Journal of Advances in Science and Technology

Vol. 10, Issue No. 21, February-2016, ISSN 2230-9659

PHOTONIC CRYSTALS

AN INTERNATIONALLY INDEXED PEER REVIEWED & REFEREED JOURNAL

Photonic Crystals

Dr. Smt. Rashmi Bhargava

Govt. Girls P.G College Ujjain

Abstract* – *A photonic crystal is a periodic optical nanostructure that affects the motion of photons in much the same way that ionic lattices affect electrons in solids. Photonic crystals occur in nature in the form of structural coloration—and, in different forms, promise to be useful in a range of applications.

Photonic crystals can be fabricated for one, two, or three dimensions. One-dimensional photonic crystals can be made of layers deposited or stuck together. Two-dimensional ones can be made by photolithography, or by drilling holes in a suitable substrate. Fabrication methods for three-dimensional ones include drilling under different angles, stacking multiple 2-D layers on top of each other, direct laser writing, or, for example, instigating self-assembly of spheres in a matrix and dissolving the spheres.

Photonic crystals can, in principle, find uses wherever light must be manipulated. Existing applications include thin-film optics with coatings for lenses. Two-dimensional photonic-crystal fibers are used in nonlinear devices and to guide exotic wavelengths. Three-dimensional crystals may one day be used in optical computers.

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INTRODUCTION

Photonic crystals are composed of periodic dielectric, metallo-dielectric—or even superconductor microstructures or nanostructures that affect electromagnetic wave propagation in the same way that the periodic potential in a semiconductor crystal affects electronmotion by defining allowed and forbidden electronic energy bands. Photonic crystals contain regularly repeating regions of high and low dielectric constant. Photons (behaving as waves) either propagate through this structure or they don't. This depends on the wavelength. Wavelengths that propagate are called *modes*, and groups of allowed modes form bands. Disallowed bands of wavelengths are called *photonic band gaps*. This gives rise to distinct optical phenomena, such as inhibition of spontaneous emission, high-reflecting omni-directional mirrors, and low-loss-waveguiding.

The periodicity of the photonic crystal structure must be around half the wavelength of the electromagnetic waves to be diffracted. This is ~200 nm (blue) to 350 nm (red) for photonic crystals that operate in the visible part of the spectrum—or even less, depending on average index of refraction. The repeating regions of high and low dielectric constant must, therefore, be fabricated at this scale, which is difficult.

Construction strategies

The fabrication method depends on the number of dimensions that the photonic bandgap must exist in.

One-dimensional photonic crystals

In a one-dimensional photonic crystal, layers of different dielectric constant may be deposited or adhered together to form a band gap in a single direction. A Bragg grating is an example of this type of photonic crystal. One-dimensional photonic crystals can be either isotropic or anisotropic, with the latter having potential use as an optical switch.

One-dimensional photonic crystal can form as an infinite number of parallel alternating layers filled with a metamaterial and vacuum. This produced identical PBG structures for TE and TM modes.

Recently, researchers fabricated a graphene-based Bragg grating (one-dimensional photonic crystal) and demonstrated that it supports excitation of surface electromagnetic waves in the periodic structure by using 633 nm He-Ne laser as the light source.[18]Besides, a novel type of one-dimensional graphene-dielectric photonic crystal has also been proposed. This structure can act as a far-IR filter and can support low-loss surface plasmons for waveguide and sensing applications.

Two-dimensional photonic crystals

In two dimensions, holes may be drilled in a substrate that is transparent to the wavelength of radiation that the bandgap is designed to block. Triangular and square lattices of holes have been successfully employed.

The **Holey fiber** or photonic crystal fiber can be made by taking cylindrical rods of glass in hexagonal lattice, and then heating and stretching them, the triangle-like airgaps between the glass rods become the holes that confine the modes.

Three-dimensional photonic crystals

There are several structure types that have been constructed:

- *Spheres in a diamond lattice*
- Yablonovite
- *The woodpile structure* – "rods" are repeatedly etched with beam lithography, filled in, and covered with a layer of new material. As the process repeats, the channels etched in each layer are perpendicular to the layer below, and parallel to and out of phase with the channels two layers below. The process repeats until the structure is of the desired height. The fill-in material is then dissolved using an agent that dissolves the fill-in material but not the deposition material. It is generally hard to introduce defects into this structure.
- *Inverse opals* or *Inverse Colloidal Crystals*- Spheres (such as polystyrene) can be allowed to deposit into a cubic close packed lattice suspended in a solvent. Then a hardener is introduced that makes a transparent solid out of the volume occupied by the solvent. The spheres are then dissolved with an acid such as Hydrochloric acid.
- *A stack of two-dimensional crystals* – This is a more general class of photonic crystals than Yablonovite, but the original implementation of Yablonovite was created using this method.
- "The photonic crystal beam splitter that we made is a fundamental optical component used to control polarized light," explains Dr Mark Turner from Swinburne University. "Specifically what makes our device unique is its ability to directly work with circular polarization at a microscopic scale."
- Circular polarization uses 3D laser nanotechnology to exploit circular polarization to build a microscopic prism that contains in excess of 750,000 polymer nanorods. Light focused on this beam splitter penetrates or is reflected, depending on polarization.

Fabrication challenges

Higher-dimensional photonic crystal fabrication faces two major challenges:

- Making them with enough precision to prevent scattering losses blurring the crystal properties
- Designing processes that can robustly mass-produce the crystals

One promising fabrication method for two-dimensionally periodic photonic crystals is a photonic-crystal fiber, such as a *holey fiber*. Using fiber draw techniques developed for communications fiber it meets these two requirements, and photonic crystal fibres are commercially available. Another promising method for developing two-dimensional photonic crystals is the so-called photonic crystal slab. These structures consist of a slab of material—such as silicon—that can be patterned using techniques from the semiconductor industry. Such chips offer the potential to combine photonic processing with electronic processing on a single chip.

For three dimensional photonic crystals, various techniques have been used including photolithography and etching techniques similar to those used for integrated circuits. Some of these techniques are already commercially available. To avoid the complex machinery of nanotechnological methods, some alternate approaches involve growing photonic crystals from colloidal crystals as self-assembled structures. Mass-scale 3D photonic crystal films and fibres can now be produced using a shear-assembly technique that stacks 200–300 nm colloidal polymer spheres into perfect films of fcc lattice. Because the particles have a softer transparent rubber coating, the films can be stretched and molded, tuning the photonic bandgaps and producing striking structural color effects.

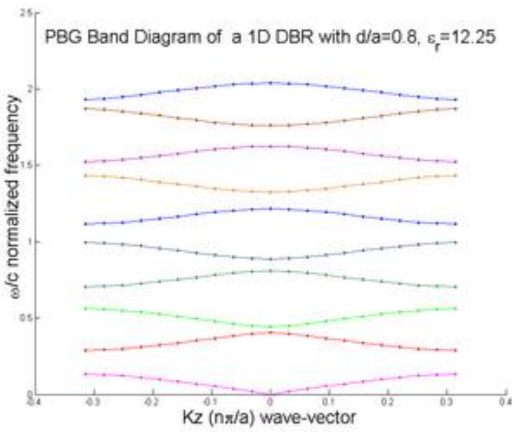
Computing photonic band structure

The photonic band gap (PBG) is, essentially, the gap between the air-line and the dielectric-line in the dispersion relation of the PBG system. To design photonic crystal systems, it is essential to engineer the location and size of the bandgap by computational modeling using any of the following methods:

- Plane wave expansion method
- Finite element method.
- Finite difference time domain method

- Order-n spectral method
- KKR method
- Bloch wave – MoM method
- Construction of the Band Diagram

Essentially, these methods solve for the frequencies (normal models) of the photonic crystal for each value of the propagation direction given by the wave vector, or vice versa. The various lines in the band structure correspond to the different cases of *n*, the band index. For an introduction to photonic band structure, see Joannopoulos.



Band structure of a 1D Photonic Crystal, DBR air-core calculated using plane wave expansion technique with 101 planewaves, for d/a=0.8, and dielectric contrast of 12.250. To speed calculation of the frequency band structure, the **Reduced Bloch Mode Expansion (RBME)** method can be used. The RBME method applies "on top" of any of the primary expansion methods mentioned above. For large unit cell models, the RBME method can reduce time for computing the band structure by up to two orders of magnitude.

APPLICATIONS

Photonic crystals are attractive optical materials for controlling and manipulating light flow. One dimensional photonic crystal are already in widespread use, in the form of thin-film optics, with applications from low and high reflection coatings on lenses and mirrors to colour changing paints and inks. Higher-dimensional photonic crystals are of great interest for both fundamental and applied research, and the two dimensional ones are beginning to find commercial applications.

The first commercial products involving two-dimensionally periodic photonic crystals are already available in the form of photonic-crystal fibers, which use a microscale structure to confine light with radically different characteristics compared to conventional optical fiber for applications in nonlinear devices and guiding exotic wavelengths. The three-dimensional counterparts are still far from commercialization but may offer additional features such as optical nonlinearity required for the operation of optical transistors used in optical computers, when some technological aspects such as manufacturability and principal difficulties such as disorder are under control.