A Review of the Development History, Basic Characteristics and Research Status of Photonic Crystals

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ABSTRACT

A photonic crystal is a type of artificial micro-structured material with periodic dielectric structure. Since it was formally proposed by Yablonovitch and John in 1987, it has developed into a frontier field that intersects multiple disciplines such as condensed matter physics, optoelectronics, and nanotechnology. This article systematically reviews the development process of photonic crystals from its early theoretical inception, concept proposal to experimental fabrication. It elaborates on the basic characteristics such as photonic band gap, photonic localization, spontaneous radiation control, and photonic wires. It also focuses on summarizing the current research status and application progress of topological photonic crystals, photonic crystal fibers, hollow-core fibers, and sensor devices. Finally, it looks forward to the future development trends.

Keywords: Photonic Crystal; Photonic Band Gap; Topological Photonics.

1. INTRODUCTION

Photonic crystals, as a type of artificial microstructure material with periodic dielectric structure, have become a forefront research hotspot in multiple interdisciplinary fields such as condensed matter physics, optoelectronics, nanotechnology, and electromagnetic field theory since they were formally proposed in 1987 [1]. Through the periodic arrangement of dielectric constants in space, they cause Bragg scattering of light waves, thereby forming photonic bandgap structures that prevent light with specific frequency ranges from propagating within them. This characteristic is similar to the electron bandgap in semiconductor crystals in regulating the behavior of charge carriers, and thus photonic crystals have been praised by the scientific community and the industry as “optical semiconductors” or “the semiconductor of the future”, carrying high expectations for triggering the photonic technology revolution in the 21st century. The American Physical Society has even designated photonic crystals as a milestone development achievement in physics, demonstrating its dual value in basic science and technological applications [2]. This article will conduct a systematic review of photonic crystals from four dimensions: development history, basic characteristics, research status, and application prospects.

2. THE DEVELOPMENT HISTORY OF PHOTONIC CRYSTALS

2.1 Early Exploration and Theoretical Birth

The idea of photonic crystals can be traced back to the late 19th century. In 1887, Lord Rayleigh, a British physicist, conducted pioneering experimental research on multi-layer periodic dielectric stacks and discovered that this structure has a one-dimensional photonic band gap, meaning it has a very high reflectivity for waves within a certain wavelength range. This discovery laid the foundation for the study of one-dimensional photonic crystals, and its structure was later widely applied in Bragg reflectors, high-reflection films, and other fields [3]. In 1971, Soviet physicist Vladimir P. Bykov conducted the first systematic study of the phenomenon of spontaneous emission of atoms and molecules embedded in photonic crystals being affected by the photonic band gap, and prospectively speculated on the regulatory effect of two-dimensional and three-dimensional photonic crystals on spontaneous emission [4]. However, due to the lack of a systematic theoretical framework at that time, these studies did not attract much attention from the academic community. In 1979, Ohtaka further discussed the concept of three-dimensional photonic crystals and developed a method for calculating the photonic band structure, providing an important methodological basis for subsequent research. Ghadarghadr et al. emphasized in reviewing the early theoretical development of photonic crystals that the energy band calculation methods accumulated during this stage provided indispensable theoretical tools for the conceptual breakthrough in 1987 [5].

2.2 The Formal Proposal of the Photonic Crystal Concept

1987 was a milestone year in the history of photonic crystal development. Eli Yablonovitch from Bell Laboratories in the United States and Sajeev John from Princeton University independently published two landmark papers in "Physical Review Letters", respectively proposing the new concept of "photonic crystal" [6]. Yablonovitch's research started from changing the photon density of states to control the spontaneous emission embedded in the photonic crystal material, with the core goal being to regulate the interaction between matter and light. John's research focused on using photonic crystals to control the localization and propagation behavior of light, exploring the strong localization phenomenon of photons in disordered dielectric superlattices. These two papers jointly revealed the profound regulatory ability of high-dimensional periodic optical structures on the behavior of photons, marking the official birth of photonic crystals as an independent research field. Since then, the number of academic papers on photonic crystals has shown a geometric growth trend, and the research scope has rapidly expanded from theory to microwave, acoustic, and optical wavebands.

2.3 Experimental Preparation and Technological Breakthroughs

After the concept was proposed, the experimental preparation of photonic crystals underwent a process of gradually advancing from the microwave frequency band to the optical frequency band. Due to the scale invariance of electromagnetic waves, the solutions of Maxwell's equations do not contain natural length scales, so microwave structures of the order of centimeters are physically equivalent to optical structures of the order of nanometers. In 1991, Yablonovitch successfully fabricated the first photonic crystal with a three-dimensional photonic band gap in the microwave range, its structure being an anti-diamond structure formed by drilling holes on transparent materials and layer-by-layer stacking, later named "Yablonovite" structure. In 1996, Thomas Krauss et al. using existing semiconductor industrial technology successfully fabricated the world's first two-dimensional photonic crystal in optical size, opening up a new path of using semiconductor processes to manufacture photonic crystals. This breakthrough made it possible for photonic crystals to move from the laboratory to industrialization. In 1998, Philip Russell fabricated the first photonic crystal fiber, showing many superior characteristics compared to traditional fibers. Since the beginning of the 21st century, the preparation of three-dimensional photonic crystals has also made significant progress. Researchers have developed various preparation methods such as layer-by-layer assembly and self-assembly, forming three-dimensional regular structures through the self-assembly of nano-sized microspheres, gradually overcoming the bottleneck of the high difficulty in manufacturing three-dimensional photonic crystals. Qihuang Gong and Xiaoyong Hu [7] systematically summarized the significant progress made in the preparation process and performance improvement of photonic crystal fibers since their inception, believing that they have fully entered the engineering application stage from the experimental verification stage. In 2017, with the development of topological insulators in condensed matter physics, photonic crystal topological insulators and photonic Weyl crystals were successively realized, becoming one of the most active research directions at present. Xi Xie et al. [8] in the latest research on topological photonic crystals confirmed that introducing topological protection mechanisms can make photons immune to the influence of structural defects and disordered scattering during propagation, and this discovery has opened up a new path for the practical application of photonic crystals.

3. BASIC CHARACTERISTICS OF PHOTONIC CRYSTALS

3.1 Photonic Bandgap

The photonic bandgap is the most fundamental and core characteristic of photonic crystals. When the dielectric constant varies periodically in space and the variation period is equal to the wavelength of the light wave, the dispersion relationship of the light wave will exhibit a band-like structure, namely the photonic band structure. The frequency discontinuity regions between energy bands are called "photonic frequency bandgap", and light or electromagnetic waves with frequencies within this bandgap cannot propagate in this periodic structure at all. The physical essence of this phenomenon is highly similar to the electron bandgap in semiconductors. The periodic arrangement of ions in semiconductors generates an energy band structure, and the bandgap prevents the migration of electrons; in photonic crystals, the periodic arrangement of high and low refractive index media generates a photonic band structure, and the bandgap prevents the propagation of specific frequency photons. The appearance of the photonic bandgap depends on the periodicity of the structure and the ratio of dielectric constants. Generally speaking, the larger the ratio of the dielectric constants of the two media, the stronger the scattering of the incident light, and the more likely a complete photonic bandgap will occur. If only a periodic structure exists in one direction, the photonic bandgap can only occur in that direction; if periodic structures exist in all three directions, a three-dimensional photonic bandgap can be achieved, and light with a specific frequency will be prohibited from propagating in all directions after entering. This is one of the most important characteristics of photonic crystals.

3.2 Photonic Localization

Another important characteristic of photonic crystals is “photonic localization”. Just as introducing defect structures in semiconductor materials can capture electrons and holes, introducing certain defects or impurities in photonic crystals will disrupt the original periodic symmetry, resulting in frequency-narrow defect states appearing in the photonic bandgap. Light or electromagnetic waves with frequencies within the defect state will be strongly localized at the defect position. Once deviating from the defect position, the light intensity will rapidly decay. For light inside the defect, the defect state acts like a potential well; for light outside the defect, the entire defect region constitutes a perfect reflector. This property provides a new physical mechanism for the manufacture of high-performance optical devices.

3.3 Regulation of Spontaneous Emission

Photonic crystals have a unique regulatory ability for spontaneous emission. This characteristic stems from Yablonovitch’s original idea. The probability of spontaneous emission is proportional to the state density of the photon at the frequency. When an atom is placed inside the photonic crystal and its spontaneous emission light frequency exactly falls within the photonic bandgap, since the state density of photons at this frequency is zero, the probability of spontaneous emission is also zero, and thus spontaneous emission is completely suppressed. Conversely, if impurities are introduced in the photonic crystal, high-quality impurity states with extremely high-quality factors will appear in the photonic bandgap, having a large state density, thereby significantly enhancing spontaneous emission. This bidirectional regulation ability of spontaneous emission makes photonic crystals have irreplaceable application value in laser and light-emitting device fields.

3.4 Photonic Wires and Lossless Optical Paths

If a line defect is introduced along a specific route in the photonic crystal, a “photonic wire” is formed. Only photons propagating along the photonic wire can pass through smoothly, and any photons attempting to leave the wire will be completely prohibited by the photonic bandgap. In an ideal state, this constitutes a lossless optical path, and its transmission efficiency is even better than that of traditional optical fibers. This property provides a new solution for the directional transmission of optical signals in integrated optical circuits.

4. RESEARCH STATUS OF PHOTONIC CRYSTALS

4.1 Deepening and Expansion of Theoretical Research

Since the concept was proposed in 1987, the theoretical research on photonic crystals has evolved from the initial calculation of energy band structures to a vast system covering various cutting-edge fields such as topological photophysics, nonlinear optics, and quantum optics. In 1990, Ho et al. from the Ames Laboratory invented the plane wave expansion method, which remains the most widely used theoretical tool in the calculation of energy bands of photonic crystals to this day. In recent years, with the introduction of the concept of topological insulators in condensed matter physics, photonic crystal topological insulators have become the most popular research direction. In topological photonic crystals, the propagation of light is protected by topology, and is naturally robust against structural defects and disorder, opening up a new path for the manufacture of highly fault-tolerant photonic devices. Additionally, the realization of photonic Weyl crystals further enriches the topological classification of photonic crystals, providing a broad platform for exploring new optical physical phenomena. At the same time, research on tunable photonic crystals has also made significant progress, mainly including two directions: refractive index modulation and lattice parameter modulation. In refractive index modulation, liquid crystal-filled photonic crystals can achieve dynamic regulation of the forbidden band through external stimuli such as electric fields, light fields, and temperature; dye-filled photonic crystals utilize the refractive index change caused by photochemical reactions to achieve band displacement. In lattice parameter modulation, flexible photonic crystals based on hydrogels can continuously adjust the position of the photonic forbidden band through various methods such as temperature, pH value, humidity, and mechanical stretching, and the optical properties of some structures can even be observed directly with the naked eye.

4.2 Dimension Classification and Structural System

According to the dimension in which the photonic forbidden band exists in space, photonic crystals can be classified into three major types: one-dimensional, two-dimensional, and three-dimensional. One-dimensional photonic crystals are regularly arranged multi-layer semiconductor materials, such as Bragg reflectors, and their structure is the simplest and easiest to fabricate, and have been widely applied in fiber Bragg gratings and high-reflection films, etc. Two-dimensional photonic crystals generate photonic crystal effects by confining light within the crystal plane through total internal reflection in semiconductor thin films, and are the most deeply studied and widely applied type, having been commercialized in photonic crystal fibers and semiconductor lasers, etc. Three-dimensional photonic crystals have lagged behind in research, and their preparation is much more difficult than two-dimensional structures, but due to their all-round photonic band gaps, they theoretically have the most complete light control capabilities. Currently, the preparation of three-dimensional photonic crystals mainly relies on layer-by-layer assembly and self-assembly methods, and some research groups have achieved a three-dimensional regular structure with a complete band gap by allowing uniformly sized nanospheres to self-assemble, obtaining an anti-crystalline structure with a complete band gap.

4.3 Application Progress in the Field of Fiber Lasers

The application of photonic crystals in the field of fiber lasers has become an important engine for current industrial development. Fiber lasers use rare-earth element doped glass fibers as gain media and are known as "the fastest cutter" and "the most accurate ruler", widely used in cutting, welding, marking, medical and communication fields. According to the classification of fiber structure, photonic crystal fiber lasers are an important type among them, with a fiber cross-section having a periodic air hole array, and through flexible design of air hole parameters, single-mode transmission, large mode area, and controllable dispersion characteristics can be achieved. As of 2025, the market size of fiber lasers in China has reached 16.795 billion yuan, with a year-on-year growth of 6.85%, and the output has reached 493,800 units. The domestic substitution process has accelerated significantly, with the market share of Ruike Laser reaching 18.6%, surpassing the US IPG Company. In terms of technology, China has reached international leading levels in 10-watt single-mode fiber lasers and 300W femtosecond lasers, and the 160kW ultra-high-power product has broken the global record. In 2005, American researchers used two new types of two-dimensional photonic crystals to reduce the group velocity of light by more than a hundred times. This technology is expected to be applied in high-power, low-threshold photonic crystal lasers in the future.

4.4 Industrialization Breakthrough of Hollow-core Photonic Crystal Fibers

Hollow-Core Photonic Crystal Fiber (HC-PCF) is one of the most groundbreaking applications of photonic crystal technology in the field of optical fibers. Its core is a hollow micrometer-sized pore channel, which achieves low-loss, low nonlinearity, and high-power transmission of light in the air through photonic bandgap or anti-resonance effects, fundamentally breaking through the physical limits of traditional solid-core optical fibers. By 2025, China has built three production-capable hollow-core photonic crystal fiber drawing lines, which are mainly operated by Changfei Fiber, Hengtong Optoelectronics, and Zhongji Xuchuang. The total market size of hollow-core photonic crystal fibers in China reached 128 million yuan in 2025, with a year-on-year growth rate of 32.7%, significantly higher than that of traditional communication optical fibers. From the application structure perspective, high-end laser manufacturing, quantum precision measurement, and aerospace optical interconnection are the three core driving forces. Among them, the AI data center interconnection scenario became the largest demand source for the first time in 2025, accounting for 43.8%. The import dependence rate has dropped from 91.5% in 2022 to 54.2% in 2025, and the domestic substitution is moving from "availability" to the substantive stage of "good usability". The market size is expected to reach 172 million yuan in 2026. The Ministry of Industry and Information Technology's "Action Plan for High-Quality Development of Optoelectronic Devices (2025-2027)" has listed hollow-core fibers as a key research direction, and the total budget for related topics in national-level projects amounts to 490 million yuan.

4.5 Other Important Application Directions

Apart from the above fields, photonic crystals have shown broad application prospects in many other directions. In the field of light-emitting devices, by utilizing the suppression effect of the photonic bandgap on spontaneous emission, the probability of spontaneous transition caused by spontaneous transition can be greatly reduced, and thresholdless lasers and high-efficiency photonic crystal light-emitting diodes can be designed and fabricated. In the filtering and sensing field, photonic crystals can be made into extremely narrow bandpass filters, combined with surface-enhanced Raman spectroscopy (SERS), the Raman signal can be amplified by a million times, and they have great potential in medical diagnosis, drug delivery, and environmental monitoring. In the field of optical communication, significant progress has been made in the research of photonic crystal optical waveguide splitters, couplers, optical switches, optical delayers, and optical polarization controllers. In the field of bionics, the discovery of natural photonic crystals provides inspiration for artificial design-opal is essentially a natural photonic crystal, and periodic microstructures with photonic crystal structures have been found in the scales of Brazilian beetles, antelopes' shells, and butterfly wings. These natural wonders provide valuable blueprints for the bionic design of photonic crystals.

5. CONCLUSION

Since its inception in 1987, the field of photonic crystals has undergone nearly four decades of development. Starting from Lord Rayleigh's initial exploration of one-dimensional periodic structures, to the landmark theoretical breakthroughs by Yablonovitch and John, and then to the pioneering semiconductor process preparation path established by Krauss, the research on photonic crystals has evolved from a theoretical sprout to a comprehensive academic discipline covering basic physics, materials science, and optical electronics engineering. Its core characteristics-the photonic band gap, photonic localization, spontaneous radiation control, and photonic wire effect-provide unprecedented physical means for manipulating and controlling photons. Currently, two-dimensional photonic crystals have achieved commercial applications in photonic crystal fibers and fiber lasers. Three-dimensional photonic crystals and topological photonic crystals are becoming the forefront of academic research, while hollow-core photonic crystal fibers have witnessed a key breakthrough in industrialization in 2025. Looking ahead, with the advancement of high-power, ultra-fast, and intelligent trends, as well as the explosive demand for ultra-low loss optical interconnection from AI computing infrastructure, photonic crystals will undoubtedly play an irreplaceable core role in strategic fields such as high-end manufacturing, quantum information, and aerospace, truly driving the arrival of the photon technology revolution in the 21st century.

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