

TRAPPING OF LIGHT IN NATURAL AND ARTIFICIAL PHOTONIC CRYSTALS AND IN HOLLOW CORE PHOTONIC CRYSTAL FIBER

SHYAMAL KUMAR BHADRA*

Quest for new materials in conjunction with technological advancement is an important part of intensive research and development. Truth is that the solution is embedded in natural materials. We find structural colouration in natural materials like plants and species. Some natural species possess photonic structures that produce beautiful colours and similar properties could be mimicked in artificial photonic crystals. We describe these aspects with available references and explain trapping of light in hollow core photonic crystal fibers (HCPCF). Bandgap guidance, related properties and designing various photonic structures are explained with computational photonics, and finally fabrication of HCPCF is described. CSIR-CGCRI has created a comprehensive facility to fabricate such optical fibers including nonlinear photonic crystal fiber (NPCF) for supercontinuum generation.

Some plants, flowers and animals are visually very attractive. There is always a question that how their colour originates. When a broad white spectrum of light falls on the surfaces of substances some band of colours of light are absorbed and some are not i.e., reflected back. If it is shorter wavelengths the object appears to be blue and for longer wavelength it shows red-colour. When we see leaves and flowers on the trees in autumn in different hue, it is due to metamorphosis of chemical make-up in the plant bodies. A typical autumnal colours of plants are shown in Fig. 1.



Fig. 1. Feast of autumnal colours in leaves and twigs of plants (Photo taken by the author at Kanha National Park in late October, 2015)

Let us now look for other forms of colours in species. It is possible to create designer colours without using

chemical dyes and pigments only by controlling the surface structural features in nano-metric scales so that particular band of light reflects forming structural colours which is common in nature such as some butterflies and fruit flies create a particular structural colouration or iridescent of colour. It is very common to see that when a beam of

* Fiber Optics and Photonics Division, CSIR-Central Glass & Ceramic Research Institute, Kolkata
e-mail: skbhadra88@gmail.com

visible light falls on a prism, light is dispersed according to the wavelength of light forming rainbow of colours from red to violet. This is called prismatic colours. Colour created by photonic crystals or structural colouration is generally termed as iridescence, a word synonyms with rainbow. Here colour changes with the viewing angles. Therefore iridescence is different from prismatic colour.

Photonic Structures in Natural Speices

We see in our garden various types of butterflies with fancy combination of colours. Butterflies have been the most studied biological species when it comes to colours. Diffraction of light in grating structure, combination of multilayer reflectors and nano or micro-metric scale photonic crystal structures produce colours. However, the first two are treated as reflectors, where a light of particular wavelength is reflected once within the structure, whereas light is reflected many more times in photonic crystals¹.

There are photonic structures observed in scales of butterflies which are composed of scutes, flutes and ribs. Scute is composed of photonic structures with multilayer reflecting and diffracting elements on the scales of butterflies. This scute can change in structures with the help of layers, spacings, and tilts position of the elements. Flutes are multilayer hollow structures crafted with alternating layers of chitin and air. Chitin is high refractive index cellular material. The thicknesses and angular orientation of these elements dictate which band or colour of light will be reflected that produce multiple interferences resulting structural colourations. John Huxley at the Natural History Museum (NHM), London, had conducted extensive study predominantly in butterfly colouration, later A. R. Parker and his group continued the work and generated a huge data base on the genesis of structural colouration of butterflies².

Figure 2 shows the butterflies and corresponding SEM images of common type photonic structures found in scales of dorsal or upper side view of planes of butterflies. How beautiful structures present in those species. It

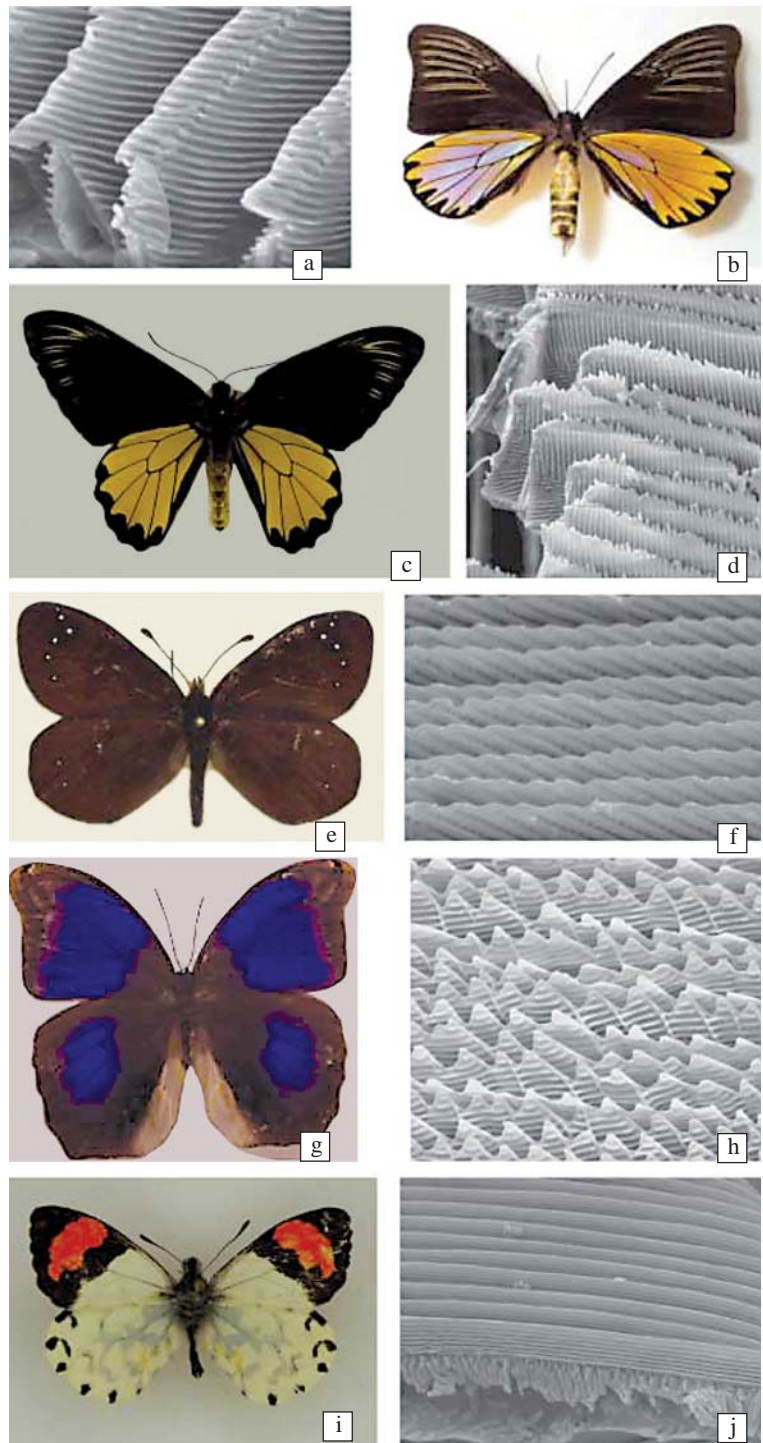


Figure 2. Dorsal view or the upper side of the body of different butterflies given in biological names and SEM images of the lateral views of the cover scales from the iridescent regions.

(a) SEM showing horizontal and vertical diffracting scute tips from the iridescent blue dorsal regions, (b) Blue iridescence visible in backscatter of *Troides magellanus*, (c) *Troides miranda* (d) SEM showing positions of scutes and flutes from scales in yellow regions, (e) *Percnodaimon pluto* (f) SEM showing tilted scutes from iridescent region on dorsal wings, (g)*Eryphanis aesacus* (h) SEM showing flutes and scutes , (i) *Eroessa chiliensis* and (j) Parallel continuous scutes in the orange regions.

(Reproduced from the review article of *Phil. Trans. R. Soc. B* (2008) by A. L. Ingram & A. R. Parker "Diversity of butterfly photonic structures" - With permission from the Authors)

is therefore obvious that when the dimension of natural structures become comparable to visible band of light, it produces beautiful combination of colours in the wings of butterflies.

Another amazing example of light trapping in photonic structure is the color production in peacock feather as shown in Fig.3 (a). The eye region of tail feather is composed of multiple coloured zones. The tail feather has a central stem with array of barbs surrounding it where individual barb has an assembly of barbules - look like flat ribbon slightly curved and segmented (Fig.3-b). The outer circular conical shell, the cortex in differently coloured barbules features photonic-crystal structure where light reflects³. Depending upon the air hole structure and angular variation of the holes a symphony of colours that we see when a peacock dances.

changing their structural colours which is analogous to rainbow we see in the sky that changes with time³.

Light trapping in photonic crystals

Recently a group of researchers at Berkeley University, California, has shown that flexible high contrast silicon metastructure (HCM) can change colours by stretching the membrane which is made of polydimethylsiloxane (PDMS)⁴. The design HCM exhibits green, yellow, orange and red colours ; that resembles to colour palette. It is now possible to create artificial flowers.

The stated HCM is developed using soft lithographic technique on PDMS membrane. PDMS is very hard and flexible polymer. As claimed by the authors vivid colours can be achieved under white light illumination and they

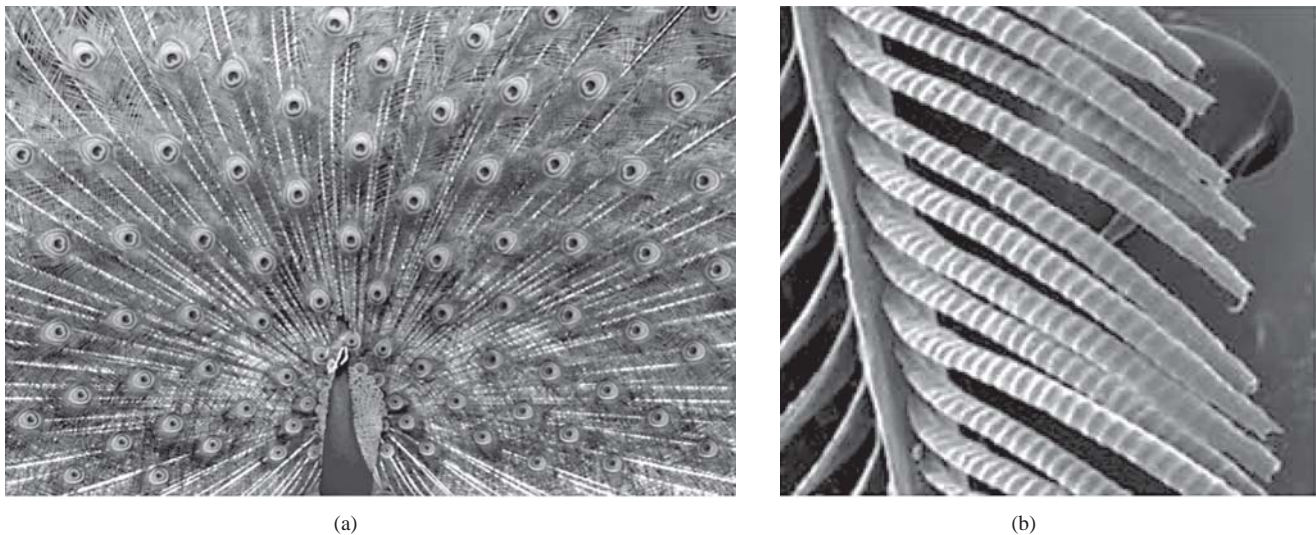


Fig. 3 (a) A beautiful symphony of colours in peacock feathers appeared due to photonic microstructures present in feather hairs and scaffolds (Taken from internet archive)

(b) Scanning Electron Microscope image of peacock barbules, beautiful features of the structure are evident that cause fantastic colours when light falls on it (Adapted from the article: Physics of structural colours, S. Kinoshita, et al, Reports and Progress in Physics (IOP). **71**. 076401(2008) with permission).

It is found that different colours of light reflect from the fine structured holes at different angles like iridescence and due to optical mixing we see deep blue or deep green colours in peacock feathers. It appears that photonic materials with splendid demonstration of fancy colours exist commonly in nature. Many species response to change in surrounding environment by

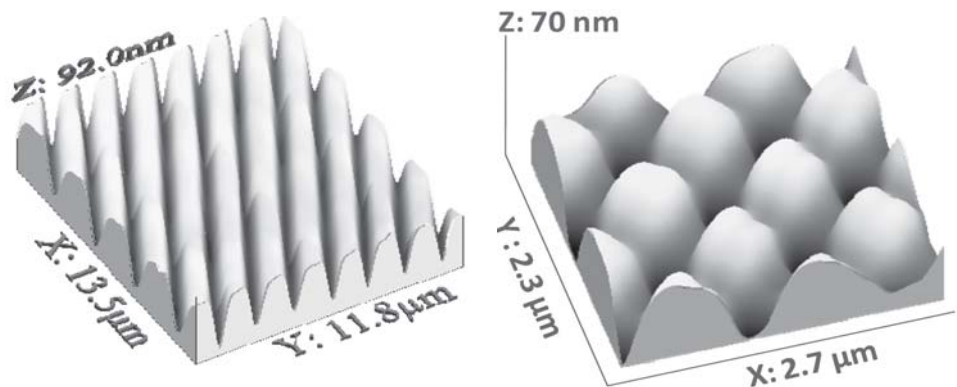


Fig. 4. AFM images of cross pattern by using negative replica of PDMS stamp in silica by soft lithography technique (Courtesy: Ms Saswati Sarkar, CSIR-CGCRI).

demonstrated artificial flowers of different colours. It may be noted that this flower has no colour without the presence of light. In this case photonic diffractive process is responsible for the generation of colours. This is an example of trapping of light to get beautiful colours. Figure 4 shows the AFM (Atomic Force Microscopy) image of nano-micro- metric structures imprinted on silica thin films by PDMS stamp. Light can be diffracted or trapped with the help of this type of structures. Due to the flexibility one can control the colour by stretching the HCM. More recently it was demonstrated that light can be guided and trapped in metal-dielectric hybrid photonic crystals which are termed as artificial metamaterials or negative index materials where basic principle of light is different from the fundamental laws.

In late eighties, the principles of photonic crystals were discovered, leading to the suggestion of radically new mechanisms of light guidance. The term *photonic crystal* was first used in 1987 after E. Yablonovitch and S. John published two milestone papers on this topic^{5,6}. Light propagates in the complex periodic structures in controlled fashion at the level of single wavelength.

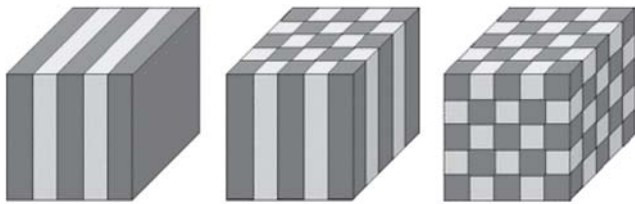


Fig. 5. Schematic presentation of 1D, 2D & 3D photonic crystal structures⁷.

As stated by Eli Yablonovich, nanostructured materials containing ordered array of holes could lead to an optoelectronics revolution, doing for light what silicon did for electrons⁸. Photonic crystals in different dimensions can be fabricated in dielectric and semiconductor materials as shown schematically in figure 5. It is reported that the first successful photonic crystal structure was made in a block of ceramic material by creating array of holes which are produced at an angle 35 degrees from the vertical axis of the hole. This photonic structure is named “yablonovite”. This structure enables blocking of a band of millimeter waves.

Depending on their wavelengths, photons (behaving as waves) are allowed or forbidden to propagate through such photonic structures. This property enables one to control and manipulate the flow of light with amazing properties and produce effects that are impossible to get with conventional optics. Electromagnetic field (light) for

a particular colour that are allowed to propagate are known as modes and group of such allowed modes form bands. Disallowed bands of wavelengths are called photonic band gaps as happened in electronic bandgap in semiconductor crystals. Recently researchers have demonstrated various techniques to make 2D & 3D (Fig. 5) photonic crystals of niche materials and presented unique structural properties so that light can be trapped selectively in order to produce desired colour or trapping of particular band of light⁷.

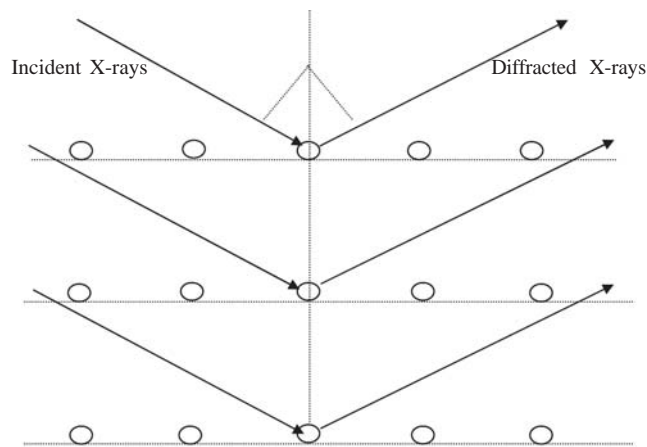
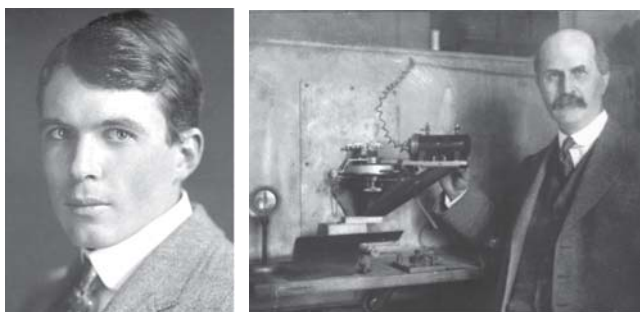


Fig. 6. A beam of X-rays incident on a crystal and scattered. Circles are the periodic lattice points of the crystal.

Let us look back to the fundamental properties of crystals. A regular crystal structure is defined as a set of lattice points that are arranged periodically and in certain orientation in a material so that if one views from any lattice point same crystalline structure will be seen as shown in Fig.5. Once this periodicity is lost and if atoms or lattice points are randomly arranged we call the material as amorphous or noncrystalline. Certain dielectric crystals are transparent and they response to light. If we irradiate the photonic crystal with a band of light a particular colour of light can be trapped depending on the nature of the structure (Fig.6). As we know X-rays (very small wavelength in electromagnetic spectrum) are scattered by the atoms, however, when these rays are incident on a crystal with lattice spacing comparable to the wavelength, they are scattered by atoms as shown in Fig. 6. Each scattered wave remains in same phase with other then it undergoes constructive interference since the path length of each scattered wave is an integer multiple of the wavelength of the incident rays. Therefore we see the diffracted intense beam or peaks which is known as Bragg peaks⁹. Multiple Bragg peaks could be observed from different crystal planes. With the help of X-rays, getting image of human bones is very common since bone composed of polycrystalline structures.

It may be mentioned that William Lawrence Bragg (Fig. 7) was first presented this discovery on 11 November 1912 to the Cambridge Philosophical Society. Later William Lawrence Bragg and his father, William Henry Bragg, were awarded the Nobel Prize in physics in 1915 for their work in X-ray spectra, X-ray diffraction and crystal structure, when William Lawrence Bragg was only 25 years old. Since then X-ray crystallography became a subject of study for material scientists for knowing the intricacy of crystalline phases and material properties. From structural point of view materials can also be classified into two groups crystalline and non-crystalline⁹.



William Lawrence Bragg William Henry Bragg with the first spectrometer
(Image courtesy of the Royal Society)

Fig. 7. W H Bragg with the first spectrometer and his son W L Bragg. Both won the Nobel Prize in Physics in 1915.

Before the works of Braggs, interestingly British Physicist Lord Raleigh had suggested in 1887 that a material with a repeating regular structure- such as crystal- could block particular band of wavelengths of light. Light reflected from different surfaces, interferes and produces – “stop bands”. After 100 years i.e., in 1987 Eli Yablonovitch established the principle of photonic band gap or “stop band” in photonic crystals.



Eli Yablonovitch Philip S J Russell
Fig. 8. Founders of photonic crystal and fiber Eli Yblonovich and Philip S J Russell

Philip P J Russell and his group in 1997 (Fig. 8-b) has demonstrated hollow core photonic crystal fiber (HCPCF) in silica matrix that can trap particular frequency of light¹⁰ – termed as photonic bandgap fiber. Similar to the 2D-photonic crystals as proposed by Yablonovich (Fig. 8-a). However, photonic crystal fiber (PCF) are broadly categorized into two types: photonic band gap (PBG) fiber which guides light through hollow core by the photonic band gap effect and index-guided photonic crystal fiber in which light guidance occurs through the solid core following the phenomenon of modified total internal reflection (M-TIR). It is also suggested that, in HCPCF, guidance of light follows successive Bragg reflections.

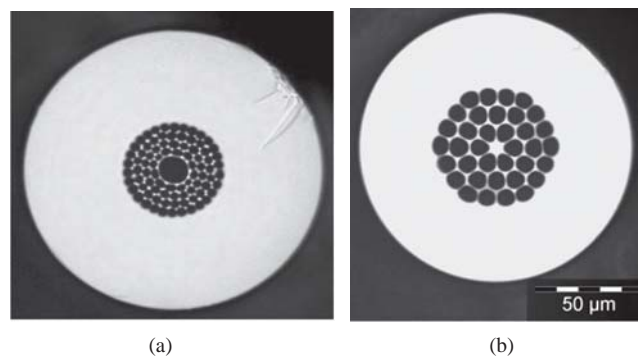
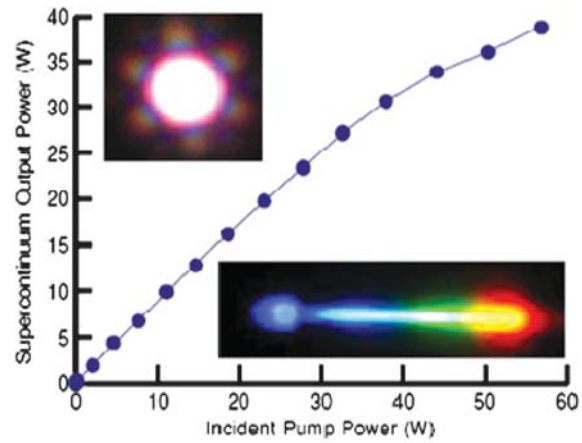


Fig. 9 (a) Hollow core photonic crystal fiber in silica-air matrix (CSIR-CGCRI), (b) Solid core photonic crystal fiber in silica-air matrix (CSIR-CGCRI)

Now let us see how the solid silica core PCF produces multicoloured light by different mechanism. This is not by iridescence but by large confinement of light in the core of PCF. In solid core PCFs, the central silica core is surrounded by a periodic array of air-holes running along the propagation distance as shown in Fig.9 (b). The unique geometric arrangement of air holes in a PCF offers huge index contrast enabling high nonlinearity and extreme dispersion tailoring never imagined before. The propagation of light or electromagnetic wave depends on the medium in which it propagates. Light interacts with the atoms and molecules, and experiences loss and dispersion. The latter effect relates to wavelength dependence of the refractive index of the medium. If the intensity of light is high enough, the medium responds in a nonlinear way¹¹. Refractive index becomes intensity dependent resorting to Kerr effect. Therefore nonlinear processes occur with low pump power of light in PCF. Spools of NPCF fabricated at CSIR-CGCRI are shown in Fig, 10-a. At the output we get a supercontinuum band of light including intense white light as shown in Fig. 10-b.



(a)



(b)

Fig. 10. (a) Spools of nonlinear photonic crystal fibers and (b) Supercontinuum white light generated in NPCF by pumping pico-second laser of average power ~ 60 Watt and average supercontinuum output ~39 Watt. (NPCF fabricated at CSIR-CGCRI and SC experiment done at ORC, Southampton University, published in *Optics Express*, April, 2010)

Glass-air PCF seemed to offer for the first time the revolutionary opportunity of escaping the mode of guidance by total internal reflection in a medium, allowing low-loss single mode guidance of light in a hollow core fiber (HCPCF), hence overcoming all limitations inherent to interactions between light and matter. In HC-PCF light guidance is mostly due to Bragg reflections from the photonic cladding that consists of air-silica matrix. Interestingly the light guidance can be switched from Bragg's reflection to MTIR by increasing the core refractive index values such as by filling liquids. Therefore by changing the core index one can trap different colours of light. Now let us describe the guidance of light in PCF and HCPCF in the following section.

Theory and computational photonics

The refractive index profile along the cross section of step index fiber is a step function. This kind of fiber can support either single mode or multiple modes depending on the V number, which is related to the fiber parameters as follows

$$V = \frac{2\pi a}{\lambda} \sqrt{n_{\text{core}}^2 - n_{\text{clad}}^2} \quad (2)$$

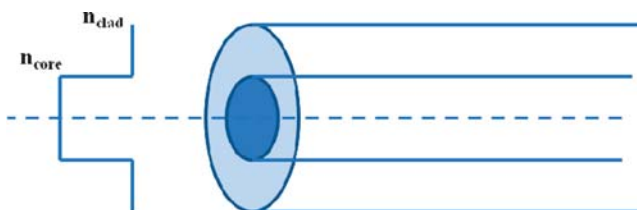


Fig: 11. Schematic diagram of a step index fiber.

Where, a , n_{core} and n_{clad} are core radius, refractive indices of core and cladding respectively; and λ is the operating wavelength.

The effective refractive index of a guided mode is defined as the following relation

$$n_{\text{eff}} = \frac{\beta}{k_0} \quad (2)$$

Where β is the propagation constant and k_0 is the free space wave number. A core guided mode satisfies the following condition

$$n_{\text{clad}}^2 < \frac{\beta^2}{k_0^2} < n_{\text{core}}^2 \quad (3)$$

A step index fiber supports single mode for $V < 2.4048$. Maxwell's wave equation (MWE) gives only one solution of n_{eff} which satisfies condition (3) for such fiber operating at a specific wavelength. The corresponding mode is called the fundamental mode (FM). The value of n_{eff} is the maximum for FM. For $V > 2.4048$ more than one solutions of MWE satisfy (3). Modes having n_{eff} less than the fundamental mode are known as higher order modes. Let us consider a step index fiber with $a=4 \mu\text{m}$; $n_{\text{core}}=1.45$, $n_{\text{clad}}=1.445$. This is a single mode fiber at $1.55 \mu\text{m}$. The normalized electric field distributions of the fundamental mode in transverse and longitudinal directions are shown in figure 12 (a) and (b) respectively.

Solid Core PCF

The schematic diagram of a nonlinear photonic crystal fiber (NPCF) is shown in figure 13(a). The cross sectional

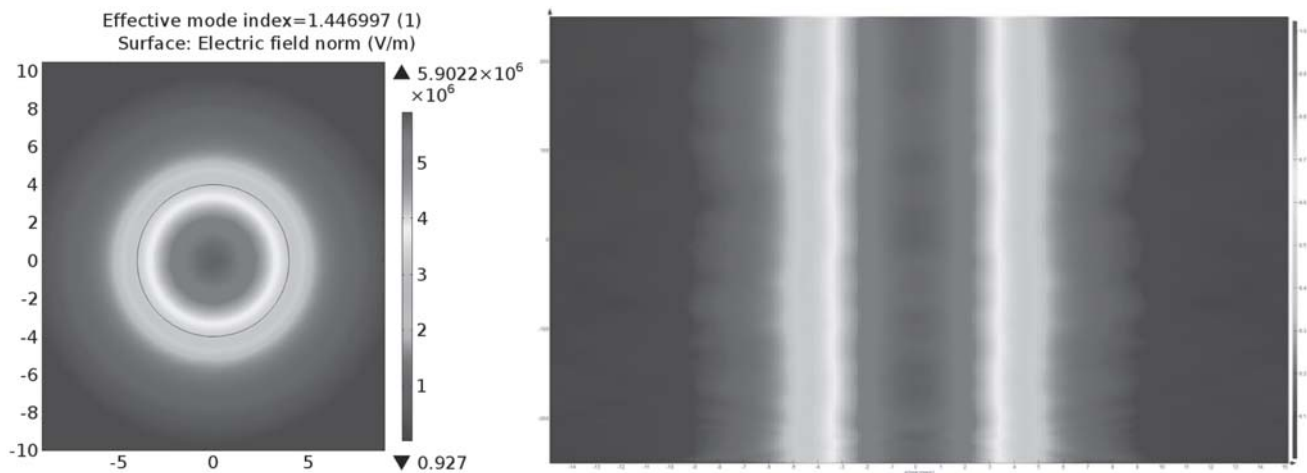


Figure 12. Electric field distribution of the fundamental mode along (a) transverse and (b) longitudinal directions of the fiber calculated by finite element method (FEM) and finite difference time domain (FDTD) methods respectively.

view of such NPCF having solid core is shown in figure 13(b)

Unlike step index fiber having almost constant cladding index the effective index of the cladding of a NPCF is modified due to micro structuring (Fig.13-a). Light is guided through the high refractive index core by modified total internal reflection (MTIR) in a NPCF. The effective index of the fundamental crystal (or cladding) mode is denoted as n_{FSM} , where FSM stands for the fundamental space filling mode. The numerical value of n_{FSM} depends on NPCF parameters d (diameter of air hole) and Λ (pitch, centre to centre distance between two consecutive air holes)(Fig. 13-b).

The effective index of the core guided mode in NPCF satisfies the following relation

$$n_{FSM}^2 < n_{eff}^2 < \frac{\beta^2}{k_0^2} < n_{core}^2 \quad (4)$$

The single mode operation for wide band of wavelength is ensured in a NPCF with the ratio d to Λ less than or equal to 0.43. Thus the NPCF is known as the “endlessly single mode” fiber. Numerical values of n_{FSM} and the effective index of the fundamental core guided mode (n_{eff}) are calculated by solving Maxwell’s vector wave equation using appropriate boundary conditions. For hexagonal arrangement of air holes in the cladding n_{FSM} is calculated by solving Maxwell’s equation within $1/6^{th}$ highly symmetric portion of a unit cell. The magnetic field distribution of FSM for $\Lambda=2.21 \mu\text{m}$ and $d=0.94\Lambda$ at 1300nm is shown in figure 14(a). The electric field

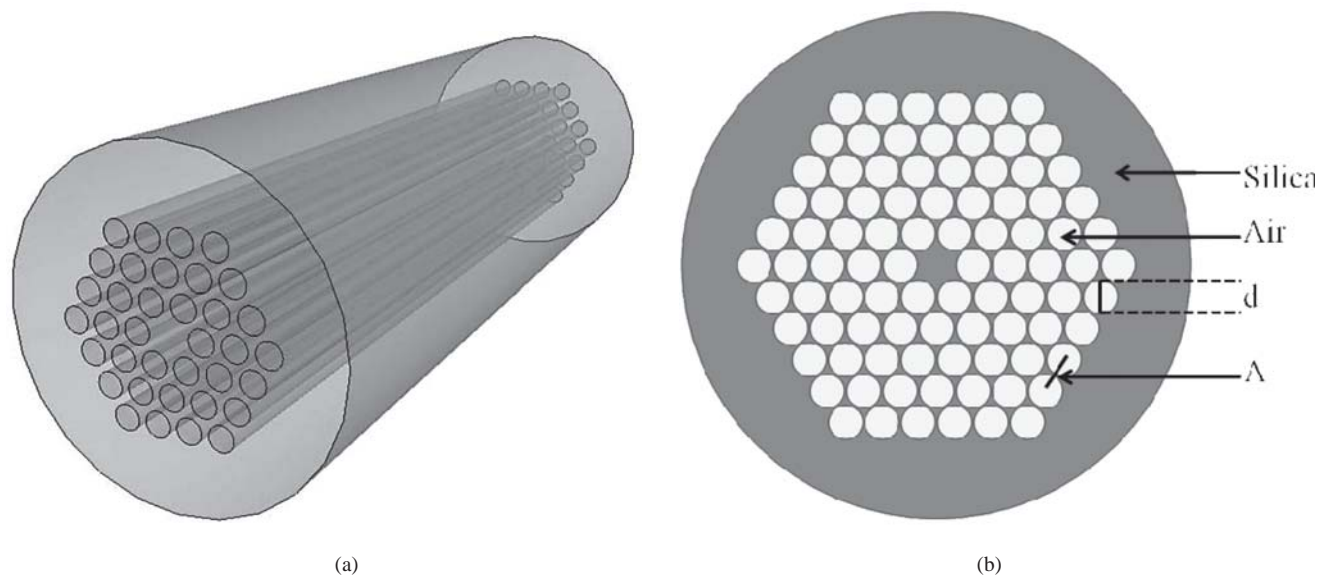


Figure 13. (a) The 3D schematic diagram of a PCF; cross section of (b) solid core core PCF.

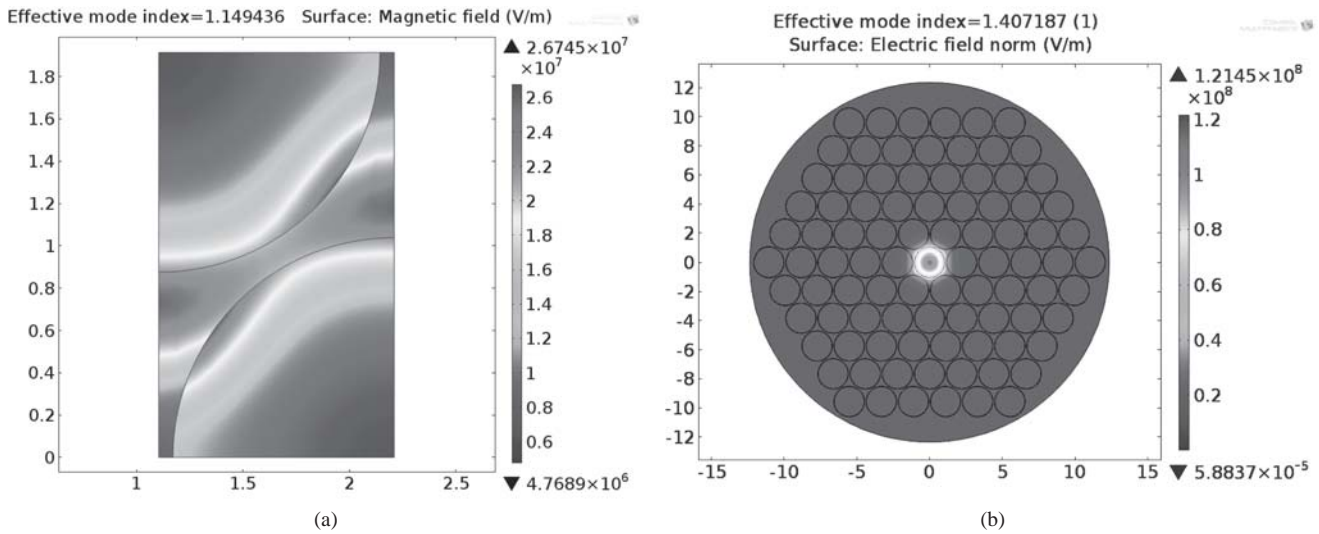


Figure 14. (a) The magnetic field distribution of the fundamental spacilling mode and (b) The electric field distribution of the fundamental eigen mode calculated by FEM.

distribution of the fundamental core guided mode of the same fiber at 1300nm is shown in figure 14(b).

The dispersion of FSM and fundamental core guided mode can be obtained by calculating n_{FSM} and n_{eff} for different values of wavelength. The variations of n_{FSM} with

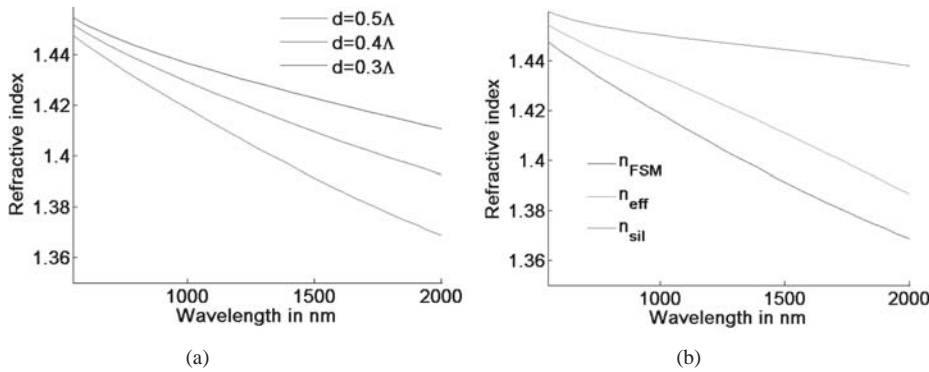


Figure 15. (a) Variation of n_{FSM} with wavelength for different d to Λ ratios, (b) dispersion of silica glass, FM and FSM.

wavelengths for three different values of d to Λ ratio are shown in figure 15(a). The dispersions of silica glass, FSM and fundamental mode (FM) are shown in figure 15(b).

The numerical value of n_{FSM} decreases with the increase in d to Λ ratio for fixed operating wavelength.

Therefore, the contrast between core and cladding indices can be set to any desired value by controlling d and Λ . It can be noticed that the dispersion curve of FM lies in between that of FSM and silica which establishes MTIR.

Band gap guidance in Hollow Core PCF (HCPCF)

A HCPCF guides light through a low index core on the basis of PBG guidance mechanism. Photons moving in a photonic crystal experience periodical change of dielectric media. The schematic diagram of unit cells in direct lattice space and reciprocal lattice space are shown in figure 16 (a) and (b) respectively.

Electromagnetic waves with certain frequencies are not allowed to propagate through the crystal. These frequencies create PBG and can be guided through

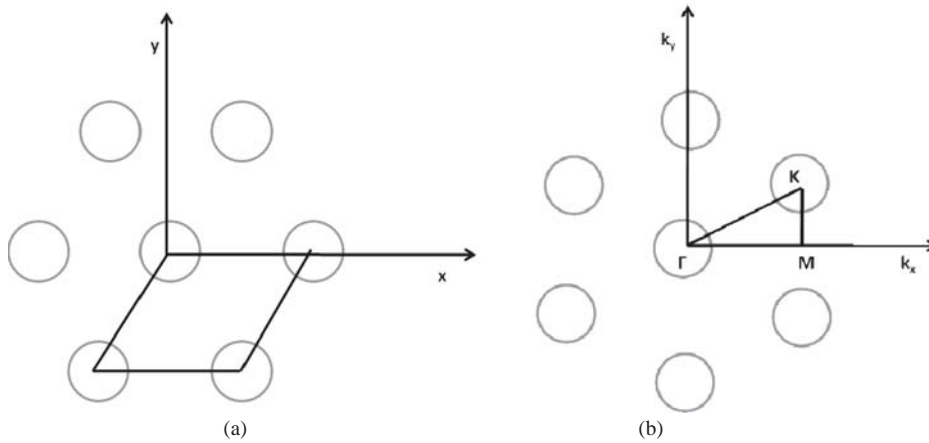


Figure 16. The unit cells of (a) direct lattice and (b) reciprocal lattice.

the hollow defect. One has to calculate photonic band structure (PBS) to determine the operating wavelength of a HCPCF. A PBS is defined as the collection of eigen frequency dispersion plot with inplane wave vector. The electric field distribution of the fundamental eigen mode of the cladding, PBS and the electric field distribution of the fundamental core guided mode are shown in figure 17 (a), (b) and (c) respectively.

capillaries are assembled in hexagonal pattern in an appropriate preform stack whose structure corresponds approximately to the desired fiber structure. After inserting the preform stack into a silica tube and fusing during the drawing process, we obtain a micro-structured “cane” of 2 & 3 mm. The final step involves drawing the cane into fiber with the desired dimensions of microstructures. The size of the air-holes and their regularity can be controlled

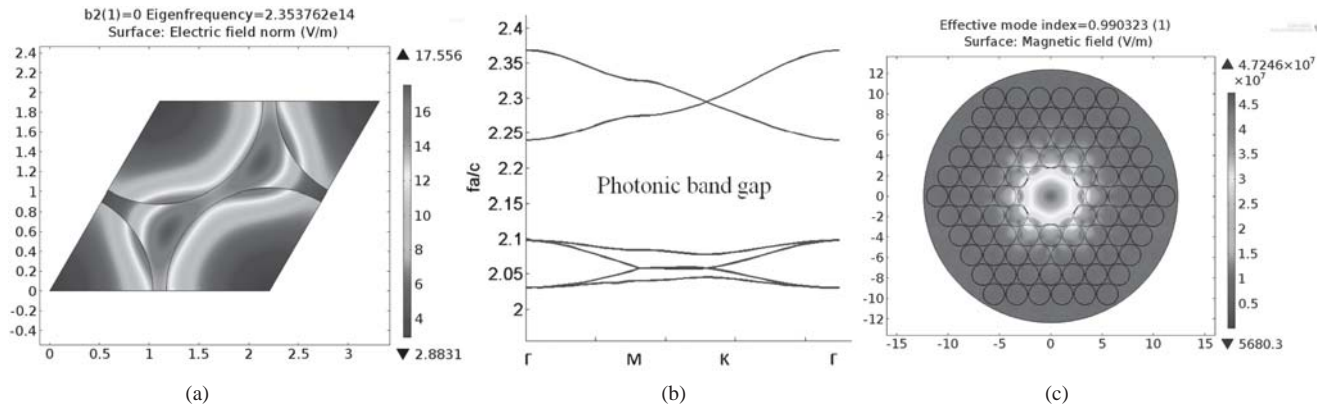


Figure 17. (a) The electric field distribution of the fundamental eigen mode of the cladding, (b) PBS, (c) the electric field distribution of the fundamental core guided mode calculated by FEM.

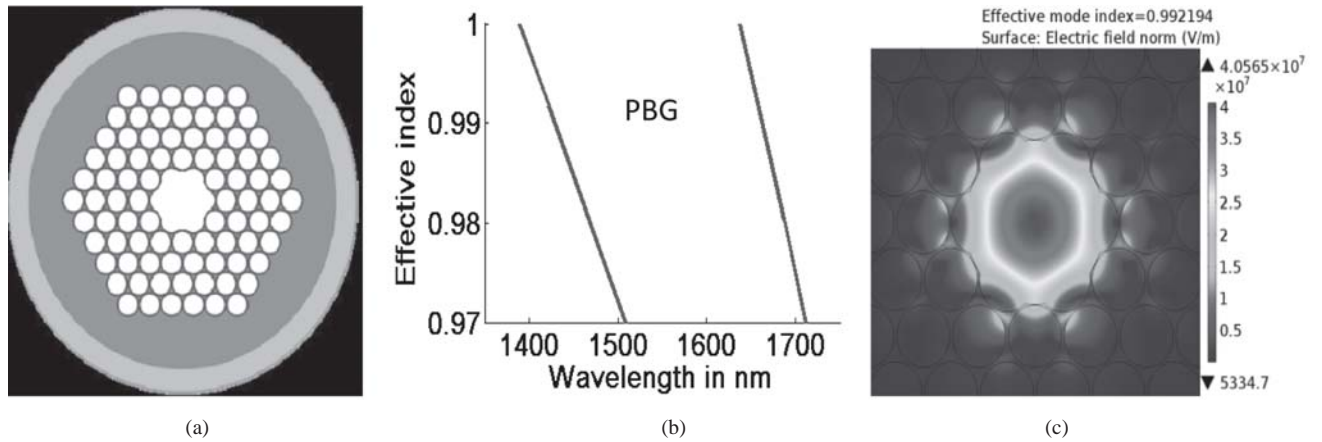


Figure 18. Photonic band gap guidance ($n_{core} < n_{cladding}$) around 1550 nm calculated theoretically in HCPCF (Left) and trapping of light is shown (Right) by FEM

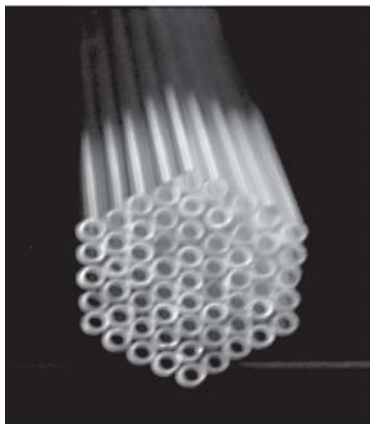
The position of PBG depends on d , Λ and the refractive index contrast between the host glass and air. Trapping of light is shown in particular structure of HCPCF (Fig. 18-a). Its operating wavelength as calculated is around 1550 nm (Fig. 18-b) and trapping of fundamental mode is shown (Fig. 18-c).

Fabrication of HCPCF

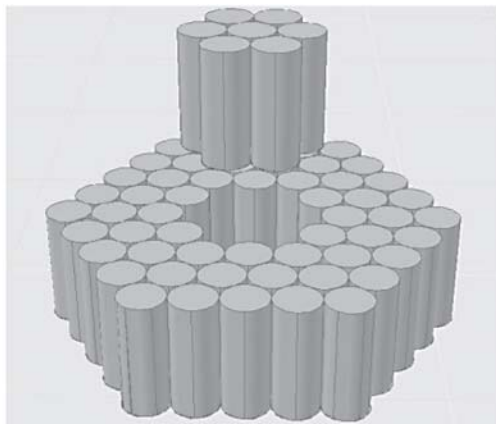
The fabrication of high quality custom-designed hollow Core PCF is required the “stack-and-draw” procedure of high purity silica capillaries. Silica capillaries are drawn in capillary/cane drawing tower. The silica

by tuning the furnace temperature, preform feed rate and drawing speed, as well as the pressure inside the capillaries and maintaining differential pressure (Fig. 19). Like standard fibers, the fabricated HCPCF is coated with a polymer jacket for improved mechanical strength.

In figure 19-b, it is seen that 7capillaries are removed from the center of a stack of silica capillaries subsequently 2 or 3mm diameter canes are drawn which are further inserted into a 8/2mm or a 10/3mm pure silica tube in order to draw fiber of desired diameter (Fig 20-a). Usually the diameter of the fiber is 125 micron.



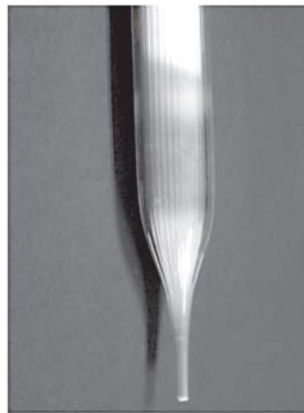
(a)



(b)



(c)

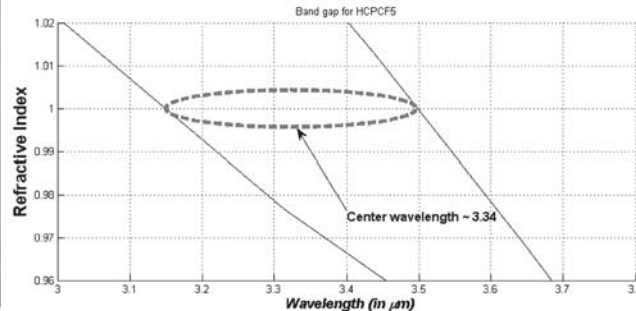


(d)

Fig. 19. (a) Hexagonal assembly of silica capillaries, (b) seven capillaries are taken out from the central portion of the preform, (c) Cane drawing at furnace temperature of 2100 C and (d) preform end after cane drawing (CSIR-CGCRI)



(a)



(b)

Fig.20. (a) A cross-section of fabricated HCPCF is shown fiber diameter 125 micron, core diameter 14 micron, air hole diameter 5.2 micron and pitch ~5.4 micron and (b) using the parameters the calculated operating wavelength of the HCPCF is 3.34 micron (Experiment at CSIR-CGCRI).

The operating wavelength of the drawn HCPCF is around 3.34 micron (Fig. 20b). It is a great challenge to

fabricate such HCPCF with operating wavelength around 1500 nm. This class of fiber has many important applications in photonic sensors, optical amplifiers and trapping of high power light to perform various experiments of particle transport and gas filled lasers.

Acknowledgement

Author is indebted to his students who did the actual work. He is grateful to Dr. K Muraleedharan, Director, CSIR-CGCRI for his kind support. He is thankful to DST and CSIR for financial support and beholden to all the staff members of FOPD for their unstinted support. □

References

1. A R Parker and H.E. Townley, *Nature Nanotechnology*, **Vol 2**, 347-353, (2007).
2. A. L. Ingram & A. R. Parker, *Phil. Trans. R. Soc. B*, (2008)
3. S. Kinoshita, *Bionanophotonics*, Pan Stanford Publishing, (2013)
4. L. Zhu, J. Kapraun, J. Ferrara and C J. Chang-Hasnain, *Optica*, Vol. 2, No. 2, March (2015)
5. E. Yablonovitch, *Phys. Rev. Lett.*, **58**, 2059-2062, (1987)
6. S. John, *Phys. Rev. Lett.*, **58**, 2486-2489, (1987)
7. J.D. Joannopoulos, S G Johnson, J N Winn and R D Meade, *Photonic Crystals: Molding the Flow of Light* (2nd Edn.), Princeton University Press, (2008)
8. E. Yablonovich, *Scientific American*, (2001)
9. N. Ashcroft and N. D. Mermin, *Solid State Physics*, Harcourt Asia PVT. Ltd., (2001)
10. P. Russell, *Science* **299** (5605), 358-362, (2003)
11. G P Agrawal, *Nonlinear Fiber Optics* (5th Edn.), Academy Press, (2013)