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Research on applications of photonic crystals

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Abstract. A photonic crystal is a dielectric structure in which the refractive index varies periodically in space. Due to its special physical properties, it has theoretical research value and wide application prospects. This paper introduces photonic crystals from the aspects of principle, preparation and application, and makes a summary and outlook on them. This paper focuses on the basic principles and applications of photonic crystals, so as to help more people to have a general understanding of photonic crystals.

Keywords: Photonic crystals, Preparation methods, Photon Ban Band, Application areas.

1. Introduction

The concept of photonic crystals has been relatively well researched and developed since the 1980s. It has been widely used in many fields such as communication, stealth and biomedical detection. Especially in the 21st century, information is growing exponentially and there is an urgent need for a faster and more efficient way. Photons, which have the advantages of high transmission speed, high density and high fault tolerance, are an inevitable trend to replace electrons as information carriers. This paper analyses and summarizes the research and application of photonic crystals on the basis of previous research. This paper will help people who do not yet know about photonic crystals to understand the basic research and applications of photonic crystals, so that this new and profound material can be better known to a wider audience.

2. Principle of photonic crystals

This paper studies photonic crystals by analogy with the principles of crystals. The atoms in a crystal are arranged in space in a certain regular periodic repetition and generate a periodic potential field. Due to this periodic potential field, electrons moving in the crystal are subjected to Bragg scattering by the periodic potential field, resulting in an energy band structure. A band gap may exist between the bands, and the energy of an electron wave is prohibited from propagating in the band gap. In fact, not only electromagnetic waves but also other waves subjected to periodic modulation form an energy band structure, and waves whose energy falls in the band gap are also prohibited from propagating. In short, the periodic arrangement of ions in a semiconductor gives rise to the energy band structure, which in turn controls the movement of carriers in the semiconductor.

Similarly, in photonic crystals it is the periodic change in the index of refraction of light that creates the optical band gap structure, which controls the movement of light in the photonic crystal. Photonic crystals can be divided into one-dimensional photonic crystals, two-dimensional photonic crystals and

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three-dimensional photonic crystals according to the number of dimensions in space in which their photonic forbidden bands exist.

A one-dimensional photonic crystal means that the medium has a periodic structure in one direction only, while the other two directions are uniformly distributed. It has been shown that one-dimensional photonic crystals may also have a full range of three-dimensional bandgap structures. Thus, 1D photonic crystals can also have the properties of 2D and 3D photonic crystal devices. As a result, one-dimensional photonic crystals are used in a wide range of applications. The two-dimensional photonic crystal has a periodic structure in both directions. Because its band gap has reached the optical band, it is often used as a transmission medium in fibre optic communications. The photonic band gap of three-dimensional photonic crystals is mostly in the microwave band. Its most important feature is the ability to have a full range of photonic band gaps, i.e. light is completely forbidden in all directions. This feature makes it extremely valuable for research and applications

3. Preparation of photonic crystals

The main photonic crystals that exist in nature are opals, butterfly wings and peacock feathers. However, as none of them form a complete photonic forbidden band, the majority of photonic crystals still need to be prepared artificially.

3.1. Mechanical processing method

The mechanical method is an early and traditional method. In 1991, Yablonovitch et al. produced the first photonic crystal with a forbidden band of photon frequencies by modifying the previous method [1]. They covered the surface of Ga and As media with a film having a triangular hole drilling arrangement and then perforated the holes sequentially from 120 degrees apart at the hole locations. This has successfully solved the problem of pseudo-energy gaps that previously existed with the mechanical processing method. However, due to the time-consuming and laborious nature of the mechanical process, it was only an early attempt to prepare photonic crystals.

3.2. Layer-by-layer method

Materials like three-dimensional photonic crystals, for example, we can think of as dimensional periodic structures that extend in space. Based on this concept, it is natural to introduce Layer-by-layer method. The first study of this method was carried out in 1994 by Ho et al [2]. As shown in Figure 1, they stacked aluminium trioxide dielectric rods on the substrate at a distance d, after which each layer of dielectric rods was moved perpendicular to the lower layer and by d/2 distance. The resulting four layers give a typical structure for the preparation of three-dimensional photonic crystals - the Woodpile structure.

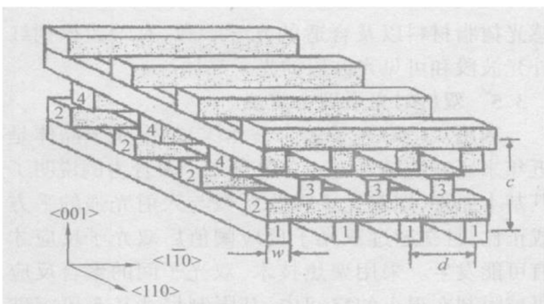

Figure 1. Demonstration of the stacking method [4].

3.3. Colloidal self-organization method

The colloidal self-organization method is a common method of preparing photonic crystals. The photonic crystals produced by this method have the structure of an opal and are therefore often referred to as "opals". Self-organization is a technique whereby the basic structural units (molecules, nanomaterials, matter on a micron or larger scale) spontaneously form an ordered structure. In the

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process of preparing opal structures by self-organizing methods, polymers such as polystyrene or silicon oxide materials are commonly used to form colloidal particles. These microspheres are widely used for the preparation of colloidal particle stencils because of their low cost and reproducibility of the process. In addition, the microspheres can be easily removed and the stencil removed to obtain a three-dimensional photonic crystal structure. Based on this approach, a method for preparing photonic crystals on a large area - the spraying method - was developed [3]. This has been investigated by Zhou et al. from the Green Printing Laboratory in China. They sprayed a solution containing colloidal particles onto different substrates by means of a spray gun. The colloidal particles have a core-shell structure and, as the core shell is mainly made up of polypropylene, the surface of the core shell contains Polyacrylic acid groups. The spheres are tightly packed due to the interaction of the carboxyl groups through hydrogen bonds. In this way, we can prepare photonic crystals on a large scale.

4. Applications of photonic crystals

4.1. Stealth technology

As technology continues to improve in all countries, stealth technology has become a popular development. So far, there are several new types of warplanes that use stealth technology. Stealth technologies can be broadly classified into the following categories: infrared stealth, radar stealth, visible light stealth and acoustic stealth. This paper focuses on the application of photonic crystals in infrared stealth.

Infrared stealth technology, is achieved by reducing or changing the infrared radiation characteristics of the target to reduce the detectability of the target. The main measures include changing the infrared radiation characteristics of the target, reducing the infrared radiation intensity of the target and regulating the propagation path of infrared radiation.

This paper focuses on the application of one-dimensional photonic crystals in infrared stealth coatings. Liu et al. [5] had obtained good performance photonic crystal coatings through a large number of theoretical calculations and analyses, and then combined the principles of photonic crystals themselves with simulations under different refractive index and thickness parameters, etc., to design two different coatings, A and B. Their reflectance and transmittance patterns were also analyzed under five different mode structures (AB, ABAB, ABABAB, ABA, ABAABA). It can finally be deduced that, according to the photonic crystal principle, the two coatings A and B are stacked in layers to form a one-dimensional photonic crystal structure of the coating, which can effectively shield or reflect electromagnetic waves in the frequency range of special frequencies. And for coatings working with electromagnetic waves in the wavelength range of 8-14μm, the reflectivity ABAABA structure reaches up to 61.76% and the transmittance AB structure reaches 93.99%.

4.2. Photonic crystal fibre

Optical fibre is a widely used tool for the transmission of signals. Traditionally, an optical fibre is a fibre made of glass or plastic and the transmission principle is "total reflection of light". Photonic crystal fibres, on the other hand, are fibres made of quartz fibres with air holes arranged uniformly in the axial direction.

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4.3. Biomedical Testing

Photonic crystals can be introduced into the biomedical field by amplifying optical signals through Bragg scattering or photonic confinement of photonic crystals, thus enabling the detection of DNA or proteins.

Li et al. have incorporated photonic crystals with a characteristic structure that enhances energy transfer into the receptor undergoing DNA detection, using photonic forbidden bands to enhance the utilization of light and thus improve the sensitivity of DNA detection. Alternatively, a hydrophilic photonic crystal channel can be printed on a hydrophobic substrate by means of inkjet printing technology. This facilitates the flow of the detected night and eliminates non-specific absorption by the special structure of the photonic crystal. Finally, the colourimetric method is used for the detection of unlabelled immunoproteins [8]. With the expansion of these methods, it may be possible to use them effectively for disease detection and drug diagnosis. In addition to this, the researchers have used the structural colour of photonic crystals to build chips that enable efficient detection of a wide range of substances, such as polysaccharides, tetracyclines and polyamines [9]. This allows the detection range of photonic crystals to be further extended.

4.4. Other applications

Photonic crystals are used in the microwave band as microwave antennas and as protective equipment for mobile phones. For microwaves, most of the energy is lost in the substrate and brings about the thermal effects of the substrate. However, we can design photonic crystals for a certain microwave band so that they can be used as a substrate for antennas. Because the microwave band falls in the forbidden band of the photonic crystal, the substrate will not absorb any more microwaves and can achieve loss-free total reflection. Similarly, by using photonic crystals to inhibit the propagation of microwaves at certain frequencies, a microwave shield can be created on the antenna of a mobile phone to prevent harmful microwave radiation from being directed at the human body [10].

5. Conclusion

This paper begins with a brief introduction to the principles of photonic crystals. The Mechanical processing method, the Layer-by-layer method and the Colloidal self-organization method are discussed. Finally, several areas of application are investigated.

The advent of photonic crystals has made the free manipulation and control of light a reality. People are able to design and manufacture a variety of photonic devices in an artificial way, depending on the requirements. Although research into photonic crystals has evolved considerably to date, the replacement of integrated circuits with integrated optical circuits is still a formidable challenge. However, there is no doubt that photonic crystals can now be used in a wide range of applications and play an important role.

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