rays encounter the boundary between two different media, their trajectories are altered according to the laws of reflection and refraction, which govern changes in direction at interfaces. The principles of geometrical optics were empirically recognized as early as 984 AD and have since been extensively applied in the design and development of optical components and instruments such as lenses, mirrors and prisms [2]. The interaction of



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Impact Factor: 6.4

ISSN No: 3049-4176

electromagnetic radiation with matter is unique for every material in the universe and is characterized by its intrinsic optical properties. One of the most important of these properties is the refractive index (RI), also referred to as optical density. The refractive index  $n$  of a medium is defined as the ratio of the speed of light in vacuum  $c$  to the speed of light  $v$  in that medium and is expressed as:  $n = \frac{c}{v}$

This parameter determines how light propagates through a material, influencing phenomena such as bending, slowing down and wavelength change upon entering the medium. Consequently, the refractive index serves as a fundamental optical characteristic that governs light-matter interaction. A central question in classical physics concerned the mechanism by which light propagates through space and media. Early theories postulated the existence of a hypothetical medium known as the luminiferous ether to support light propagation. However, a revolutionary breakthrough occurred in 1864 when James Clerk Maxwell formulated a unified theory of electromagnetism. By synthesizing the experimental and theoretical contributions of scientists such as Coulomb, Ørsted, Ampère and Faraday, Maxwell developed a complete set of equations describing electric and magnetic fields, now known as Maxwell's equations. Upon solving these equations, Maxwell arrived at one of the most profound conclusions in physics: electromagnetic disturbances propagate as waves at a speed equal to that of light. This result led to the identification of light as an electromagnetic wave, marking a milestone in the understanding of electromagnetic radiation and establishing the foundation of classical electromagnetic theory.

## Wave optics

In geometrical optics, light is treated as a collection of rays and wave-related phenomena such as diffraction and interference are not taken into account. In contrast, physical optics (or wave optics) explicitly considers these effects by treating light as a wave phenomenon. Although ray optics provides a simplified description of light propagation, it ultimately emerged from the broader wave theory of light and remains valid under conditions where the wavelength of light is much smaller than the dimensions of the optical system. As discussed earlier, James Clerk Maxwell presented a comprehensive theoretical formulation of electromagnetic waves and provided a mathematical description of their propagation through space and material media. Through this formulation, Maxwell established a fundamental connection between optics and electromagnetism, demonstrating that light is an electromagnetic wave governed by the same laws as electric and magnetic fields [3]. This unification marked a turning point in the understanding of optical phenomena and laid the foundation for modern electromagnetic theory. The optical density, commonly expressed in terms of the refractive index, of a material can be determined using a given set of intrinsic material parameters, such as electric permittivity and magnetic permeability. These parameters collectively define how electromagnetic waves propagate through a medium and influence the speed, direction and behavior of light within the substance.

Here,  $\epsilon_r$  and  $\mu_r$  represent the relative electric permittivity and relative magnetic permeability of the material, respectively. Based on the wave nature of light and the



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A Multidisciplinary Open Access, Peer-Reviewed Refereed Journal

Impact Factor: 6.4

ISSN No: 3049-4176

fundamental laws of reflection and refraction, optical phenomena such as interference, diffraction and polarization can be rigorously described. Among the various optical properties of materials, optical density, commonly expressed through the refractive index, plays a pivotal role in determining light propagation behavior within a medium. A comprehensive understanding of the interaction between light and matter constitutes the subject of optics, which focuses on the optical characteristics of materials. Furthermore, concepts from modern optics are essential for explaining the behavior and transitions of electromagnetic radiation, particularly when classical descriptions are insufficient. Modern optics extends the classical framework by incorporating wave–particle duality and quantum effects, thereby providing a deeper insight into light–matter interactions across different frequency regimes.

## Modern optics

Electromagnetic radiation is exchanged in discrete packets of energy known as photons; consequently, a photon represents the fundamental quantum unit of light or electromagnetic radiation. From a quantum perspective, electromagnetic radiation is quantized into photons, while atoms possess discrete energy levels. Transitions between these energy levels result in the emission or absorption of radiation at specific wavelengths, giving rise to characteristic emission spectra, such as the well-known line spectrum of hydrogen. These processes occur only at particular optical frequencies, highlighting the quantized nature of light–matter interaction. The development of quantum mechanics arose from the non-classical behavior observed when light interacts with matter phenomena that could not be explained using classical physics alone. By the mid-twentieth century, particularly around 1960, the fields of atomic physics and quantum electronics converged, leading to a renewed understanding of light–matter interaction. During this period, quantum mechanics related to optical phenomena was increasingly interpreted as a study of the quantum behavior of matter under electromagnetic excitation rather than light alone. The invention of the laser marked a transformative milestone in optical science, giving rise to the field of quantum optics, which focuses on the quantum properties of light and its interaction with matter. Quantum optics investigates phenomena such as photon statistics, coherence and quantum states of light and has emerged as a major research area in modern physics. It represents a specialized subfield of optical science and finds extensive applications across diverse disciplines, including astronomy, engineering, photography and medicine. Optical principles underpin a wide range of technologies, from traditional devices such as mirrors, lenses, telescopes and microscopes to advanced systems including lasers and optical fiber communication networks [5–7]. The behavior and performance of many of these devices particularly lasers and optical fibers can be effectively analyzed using the concept of periodic structures. Therefore, in the following section, the concept and evolution of periodic structures are discussed in detail.

## Basic introduction of periodic structure

Electromagnetic radiation is exchanged in discrete packets of energy known as photons; therefore, a photon constitutes the fundamental quantum unit of light or electromagnetic radiation. From a quantum-mechanical perspective, electromagnetic radiation is quantized into



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photons, while atoms possess discrete energy levels. Transitions between these energy levels lead to the emission or absorption of radiation at specific wavelengths, resulting in characteristic line spectra, such as the well-known emission spectrum of hydrogen. These processes occur only at particular optical frequencies, underscoring the quantized nature of light–matter interaction. The emergence of quantum mechanics was driven by the non-classical behavior observed in the interaction between light and matter phenomena that could not be explained by classical physics alone. Around 1960, developments in atomic physics and quantum electronics converged, leading to a renewed interpretation of quantum mechanics in which light–matter interactions were increasingly regarded as a study of the quantum behavior of matter under electromagnetic excitation rather than of light itself. Following the invention of the laser and its widespread technological applications, quantum optics emerged as a major area of research concerned with the quantum properties of light and its interaction with matter. Quantum optics applies the principles of quantum mechanics to optical systems and represents one of several important subfields of optical science, with applications spanning astronomy, engineering, photography and medicine.

Parallel to these developments in optics, semiconductor physics underwent a profound transformation with the introduction of silicon-based transistor devices in the 1950s, which revolutionized nearly every aspect of modern technology. Semiconductors form the foundation of the electronics revolution and underpin the vast majority of electronic devices in everyday use. In semiconductor crystals, atoms are arranged in a naturally occurring periodic lattice, giving rise to electronic band structures characterized by allowed and forbidden energy bands. The ability to engineer and tune the forbidden band gaps in semiconductor materials has enabled the development of novel materials and device concepts with tailored electronic and optical properties, thereby driving technological advancement across a wide range of applications. In recent years, scientists have proposed that analogous control could be achieved for photons. To realize complex optical components required for advanced photonic networks, new techniques for manipulating light are essential. This concept is often described as the optical analogue of silicon electronics, namely photonic crystals (PCs) [11]. The analogy between the behavior of electrons in periodic semiconductor lattices and photons in periodically structured dielectric media was first articulated by Eli Yablonovitch [11] and Sajeev John [12], who demonstrated that structural periodicity plays a crucial role in determining electromagnetic properties. Yablonovitch introduced the concept of a photonic band gap to control spontaneous and stimulated emission of light in three-dimensional periodic dielectric structures. As a result of these foundational studies, the concept of photonic crystals has become an integral part of modern optics. The existence and properties of photonic band gaps, which form the basis of photonic crystal behavior, are discussed in detail in the following section.

## Photonic Crystal

In photonic crystals (PCs), the absorption and modulation of low-frequency electromagnetic waves can be significantly enhanced due to their periodic dielectric structure, which enables

strong coupling with electromagnetic radiation. These structures are typically composed of multiple layers of different dielectric materials, each characterized by its own optical constants, such as refractive index and permittivity. When electromagnetic waves propagate through such layered media, strong interactions arise from the interference of light reflected and refracted at the internal interfaces. The superposition of these multiple reflected and transmitted waves leads to either constructive or destructive interference, depending on their relative phases. This interference behavior is governed by parameters such as the angle of incidence, relative refractive index contrast, layer thickness and the geometrical arrangement of the periodic structure, all of which are comparable to the wavelength of the propagating light. By appropriately designing these structural parameters, it is possible to restrict light propagation to a very narrow frequency range in which electromagnetic waves are strongly attenuated or completely inhibited. As a result, a specific range of frequencies emerges in which light propagation is forbidden, known as the photonic band gap (PBG). This forbidden bandwidth arises due to Bragg scattering in the periodic dielectric medium and represents a defining characteristic of photonic crystals [13, 14].

As discussed earlier, several natural biological materials exhibit structural features analogous to photonic crystals (PCs). In nature, microscopic periodic structures are commonly found in animal skins, furs and insect wings, where they interact with light to produce vivid structural colors. A well-known example is the iridescence observed in butterfly wings, where the perceived color changes from green to blue as the viewing angle varies. This color variation does not arise from pigments but from periodic nanostructures that selectively reflect specific wavelengths of light through constructive and destructive interference. Another prominent natural example is opal gemstones, which display striking iridescent colors due to the periodic arrangement of silica spheres within their structure. These ordered silica particles form a natural three-dimensional photonic crystal, causing wavelength-selective diffraction of visible light. Such naturally occurring photonic structures clearly demonstrate how periodic architectures can manipulate electromagnetic waves, reinforcing the relevance of photonic crystal concepts in both natural systems and engineered optical materials.

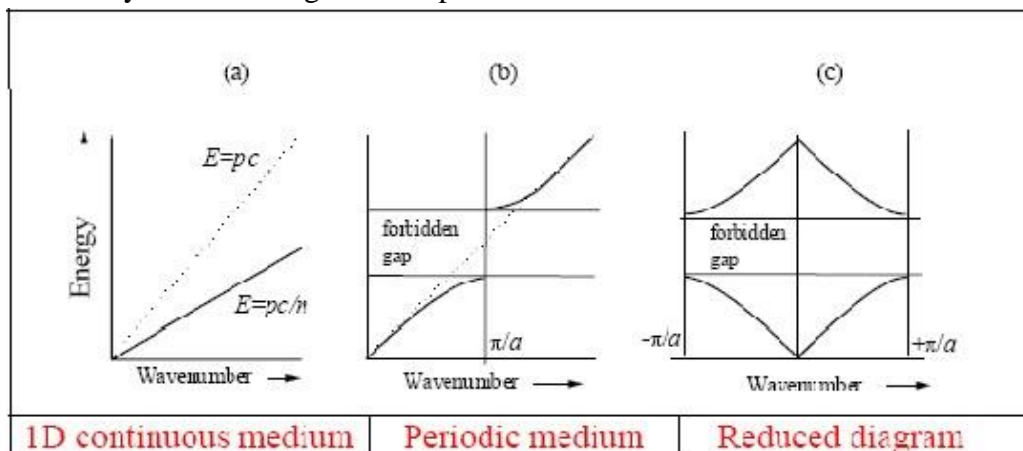


Figure 1: Photonic band structure in 1-D and Brillouin zones for EMWs [13, 14]



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A Multidisciplinary Open Access, Peer-Reviewed Refereed Journal

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ISSN No: 3049-4176

Electromagnetic waves can be effectively controlled using periodic structures, as such structures exhibit pronounced band gap properties, commonly referred to as photonic band gaps (PBGs). The position and width of the PBG are highly sensitive to the structural and material parameters of the system, including refractive index contrast, lattice periodicity and layer thickness. By appropriately tuning these material and geometrical parameters, the photonic band gap can be precisely engineered to achieve the desired optical response. In the following section, the physical mechanism responsible for the formation of the photonic band gap is discussed in detail.

## Origin of the PBG

Unlike an atomic system, a PC does not maintain its symmetry. They exhibit discrete

$$\epsilon(\mathbf{r}) = \epsilon(\mathbf{r} + \mathbf{R})$$

translational symmetry. These crystals are invariant only with respect to translations of extraordinary step lengths instead of by any distance. Since this symmetry is present, this basic step length is referred to as the lattice constant and the fundamental lattice vector, respectively.

$$\epsilon(\mathbf{r}) = \epsilon(\mathbf{r} + \mathbf{R})$$

Repeat this translation and we can see that.

For all  $\mathbf{R}$ , integer multiples of  $\mathbf{a}$ . Unit cells are the smallest crystals. ~ We have observed EMW in a similar way with the single layer without any band, as shown in Figure 1.3(a).

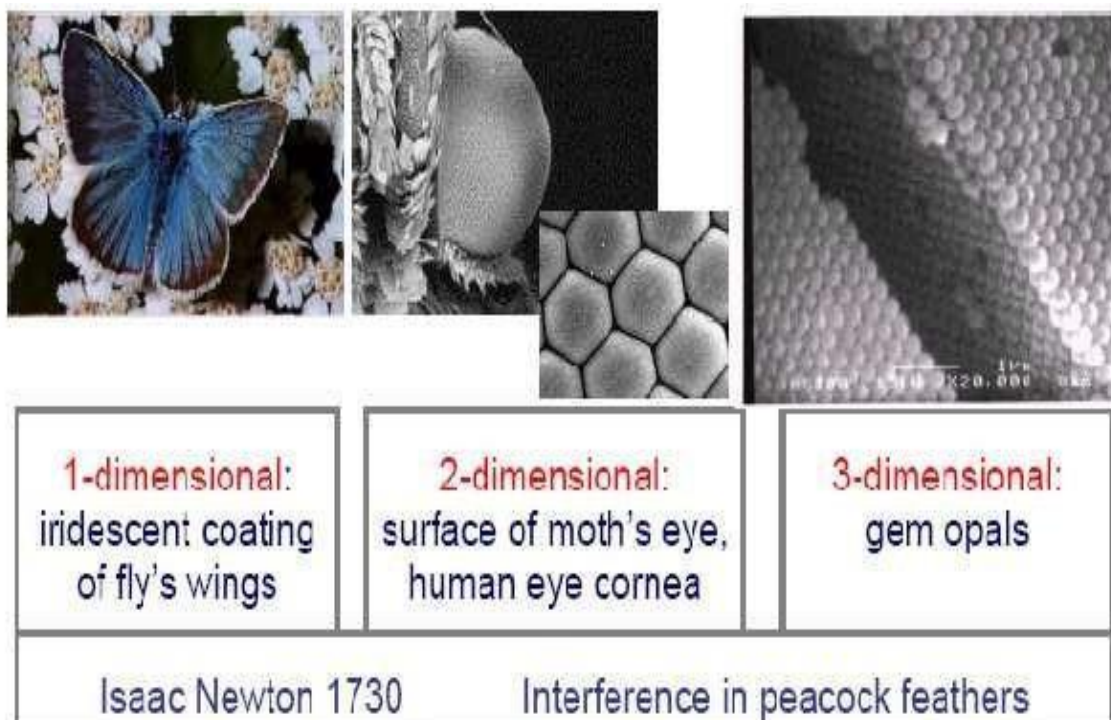


Figure 2: Natural PCs [13, 14]

Similarly, when an electromagnetic wave is incident on a periodic structure, partial reflection and transmission occur at each interface between the constituent layers. The multiple reflected

and transmitted waves undergo interference, leading to the formation of surface and standing wave patterns at the interfaces. This interference phenomenon can prohibit the propagation of electromagnetic waves within a specific frequency range, resulting in the formation of a photonic band gap (PBG), as illustrated in Figure 1.3(b). Within the PBG region, the electromagnetic field intensity is strongly suppressed inside the structure, giving rise to ultralow transmission. Conversely, at the surface or near the band-edge frequencies, localized surface waves with enhanced field intensity may appear. These surface modes exhibit distinct phase characteristics, as shown in Figure 1.3(c), where high-intensity surface waves are observed while propagation within the bulk of the structure remains forbidden.

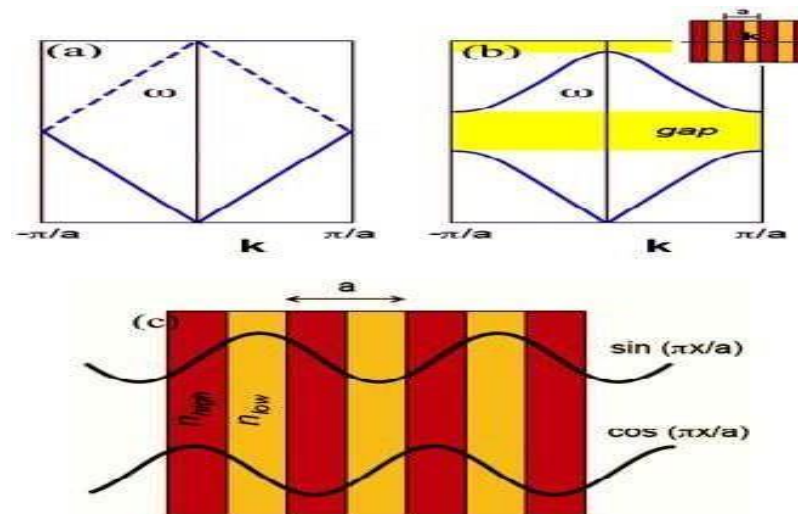


Figure 3 illustrates three characteristic cases of light propagation in a one-dimensional periodic structure: (a) absence of a band gap, (b) presence of a photonic band gap (PBG) and (c) propagation behavior of light within a 1-D periodic medium. By numerically solving the Master Equation (1.4b) for all wave vectors  $k$  within the first Brillouin zone, an infinite set of eigenmodes is obtained, each labeled by a band index  $n$  and associated with discrete, regularly spaced frequencies. This solution enables a complete characterization of the periodic structure in terms of its photonic band gaps, where the allowed modes form continuous bands as the frequency increases, separated by forbidden frequency regions. The procedures used to analyze such frequency–wave-vector relationships are collectively referred to as band-structure calculations [65, 68]. The resulting band structure provides fundamental insight into the optical properties of a photonic crystal. As shown schematically in Figure 2(a), the band structure of a one-dimensional photonic crystal exhibits a conceptual analogy to the frequency-dependent reflection characteristics of the structure. In subsequent chapters, the reflectance, transmittance and absorption spectra of one-dimensional periodic structures (photonic crystals) are analyzed using the Transfer Matrix Method (TMM). A strong analogy exists between the behavior of electrons in crystalline solids and photons in photonic crystals, as illustrated in Figure 1.4. Free electrons in space exhibit a continuous, gapless energy–momentum dispersion relation.

However, when electrons are subjected to a one-dimensional periodic potential, their energy spectrum becomes gapped, resulting in allowed energy bands and forbidden band gaps. Electrons with energies lying within the band gaps become localized and do not propagate, whereas those with energies within allowed bands can propagate through the crystal. In a similar manner, photons propagating in a one-dimensional periodic dielectric medium experience forbidden frequency ranges photonic band gaps within which electromagnetic wave propagation is prohibited. Frequencies lying outside these gaps correspond to allowed photonic bands. Despite this strong analogy, an important distinction exists between electrons and photons: electrons are described by scalar wave functions, whereas photons are vector electromagnetic waves. Consequently, polarization effects play a crucial role in photonic systems and cannot be neglected in the analysis of photonic crystals.

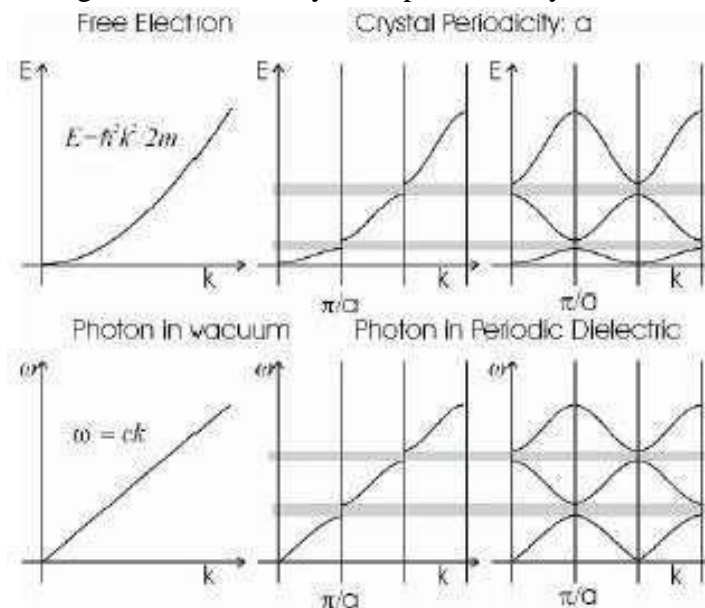


Figure 4: Energy dispersion relations for free electrons and electrons in 1-D solids [14]. Thus, periodic structures composed of materials with a high refractive index contrast exhibit pronounced photonic band gaps (PBGs), enabling effective manipulation and control of photons within such media. In the following section, periodic materials are classified according to their structural dimensionality into one-dimensional (1-D), two-dimensional (2-D) and three-dimensional (3-D) photonic structures.

## Types of PC

PCs are divided into 1-D, 2-D and 3-D crystals according to the dimension of the multilayer.

### 1-D PC

A one-dimensional photonic crystal (1-D PC) is formed by varying the dielectric constant in only one spatial direction, as illustrated in Figure 1.5 [8]. In such structures, layers of alternating low- and high-refractive-index materials are periodically stacked with different thicknesses, creating a refractive-index modulation along a single axis. This simple periodic

arrangement leads to the formation of a photonic band gap for electromagnetic waves propagating normal to the layers. One-dimensional photonic crystals are relatively easy to fabricate and cost-effective over a wide and useful wavelength range, making them particularly attractive for practical applications. Typical applications of 1-D PCs include microwave antenna substrates, frequency-selective and directional filters, omnidirectional high-reflectivity mirrors and waveguide enclosure coatings. The specific functionality and performance of these devices depend on factors such as the periodic structure, material properties and the operating frequency region [15, 16].

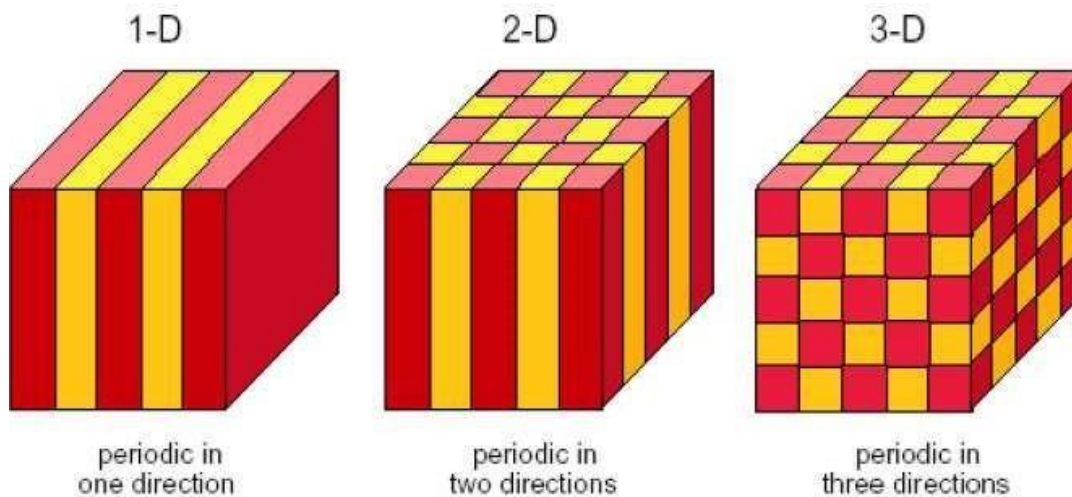


Figure 5: Conceptual schematic of periodic PCs in one, two and three dimensions, showing crystal material structure regularity.

## 2-D PC

In two-dimensional photonic crystals (2-D PCs), the dielectric constants are periodically modulated in two spatial directions, while the structure remains invariant (or effectively infinite) in the third direction. As a result, electromagnetic wave propagation can be confined and guided within the two-dimensional plane. Figure 1.5 illustrates typical two-dimensional lattice configurations, which can be realized in a variety of geometries and material systems. Compared to three-dimensional dielectric arrays, 2-D photonic crystals are considerably easier to fabricate, making them attractive for both experimental studies and practical applications. Two-dimensional photonic systems also provide a convenient platform for investigating fundamental optical phenomena, such as Anderson localization of light, where wave transport is suppressed due to disorder-induced interference effects [17]. In a 2-D dielectric array, electromagnetic wave dispersion within the plane exhibits distinct characteristics for different polarization states. Specifically, transverse electric (TE) and transverse magnetic (TM) modes display markedly different dispersion relations, where the electric field is oriented parallel and perpendicular to the plane of periodicity, respectively [18]. Consequently, for a given frequency range, it is possible that electromagnetic wave propagation is prohibited for one



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Impact Factor: 6.4

ISSN No: 3049-4176

polarization while remaining allowed for the other. This polarization dependence implies that, for all propagation directions and polarizations, a frequency region may not completely suppress electromagnetic wave transmission. As a result, the formation of a complete photonic band gap in two-dimensional photonic crystals is less common, since band-gap conditions for different polarizations do not generally coincide.

### 3-D PC

This behavior arises because, in three-dimensional photonic band gap (3-D PBG) structures, the refractive index modulation is periodic in all three spatial directions. Such fully periodic dielectric architectures are capable of completely suppressing the spontaneous emission of light from atoms, molecules and other electromagnetic excitations within specific frequency ranges. In addition, these structures can localize electromagnetic modes, effectively confining electromagnetic energy within the crystal. Feedback effects resulting from this strong light-matter interaction have profound implications for laser operation, including modified emission rates and threshold behavior. In three-dimensional photonic crystals, such as inverse opal structures, conventional linear light propagation is forbidden over certain frequency intervals corresponding to the photonic band gap [19, 20]. This complete inhibition of propagation distinguishes 3-D photonic crystals from their lower-dimensional counterparts and enables unprecedented control over electromagnetic waves. Photonic crystals derive their unique properties from the periodic arrangement of constituent materials, rather than from the intrinsic characteristics of the materials alone. Consequently, the overall optical response of the system must be interpreted as a collective property of the crystal structure itself. These structural effects govern the electromagnetic behavior of photonic crystals and form the basis for the optical properties discussed in the following section.

### Properties of PCs

Several parameters on which the optical features of PC depend are: RI

contrast

The ratio of the high electric constant materials to those of the low electric constant materials is it.

Lattice parameter (a)

The lattice parameter represents the characteristic spacing between the periodically repeated units of a structure. In photonic crystals, the operating wavelength range is primarily determined by this lattice parameter, as it sets the fundamental length scale for electromagnetic wave interaction with the periodic medium. As illustrated in Figure 1, the wavelength range over which a photonic crystal functions can be tuned by adjusting the lattice constant. In addition to this structural parameter, another key mechanism governing photonic crystal behavior is its unique property known as the photonic band gap (PBG), which defines frequency ranges in which light propagation is forbidden. Filling fraction (f)



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Impact Factor: 6.4

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Density is defined as the ratio of the actual (solid) volume of material to the total volume of the composite structure. For example, in a composite system such as a multi-service geosynthetic, density represents the fraction of the total composite volume occupied by the constituent material relative to the overall volume of the roll or assembly. When a composite is formed from two different materials, the resulting structure exhibits modified physical and optical characteristics. In such composite systems, variations in material composition lead to changes in optical density or refractive index (RI), which in turn influence the effective optical parameters of the structure. These parameters are governed by the relative volume fractions and intrinsic properties of the constituent materials and they play a crucial role in determining the overall optical response of the composite medium.

## **Symmetry of the structure**

The symmetry of a lattice is determined by the spatial arrangement of the fundamental building elements of a photonic crystal (PC). Lattice symmetry plays a crucial role in defining the structural and optical characteristics of the crystal, as it governs the allowed modes of wave propagation. By analyzing the symmetry properties of a periodic structure, one can identify high-symmetry points, as well as locate and characterize defects within the lattice. These features significantly influence the photonic band structure and the overall electromagnetic behavior of the photonic crystal.

## **Topology**

Finally, the photonic band gap can be modified by interpenetrating or isolated structural topologies within photonic crystals. This fundamental concept of topology in photonic crystal design was originally proposed and discussed by Economou [20] and Sigalas [20]. Their work provided a foundational theoretical framework for understanding how different lattice topologies influence the formation and control of photonic band gaps, thereby offering critical insight into the structural origins of PBG behavior in periodic dielectric systems.

## **Scalability**

This approach alters the size, shape and arrangement of the fundamental building blocks within the electromagnetic regime, leading to the formation of tailored periodic structures. The concept of building-block engineering plays a crucial role in determining the electromagnetic response of such systems. The study of photonic crystals (PCs) and their associated properties is fundamentally based on the analysis of photonic band-structure materials. The optical and electromagnetic characteristics of these periodic structures arise from their band-gap behavior and dispersion relations. In the following chapter, these properties are systematically reviewed with particular emphasis on one-dimensional photonic crystals (1-D PCs).

## **Literature survey**

There has been significant and sustained interest in photonic crystal (PC) research since the seminal papers published in 1987 [11, 12]. The steadily increasing number of publications in this field clearly indicates that photonic crystal research continues to expand and evolve, with



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ISSN No: 3049-4176

no evidence of saturation at present. In this context, a brief overview of the various dielectric, metallic and composite materials employed in the design and fabrication of photonic crystals is presented. Thus far, the discussion has focused on the interaction of light with structured dielectric media. Early experimental observations of such interactions were made using colloidal particles with lattice constants comparable to the wavelength of visible light, typically around 500 nm [21]. Initially, the observed optical response was attributed to Bragg reflection of visible light, which was later recognized as a manifestation of periodic dielectric ordering. These observations motivated Ohtaka [22] to develop a dynamic theory of diffraction of visible and ultraviolet light using a three-dimensional periodic dielectric array. Unlike earlier scalar approximations, Ohtaka employed the full vectorial nature of electromagnetic waves, drawing conceptual inspiration from electronic band theory in semiconductors. Despite its theoretical depth, this work received limited recognition at the time, although its modeling approach later influenced numerical band-structure calculations.

A major breakthrough occurred in 1987, when two landmark papers appeared in the same issue of *Physical Review Letters*. In the first, Eli Yablonovitch [11] proposed the use of threedimensional periodic dielectric structures to suppress spontaneous emission, introducing the concept of a photonic band gap (PBG) a forbidden frequency region for photons analogous to electronic band gaps. In the second paper, Sajeev John [12] explored Anderson localization of photons in disordered dielectric superlattices [23], demonstrating that electromagnetic radiation could be spatially confined due to multiple scattering. These two publications are widely regarded as the foundational origins of photonic crystal and PBG materials research. In 1989, John [24] further demonstrated that a complete photonic band gap could exist in a facecentered cubic (fcc) lattice between the second and third photonic bands. The year **1990** marked a pivotal period in photonic crystal research. Satpathy et al. [25] and Leung et al. [26] were among the first to apply the plane-wave expansion method, initially using scalar approximations, to calculate photonic band structures. Subsequently, strong agreement between theoretical predictions and experimental observations was demonstrated [27], prompting notable commentary in *Nature* regarding the maturation of the field. However, for fcc lattices composed of spherical inclusions, Ho et al. [28] showed that a complete PBG was absent. This limitation was overcome in later work by Yablonovitch et al. [29], who demonstrated a complete photonic band gap in an fcc lattice with non-spherical inclusions, a structure later referred to as Yablonovite. Further advances were achieved by Sözüer et al. [30], who extended plane-wave methods to investigate higher photonic bands, demonstrating a complete PBG between the eighth and ninth bands in an fcc lattice of air holes embedded in a semiconductor. In 1994, a full photonic band gap between the second and third bands was experimentally realized using a layer-by-layer woodpile structure with diamond symmetry. By the end of that year, a Yablonovite structure optimized for microwave frequencies had been successfully fabricated.



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Between 1997 and 1999, rapid experimental progress continued. Velev et al. [33] produced the first inverse opal photonic crystal, while Lin et al. [34] demonstrated strong scattering of photons near photonic band-edge frequencies in two-dimensional photonic crystals. Kosaka et al. [35] explained experimentally observed anomalous dispersion phenomena using group velocity analysis. In 1999, Fleming and Lin [36] demonstrated a near-infrared photonic crystal-based device and Noda et al. [37] fabricated an eight-layer photonic crystal using wafer fusion techniques. Synthetic opals with controlled periodicity were reported shortly thereafter [38], followed by the demonstration of a silicon inverse opal photonic crystal by Painter et al. [39].

More recent developments in photonic crystal research have focused on negative-index materials and metamaterials. In 1999, John Pendry [40] theoretically demonstrated that metallic structures incorporating split-ring resonators (SRRs) could exhibit a negative effective refractive index. This prediction was experimentally confirmed by Shelby et al. [41], who observed negative refraction in a composite medium consisting of SRRs and metallic wire arrays. Pendry later proposed the concept of a perfect lens based on negative-index materials [42]. Subsequent studies showed that photonic crystals can also exhibit negative refraction [43]. In 2003, Li et al. [44] introduced a novel photonic band gap formed by alternating layers of positive-index and negative-index materials. Panoiu et al. [45] demonstrated a periodic lattice of metallic rods embedded in positive-index materials, exhibiting both a photonic band gap and a negative effective refractive index. Experimental validation of low-loss superconducting photonic structures was provided by Ricci et al. [46], while Pimenov et al. [47] demonstrated negative refraction at millimeter-wave frequencies in ferromagnetic superconducting superlattices. Recent theoretical investigations have further explored exciton–photon coupling in one-dimensional photonic crystals composed of alternating dielectric slabs. These studies revealed that the lower branch of the exciton-polariton spectrum splits into multiple bands separated by small band gaps [48]. Classical electrodynamics has also been employed to study spontaneous emission from atoms embedded in one-dimensional photonic crystals, revealing oscillatory emission spectra that follow the photonic band structure [49]. Additional work has shown that dielectric slabs can self-organize into stable photonic crystals through light-induced optical binding [50]. Theoretical models describing electromagnetic wave propagation in axially symmetric multilayer periodic mirrors composed of resonant absorbing atoms have also been developed, including analyses of dissipative effects [51]. Finally, the evolution of nonlinear modes in one-dimensional periodic structures has been investigated using finite-difference methods and Floquet–Bloch theory, with numerical results demonstrating strong agreement with experimental observations [52].

Several studies have focused on the analysis of the Electromagnetic Density of Modes (EDOM) in one-dimensional photonic crystals (1-D PCs) for both electric (TE) and magnetic (TM) polarizations. In particular, two computational approaches were proposed and examined, one



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ISSN No: 3049-4176

of which employed EDOM to achieve population inversion for controlling and directing the emission of higher-frequency radiation sources, such as X-rays [53]. In these investigations, the Transfer Matrix Method (TMM) was commonly used to calculate the photonic band structure, as well as the reflection and transmission coefficients of the periodic structures. The governing equations of the photonic structures were solved to identify the presence of photonic band gaps, using an approach analogous to the Kronig–Penney model developed for electronic band structures [54]. In related work, Maxwell’s equations were solved analytically using eigenmode analysis for empty-lattice configurations, yielding compact expressions for wave transmittance and enabling the determination of waveguide-mode excitation efficiency [55]. Using relatively simple analytical formulations, band-gap positions were calculated and this framework was further extended to determine band-gap edges for an infinite number of gaps at arbitrary incidence angles for both polarizations, facilitating photonic crystal device design [56]. The influence of polarization and oblique incidence was incorporated through the concepts of effective optical width and excitonic receptivity in quantum well systems [57]. The TMM has also been extensively applied to study electromagnetic wave propagation in onedimensional metal–dielectric photonic crystals (1-D MDPCs), accounting for parameters such as electron density, metal layer thickness, metal type and plasma frequency [58]. Resonant mode splitting in nanometal–dielectric multilayer structures was analyzed using the same approach [59]. Furthermore, theoretical investigations were conducted on the transmission of terahertz (THz) electromagnetic waves in one-dimensional superconducting metal–dielectric superlattices [60], as well as on the optical characteristics of multilayer structures composed of superconducting and dielectric films [61]. Multi-channel transmission filters operating in the THz range within the photonic pass band were realized and at low temperatures, these structures exhibited comb-like resonance peaks in their transmission spectra [62]. It was also shown that ternary metal–dielectric photonic crystals exhibit significantly wider photonic band gaps than binary all-dielectric structures. These theoretical investigations were predominantly based on the TMM combined with the Drude model for metals [63]. The spectral properties of defect modes in one-dimensional imperfect periodic structures have also been extensively studied. In particular, symmetric and asymmetric stacking of two defective photonic crystals for TE and TM polarizations was analyzed [64]. Subsequent work employed the characteristic matrix method to investigate a one-dimensional lossy symmetric defective plasma photonic crystal, incorporating two defect layers composed of magnetized cold plasma and examined its optical response [65]. Additional theoretical studies explored tunable photonic band structures in plasma photonic crystals, where an externally applied static magnetic field modified the bulk cold-plasma layers.

Researchers have further investigated electromagnetic wave propagation in 1-D lossy photonic crystals with central defect layers, composed of alternating positive- and negative-refractiveindex materials, arranged in both symmetric and asymmetric geometries [67]. The



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Impact Factor: 6.4

ISSN No: 3049-4176

transmittance properties of one-dimensional superconductor–dielectric photonic crystals, with particular emphasis on cutoff frequency behavior, were also examined [68]. Two-fluid plasma models were applied to study transmission characteristics and the optical response of 1-D photonic crystals composed of low-temperature superconductors (NbN) and double-negative metamaterial layers was reported [69].

The transmission properties of dielectric–semiconductor metamaterial photonic crystals in the THz band were theoretically evaluated, revealing strong dependence of cutoff frequencies and filling factors on layer thicknesses [70]. One-dimensional photonic crystals incorporating nanocomposite defect layers were investigated for infrared transmission applications, demonstrating suitability for narrow-band filtering and optoelectronic devices [71]. However, it was found that the electric permittivity of defect modes in semiconductor-doped magnetized cold-plasma structures exhibits polarization-dependent shifts, particularly for TM waves [72]. Recent studies have examined single transmission modes within the reflection bands of symmetric defective 1-D photonic crystals composed of double-negative metamaterials and high-temperature superconductors, showing that mode characteristics depend strongly on defect-layer thickness [73]. Additionally, the filtering behavior of multi-channel onedimensional magnetized plasma photonic crystals was analyzed under applied microwave magnetic fields. In such structures, an external magnetic field caused either blue-shifts or redshifts in channel frequencies depending on its orientation [74].

Resonant absorption phenomena in defective one-dimensional superconducting photonic crystals at THz frequencies were also theoretically investigated [75]. Further TMM-based analyses of microwave transmission in defective photonic crystals, where magnetized plasma acted as the defect layer, revealed pronounced defect peaks within the photonic band gap [76]. These results demonstrate that such engineered one-dimensional photonic crystal structures provide a robust platform for a wide range of microwave and terahertz applications. Onedimensional photonic crystal (1-D PC) structures have been successfully demonstrated for biosensing applications, including the development of highly sensitive photonic biosensors. In particular, photonic crystals incorporating intentional defect layers have been employed for the detection of cancer cells. Most contemporary photonic biosensors operate on the principle that variations in the refractive index of the analyte induce measurable shifts in the transmission or reflection spectra of the photonic structure [77]. In terms of sensitivity and precision, photonic sensing technologies are regarded as superior to many conventional biosensing approaches. For biomedical applications, a specific 1-D defective photonic crystal configuration has been analyzed and proposed for use as a blood glucose biosensor, inspired by the concept of a layered retinal structure with a controlled defect region. The proposed structure is  $\text{Air}/(\text{SiO}_2/\text{Si})_5/\text{SiO}_2/\text{D}/\text{SiO}_2/(\text{SiO}_2/\text{Si})_5/\text{SiO}_2$  with a  $\text{SiO}_2$  substrate, where the defect layer (D) is filled with multiple layers of blood glucose solution at different concentrations. The Transmission Matrix Method (TMM) was employed to numerically calculate the transmission



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Impact Factor: 6.4

ISSN No: 3049-4176

spectra of the structure. The results demonstrated that variations in glucose concentration lead to distinct spectral shifts, indicating that the proposed design exhibits enhanced sensing performance compared to several previously reported glucose sensors [78].

In addition to biosensing, the ultraviolet (UV) transmission characteristics of one-dimensional metal–dielectric photonic crystals have also been investigated. Owing to the extremely narrow pass-band filtering behavior required for operation as a multilayer Fabry–Pérot resonator in the short-wavelength UV region, the incorporation of a defect layer within the periodic structure was found to be impractical for this application [79]. Based on the comprehensive literature review, the selection of suitable materials for the present study on photonic band gaps (PBGs) in one-dimensional photonic crystals can be justified. Previous investigations have extensively explored binary and ternary 1-D PC configurations, including dielectric–dielectric, dielectric–metal, dielectric–plasma, superconductor-based and metamaterial-assisted periodic structures. These studies provide a strong foundation for the choice of materials and structural parameters adopted in the present work.

## Dielectric and semiconducting PC

Dielectric and semiconducting photonic crystals (PCs) are commonly referred to as dielectric and semiconducting periodic structures. In these materials, strong ionic and covalent bonding leads to thin films that exhibit either dielectric or semiconducting behavior. Depending on their electronic structure, such materials may be transparent or opaque to specific wavelength ranges, typically allowing transmission in the visible and infrared regions while blocking others. The interaction of electromagnetic waves with these films can be rigorously analyzed by applying appropriate boundary conditions to Maxwell's equations at the interfaces between different media. For microscopic systems, the wavelength of light is generally much larger than the interatomic spacing in the direction of optical layering. This scale separation allows the definition of macroscopic optical properties, enabling light–matter interaction to be described using phenomenological parameters, commonly known as optical constants. These include the refractive index, dielectric constant, dielectric susceptibility and electrical conductivity. When the refractive index is complex, the optical constants include an imaginary component that accounts for optical absorption. The attenuation coefficient, which quantifies the decay of light intensity with propagation distance, is directly related to the imaginary part of the refractive index, while the real part describes the reduction of light velocity in the medium relative to vacuum. Using Maxwell's equations, frequency-dependent optical constants can be related to other material properties such as the dielectric constant and electrical conductivity. Periodic materials consist of atoms, slow ions, impurities and other charged particles including bound and conduction electrons whose motion under an applied electric field gives rise to polarization effects. At visible and infrared frequencies, polarization is primarily due to induced dipole moments arising from the displacement of electron clouds. For isotropic materials, three scalar quantities are sufficient to characterize their optical behavior: the dielectric constant, dielectric



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Impact Factor: 6.4

ISSN No: 3049-4176

susceptibility and electrical conductivity. Dielectric and semiconducting coating materials are typically non-magnetic, as they lack unpaired free charges that could generate intrinsic magnetic responses [101]. In these materials, the dominant absorption mechanism is the interaction of light with electrons [102–104]. Incident photons may be absorbed if their energy is sufficient to excite electrons either from bound atomic states or into conduction states. A material remains transparent when the photon energy is lower than the required excitation energy. In non-metallic solids, this excitation threshold is determined by the energy band gap, defined as the energy difference between the highest occupied valence band and the lowest unoccupied conduction band. Electronic band-to-band transitions constitute the primary source of optical absorption in solids. In materials such as glass, quartz, diamond, metal oxides, salts and many polymers, valence electrons are strongly bound and do not exhibit excitation resonances in the visible range, resulting in transparency below the band-gap energy. Metals, on the other hand, contain free electrons that lead to strong reflection and high optical absorption, making them suitable for mirrors and reflective coatings. Semiconductors exhibit optical properties intermediate between those of metals and insulators. In general, dielectrics show dominant absorption in the ultraviolet region, whereas semiconductors exhibit significant absorption in the visible and near-infrared ranges [101].

## Conclusion

In summary, dielectric and semiconducting photonic crystals provide a robust framework for manipulating electromagnetic-wave propagation through periodic refractive-index modulation. Their optical behavior can be effectively captured via macroscopic optical constants and the dominant absorption mechanisms are primarily governed by electronic transitions and polarization effects. The contrast between dielectrics (typically UV absorption) and semiconductors (visible/NIR absorption) offers practical flexibility in choosing materials for specific wavelength bands. By leveraging Maxwell-based modeling and interface boundary conditions, one can design multilayer PCs with tailored photonic band gaps and engineered transmission windows. Consequently, dielectric–semiconductor PCs are highly relevant for optoelectronic and photonic applications, including narrowband/broadband filters, reflective structures, sensing platforms and integrated photonic components, where controllable spectral performance is essential.

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