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PHOTONIC BANDGAP FIBERS

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Abstract

The constant pursuit of more efficient low loss and high power transmission waveguides in optical telecommunication has led to the design of alternative advanced materials with specifically engineered optical properties. One such material is the so called photonic bandgap material. This paper examines the theory, fabrication and application of photonic bandgap fibers in optical telecommunication.

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1. Introduction

Photonic crystals are microstructured periodic dielectric media that affect the propagation of electromagnetic (***Em***) waves similar to the way periodicity in a real crystal affects the motion of electrons. Photonic crystals are of particular importance in optics as they offer great capability of manipulating the fundamental laws of refraction and diffraction. Depending on the internal arrangements and fabrication, these materials can exhibit periodicity in one dimension, two dimensions or three dimensions are respectively called ***1D, 2D,*** or ***3D*** photonic crystals. Few materials in nature show signs of ordered dielectric periodicity but one example is opal which may occur in rocks such as limonite, sandstone and basalts.

A photonic crystal designed with the ability to forbid the propagation of electromagnetic waves in certain frequency ranges (forming band gaps) is known as a photonic bandgap (PBG) material. The phenomenon of forming band gaps in a photonic crystals is known as the PBG effect. Optical fibers fabricated to employ the PBG effect are known as *Photonic bandgap fibers* (**PGBF**).

Em wave propagation in periodic media was first studied by Lord Raleigh in 1887 and he identified the fact that they have a narrow band gap prohibiting light propagation in the planes of the material. Vladimir P. Bykov[1] gave a firm theoretical treatment of ***1D*** photonic band gap structures in the 1970s. A more rigorous treatment of ***2D*** and ***3D*** periodic structures was carried out by Yablonovitch and John in 1987 by encompassing the tools of classical electromagnetism and solid state physics.

Optical communication over the years has relied on conventional optical fibers whose main guiding mechanism is essentially the phenomenon of total internal reflection. Light is trapped in an inner transparent solid core wrapped with a second material (cladding) of higher index of refraction [2].

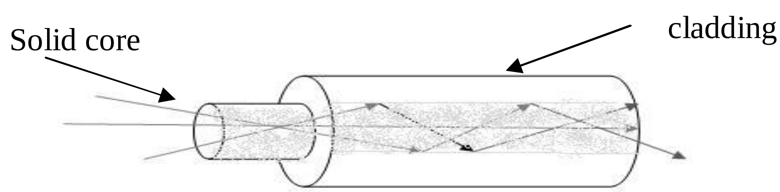

Figure 1*: A typical conventional optical fiber*

Philip Rusel et al [3] in 1996 proposed an alternative way of transmitting light in a hollow core fiber by the use of **PBG**. This has the advantage over standard optical fibers in that it allows light to be guided via low loss core materials [4] such as air or other gases; potentially reducing attenuation and dispersion.

2 Origin of Photonic bandgaps

2.1 Bloch waves

By combining *Faraday's* and *Ampere's laws* for source-free media one can write *Maxwell's equation* as an *eigen value equation* in terms of the magnetic field $\vec{H}$.

$$\vec{\nabla} \times \frac{1}{\varepsilon} \vec{\nabla} \times \vec{H} = \left(\frac{\omega}{c}\right)^2 \vec{H} \qquad (1)$$

Where

$\vec{H}$ = magnetic field
ε = dielectric function
c = speed of light

This equation has eigenvalue $\left(\frac{\omega}{c}\right)^2$ with eigen operator $\vec{\nabla} \times \frac{1}{\varepsilon} \vec{\nabla} \times$ which is *Hermittian.*

The beauty of this formalism lies in the fact that the well established linear algebraic theorems in *Quantum mechanics* can be applied to the **em** wave solution. This equation is very difficult to solve analytically, and so semi analytic and computational techniques are normally employed. In the next subsection we shall discuss some of these computational techniques suitable for 2D and 3D photonic crystals.

A photonic crystal can be modeled mathematically with a periodic dielectric function

$$\varepsilon(\bar{x}) = \varepsilon(\bar{x} + \overline{R_i}) \qquad (2)$$

for some primitive lattice vectors $\overline{R_i}$ (i = 1,2,3 for crystal periodicity in all three dimensions).

By the ***Bloch-Floquet*** theorem for periodic eigen problems, the solution of eq(1) can be of the form

$$\bar{H}(\bar{x}) = e^{i\bar{k}.\bar{x}} \bar{H}_{n,\bar{k}} \qquad (3)$$

With eigenvalues $\omega_n(\bar{k})$ where $\bar{H}_{n,\bar{k}}$ is a periodic envelope function satisfying

$$(\bar{\nabla} + i\bar{k}) \times \frac{1}{\varepsilon}(\bar{\nabla} + i\bar{k}) \times \bar{H}_{n,\bar{k}} = \left(\frac{\omega_n(\bar{k})}{c}\right)^2 \bar{H}_{n,\bar{k}} \qquad (4)$$

at each Bloch wave vector $\bar{k}$

The eigen solutions $\omega_n(\bar{k})$ are continuous and periodic functions of $\bar{k}$**,** as such the solution at $\bar{k}$ is the same as the solution at $\bar{k} + \bar{G}_j$, where $\bar{G}_j$ is a primitive reciprocal lattice vector with property

$$\bar{R}_i \bar{G}_j = 2\pi\delta_{ij} \quad (5)$$

Thus this periodicity ensures that one considers the set of inequivalent wave vectors closest to origin $\bar{k} = 0$, ie the first *Brillouin zone*.

To demonstrate the existence of bandgaps, consider the traditional 1D photonic crystal made off multilayer film with $\bar{R}_1 = a$ for some periodicity a, with uniform $\varepsilon = 1$, which has planewave eigensolutions

$$\omega(\bar{k}) = ck \quad (6)$$

and $\bar{G}_1 = \frac{2\pi}{a}$ over a and the corresponding first *Brillouin zone* is the region $k = -\frac{\pi}{a} \cdots \frac{\pi}{a}$ all other wave vectors are equivalent to some point in this zone under translation by a multiple of $\bar{G}_1$. Let us neglect the complexities imposed by the redundancy of the first *Brillouin zone* and time – reversal symmetry.

Figure 2
a one – dimensional photonic crystal

A complete photonic bandgap is a range of ω in which there are no propagating (real $\bar{k}$) solutions to equation (4) for any $\bar{k}$. There are also incomplete gaps which only exist over a subset of all possible wavevectors, polarizations, (and symmetry).

Suppose ε is perturbed so that it has non trivial periodicity $(a \neq 0)$ with same periodicity a. For example

$$\varepsilon(x) = 1 + \Delta \cdot \cos\left(\frac{2\pi x}{a}\right) \quad (7)$$

We can write the wave solution as a linear combination of $e(x) = \cos(\pi x/a)$ and $o(x) = \sin(\pi x/a)$

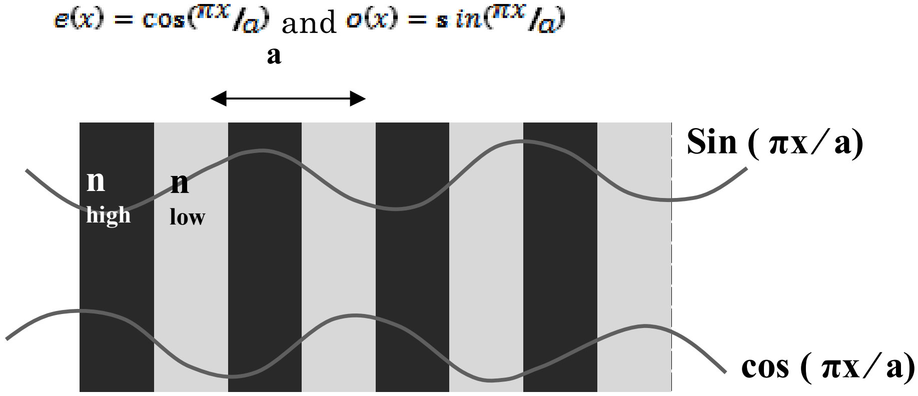

Figure 3
Splitting of panewaves of a uniform medium into $\cos(\pi x/a)$ *and* $\sin(\pi x/a)$ *standing waves by a dielectric periodicity.*

Suppose $\Delta > 0$, then the field e(x) is more concentrated in the higher ε – regions than o(x), and so lies at a lower frequency. This opposite shifting of the bands creates a band gap, as depicted in fig(4) bellow.

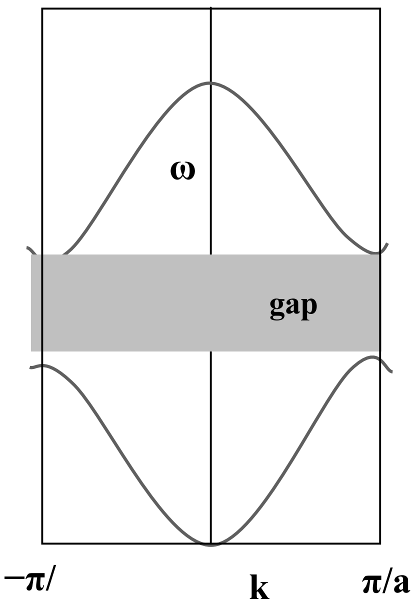

Figure 4
Band diagram, frequency ω versus wavenumber k of a uniform one dimensional medium

2.2 2D photonic crystals

As mentioned earlier, the calculation of band gaps in photonic crystals is very complicated, the problem get complex in 2D and 3D photonic crystals. These complications arise from:

The victorial boundary condition imposed on the field ($\vec{E}$ or $\vec{H}$).

Secondly, in each symmetry direction of the crystal (and each $\vec{k}$ point) there will be a band gap by the 1D argument, but these band gaps will not necessary overlap in frequency. In order that these bands overlap, the gaps must be sufficiently large.

In order to obtain a large band gap, a dielectric structure should consist of thin, continuous veins [5] along which the electric field lines can run. The veins must also run in all directions so that this confinement can occur for all $\vec{k}$ and polarization necessitating a complex topology in the crystal.

2.3 Computational techniques

Numerical techniques are inevitable in analyzing photonic band structures.
Two main approaches are used to investigate the properties of photonic crystals: [6] the first involves solving Maxwell equation eq.(1) in the frequency domain while the second deals with it in the time domain.

Frequency domain analysis

This technique is very useful as it yields the band diagrams which provide a guide to interpretation measurements and aid in device design. Whichever of the frequency – domain methods used, has as starting point in the expansion of the field in some complete basis

$$\bar{H}_{\bar{k}}(\bar{x}) = \sum_n h_n \bar{b}_n(\bar{x})$$

which transformed the partial differential eq.(4) into a discrete matrix eigenvalue problem for the coefficient h_n. This leads to a system of **N** x **N** matrices which can be diagonalized by standard methods. This method can be very impractical for large 3D systems.

Time domain analysis

In this technique, a finite difference method is usually employed to model the time evolution of the fields with arbitrary starting conditions. Though this does not directly compute eigenvalues, but provide a lot of intuitive information corresponding to directly measurable quantities such as transmission.

3 Photonic bandgap fibers

3.1 Guiding principle and Optical properties

Photonic crystal fibers (PCF) usually fall into two[7] categories:
High – index guiding fibers and photonic bandgap fibers. The first kind of PCFs are more similar to conventional optical fibers because light is confined in a solid core by exploiting a "special" kind of total internal reflection mechanism. This guiding principle is different from that of conventional optical fibers in that the refractive index of the cladding is not constant but varies with wavelength.
We are actually concerned with the later type of PCFs which employs the PBG effect.

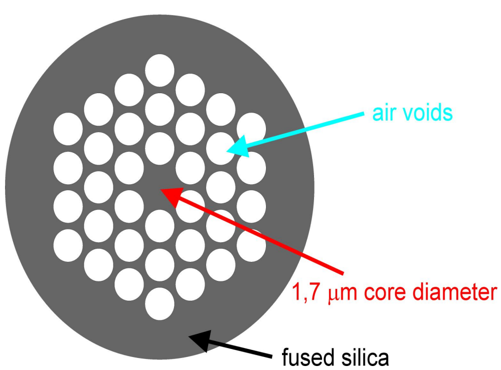

Figure 5a
Cross section index – guiding fiber

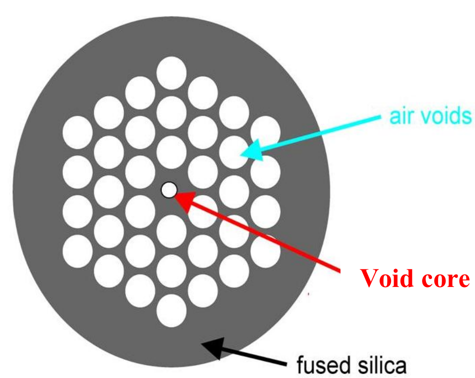

Figure 5b
Cross section bandgap – guiding fiber

Images : Physikalisch – Technische Bundesanstalt (2003)

Once light is induced to travel along the fiber, it really has no where to go, since the frequency of the guided mode lies within the photonic bandgap, the mode is forbidden to escape.

PBG materials display superior optical properties compared to conventional optical materials. PBG fibers display special dispersion properties, enhanced non-linearity and high birefringence. In addition, these properties can be fine-tuned by changing the size, shape and position of the cladding holes as well as thermally modifying the index of refraction[8] in certain sol-gel derived microstructure fibers which allows the band gap feature to be sensitively tuned.

In conventional optical fibers the dispersion characteristics is similar to that of silica due to their small waveguide dispersion. In contrast, the dispersion profile of PBG fiber is tailorable – can be tuned by changing the pitch Λ (distance between cladding hole centers) and the air – hole size (***d***). The dispersion is strong for PBG fibers with high air filling fraction (d/Λ).

The microstructuring of air holes and fabrication process gives precise control of the PBG fibers birefringence. The birefringence is usually based on the asymmetrical shape of the core or the cladding [9] and higher order magnitude can be obtained compared to conventional fibers-

Narrow core PBG fibers can exhibit high non linearity [10]. Since the magnitude of the nonlinear coefficient is inversely proportional to the mode area, PBG fibers can be designed to exhibit a very small mode area compared with conventional optical fibers by using a small core diameter and high air filling fraction.

3.2 Fabrication

PBG fibers are commonly fabricated from silica using the stack-and-draw method in three main steps.

Step 1: fabrication of the preform

This is carried out by stacking silica capillaries to form the desired fiber structure. In the case of an index – guiding fiber, the core is usually form by replacing one the capillaries with a silica rod. The preform of an air – guiding PBG fiber can be manufactured by removing some of the silica tubes from the centre of the perform.

Step 2: drawing into canes

The preform is drawn to a number of canes that can be employed to produce different sized fibers, the cane is then drawn to a final length using a drawing tower while maintaining the initial structure. The drawing is done at 1900C° to avoid collapse of the air holes.

Step 3: Jacketing

Finally a polymer jacket is inserted on the outer surface of the fiber to give strength and enhance mechanical flexibility.

To obtain desired dispersion, nonlinearity and polarization properties, the stack – and – draw method allows for an accurate design of the core shape and size to control these properties with incredible precision and accuracy.
Other methods do exist which involves the fabrication of PCFs from glass using the *extrusion technique* and from polymers by *capillary stacking method*.

3.3 Applications

PBG fiber is a subject of active research both in Science and Engineering due to its numerous applications and promising novel state–of–the art optical communication system based entirely on photons in optoelectric circuits where light is guided from one end of a microchip to another using a PBG. The applications of PBG fibers range from supercontinum generation, gas spectroscopy – gas sensing, fiber lasers, high speed optical computers [11], and data transmission.

Recent advances in quantum and optical computing might have a great promising impact in telecommunication in which transmission and computing will be greatly enchanced through all optical processing – bits encoded in the form of photon number distribution, transmission and processed without conversion to and from electrical signals. Present day fiber optical waveguides based on conventional material have been reliable and efficient to metallic guides but this novel fiber material with its exotic characteristics has the potential of extending the performance merit.

In conventional fiber–optic cables, along a tight bend (curve) the angle of incidence is too large for total internal reflection to occur, so light escapes at the corners and is lost. PBG fibers continue to confine light around tight corners since they do not depend on total internal reflection.
The hollow (gas filled) transmission path in PBG fibers offer a much lower loss high power channel than glass which is highly limited by ***Rayleigh scattering***. Though the lowest lost figure of PBG fibers is still very high compared to typical standard single – mode conventional optical fibers. The main effects causing the loss in hollow core PBG fibers are the width of the bandgap and the confinement loss due to the finite number of air holes. Thus the design and fabrication of PBG fibers that exhibit the largest bandgap is of profound importance. An example of such ingenious designs is the triangular lattice – consisting of a circular array of air holes packed in a triangular arrangement [12].

PBG fibers have a significantly larger optical bandwidth than single mode conventional optical fibers for the same mode–field diameter [13]. In conventional fibers, the single–mode optical bandwidth is limited by higher–order mode cutoff at short wavelengths and micro–bend loss at long wavelengths. The figure below shows the comparison of the attenuation spectral of conventional optical fiber and a triangular arrangement of air holes photonic fiber with $\Lambda = 2.9$ μm and $d/\Lambda = 0.44$.

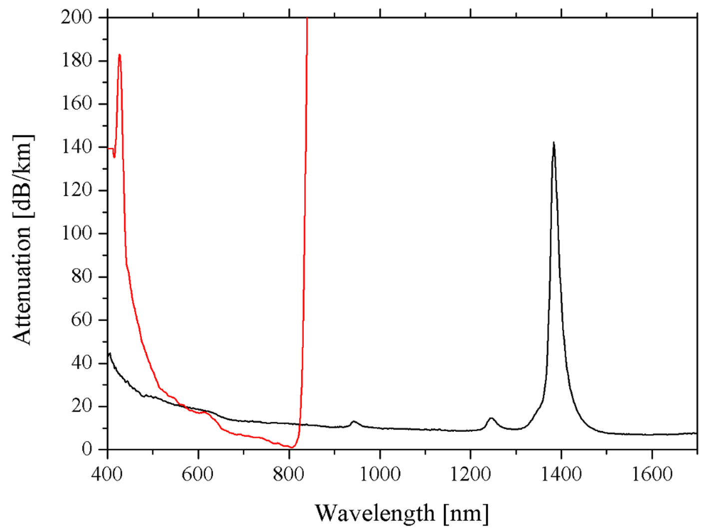

Figure xx
Attenuation spectral of conventional optical fiber(red) and PBG fiber (black).
Credit ©2004 Optical Society of America

2. Conclusion

The optical properties of PBG fibers presented confirm the superiority of this artificial material as the optical waveguide for next generation optical communication. The fabrication challenges and the still relatively high transmission loss of PBG fibers open up avenues for more fundamental research.

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