PHOTONIC CRYSTAL FIBER- AN OVERVIEW

Neha Mahnot[1], Shikha Maheshwary[2], Rekha Mehra[3]

[1, 2, 3] *Govt. Engg. College, Ajmer*

[2]shikhasm1992@gmail.com

[1]neha29mahnot@gmail.com

***Abstract-* This review paper gives an overview on Photonic Crystal Fiber (PCF) & its applications. Photonic Crystal Fiber is also known as micro structured or Holey fiber. Photonic crystal fiber is preferred over optical fiber because of its high design flexibility. Photonic crystal fiber is actually an optical fiber with a periodic arrangement of low index material in a background with high refractive index material. Light can be guided inside the PCF by either modified total internal reflection or photonic band gap guidance. Discussion of PCF in this paper includes its fabrication as well as application. Two methods namely "Stack and draw technique" & "Extrusion fabrication process" are used for the fabrication. PCF can be designed to get zero dispersion at required wavelength. PCF can be efficiently used in sensing applications using long period fiber grating (LPFG). LPFG can be fabricated using CO_2 laser irradiation technique, which is preferred over interference method. Hence Photonic crystal fiber is a better alternative to conventional optical fiber for the above applications.**

Keywords- Photonic crystal fiber (PCF), Modified total internal reflection, photonic band gap guidance, long period fiber grating (LPFG).

I. INTRODUCTION

Optical fiber is a wired transmission media that provides more reliable and versatile optical channel than the atmosphere. For any communication system the most important characteristics are bandwidth and signal to noise ratio as they decide the capacity of the channel. At present optical fiber link has loss of 0.2 dB/km at 1550 nm wavelength. The bandwidth of a single fiber-optic communication link is approximately 50 THz. Thus fiber optic communication systems form the backbone of modern telecommunication system. Other than communication, optical fiber has wide range of applications in sensors.

But, optical fiber can't provide design flexibility. So an attractive alternative fiber came into existence. Photonic crystal fiber provides excellent design flexibility by just varying its geometrical dimension. PCFs are optical fibers with a periodic arrangement of low-index material in a background with higher refractive index. The background material in PCFs is usually pure silica and the low-index region is typically provided by air-holes running along their entire length. In particular, by changing the geometric characteristics of the air-holes in the fiber cross-section, that is, their position or dimension, it is possible to obtain PCFs with excellent design flexibility [1].

By using PCF it is possible to achieve single mode even at core diameter in the range of several tenths of µm, whereas in conventional optical fiber highly diminished core is required for single mode fiber. In optical fiber zero dispersion occurs at 1310nm. To get zero dispersion at different operating wavelengths dispersion compensating fiber can be designed using PCF. Long period fiber grating constructed in PCF using CO_2 laser irradiation technique can be used to sense various parameters such as strain, pressure, temperature etc.

II. PHOTONIC CRYSTAL

Photonic crystals are periodic optical microstructures that affect the motion of photons in the same way as ionic lattice affect the electrons in semiconductors. The peacock tail and the wings of butterfly are the example of natural photonic crystal. In the peacock tail Green and blue color is actually seen due to the photonic crystal effect. In this case, production of color takes place due to the microscopically structured surface, fine enough to interfere with visible light.

Photonic crystals are periodic dielectric structures. They are termed as crystals because of their periodicity and photonic because they act on light. This phenomenon occurs when the period is less than the wavelength of the light. Photonic crystal may inhibit the propagation of certain range of wavelengths in either one direction or in all directions and hence provide the possibility to confine and trap the light in a cage.

Photonic crystal consists of repeating regions of higher and lower dielectric constant which are in periodic fashion. Photons propagate through this structure. Modes are the wavelengths that are allowed to propagate and group of modes form bands. The disallowed bands of wavelength form photonic bandgaps.

Light for some wavelength within the photonic band-gap is prohibited from propagation in any direction inside a photonic crystal. Because of this similarity with semiconductor having energy gap for electrons, photonic crystals are sometimes even called 'semiconductors for photons'. They can be created from almost any material, so it satisfies the material-compatibility requirement.

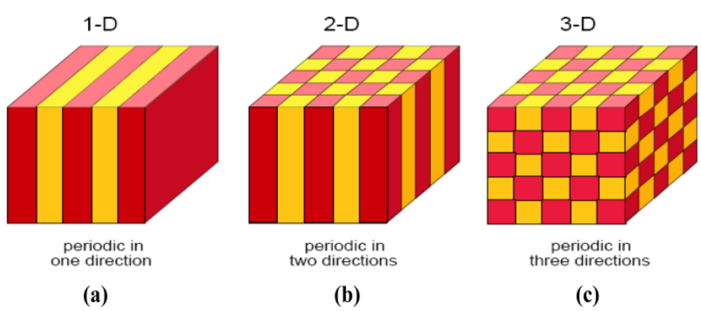

Fig. 1: Geometrical shapes of photonic crystals (a) 1D (b) 2D and (c) 3D [1]

First time the formulation of this idea is found as early as 1972 by Bykov. However, the field of research started with two independent publications of Eli Yablonovitch and Sajeev John who first calculated the optical properties of photonic crystals. Photonic crystal can be fabricated as one-dimensional, two-dimensional & three-dimensional photonic crystal.

Fig.1 describes the shape of 1D, 2D and 3D photonic crystals. In one dimensional photonic crystal, the periodic modulation of the refractive index occurs only in one direction, while the refractive index variations are uniform for other two directions of the structure. Similarly in two & three dimensional photonic crystal, the periodic modulation of the refractive index occurs in two & three dimensions respectively.

The simplest examples of 1-D, 2-D, 3-D photonic crystal are Bragg grating, photonic crystal fiber, stake of two dimensional crystals respectively.

III. PHOTONIC CRYSTAL FIBER

Photonic crystal fibers, also known as micro structured or holey fibers generated great interest in the scientific community. Today, photonic crystal fibers (PCFs) are established as an alternative fiber technology. Two main categories of PCFs exist: high-index guiding fibers and photonic band gap. PCFs belonging to the first category are more similar to conventional optical fibers, because light is confined in a solid core by exploiting the modified total internal reflection mechanism. In fact, there is a positive refractive index difference between the core region and the photonic crystal cladding, where the presence of air-hole causes a lower average refractive index. The guiding mechanism is defined as "modified" because the cladding refractive index is not constant value, as in conventional optical fibers, but it varies significantly with the wavelength.

When the PCF core region has a lower refractive index than the surrounding photonic crystal cladding, light is guided by a mechanism different from total internal reflection that is, by exploiting the presence of the photonic band gap (PBG). In fact, the air-hole microstructure which constitutes the PCF cladding is a two-dimensional photonic crystal that is a material with periodic dielectric properties characterized by a photonic bandgap, where light in certain wavelength ranges cannot propagate.

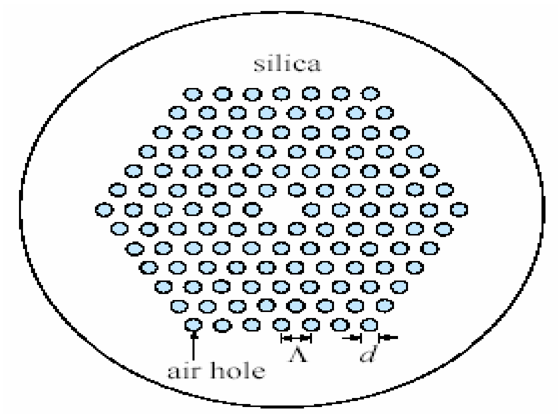

Fig 2: Schematic of the cross-section of the solid-core photonic crystal Fiber [1]

This characteristic, as well as the high refractive index contrast between silica and air, provides a range of new interesting features. High design flexibility is one of the distinctive properties of PCFs. For example, PCFs with a small silica core and large air-holes, i.e., high air-filling fraction in the transverse section, have better nonlinear properties compared with conventional optical fibers, and so they can be successfully used in many applications.

On the contrary, fibers can be designed with small air-holes and large hole-to-hole distances, in order to obtain a large modal area, useful for high power delivery.

Since their first demonstration, PCFs have been the object of an intense research activity by the most important groups all around the world. In fact, it is particularly intriguing to study the new light-guiding mechanisms offered by PCFs and the innovative properties related to the presence of the PBG.

IV. GUIDING MECHANISM

In standard optical fiber total internal reflection is the method of guiding light since core refractive index is greater than that of cladding so light is confined inside the core. In case of photonic crystal fiber the two light-guiding mechanisms are used. In solid-core photonic crystal fibers, where light is confined in a higher refractive index region, modified total internal reflection is exploited, which is quite similar to the guiding mechanism of standard optical fibers. Instead, when the light is confined in a region with a refractive index lower than that of the surrounding area, as in hollow-core fibers, it is due to the presence of the photonic bandgap.

A. Modified Total Internal Reflection

It is possible to use a two-dimensional photonic crystal as a fiber, by choosing a core material with a higher refractive index than the cladding effective refractive index. An example of this kind of structures is the PCF with a silica solid core surrounded by a photonic crystal cladding with a triangular lattice of air-holes. These fibers, also known as index-guiding PCFs, guide light through a form of total internal reflection (TIR), called modified TIR.

Basically in solid core PCF, core consists of pure silica whereas cladding contains photonic crystal which has number of air holes that decreases the refractive index of core. This modified refractive index of cladding which is less than that of core enable light to travel using phenomenon of modified total internal reflection.

We can better understand the guiding mechanism by comparing it to model filter or sieve. The cladding of PCF consists of air holes. These air-holes act like strong barriers, so they are the “wire mesh” of the sieve. The field of the fundamental mode, which fits into the silica core with a single lobe of diameter between zeros slightly equal (or greater) to 2Λ, is the “grain of rice” which cannot escape through the wire mesh. Whereas, the lobe dimensions for the higher-order modes are smaller, so they can slip between the gaps. When the ratio d/Λ, that is the air-filling fraction of the photonic crystal cladding, increases, successive higher-order modes become trapped. A well geometry design of the fiber cross-section thus guarantees that only the fundamental mode is guide.

B. Photonic Bandgap Guiding

When photonic crystal fiber design is completely different form the traditional ones, which results from the fact that the photonic crystal cladding has greater refractive index than core. They do not relay on TIR for the guidance of photons. In fact, in order to guide light by TIR, it is necessary that the core is surrounded by a lower-index cladding material. But in photonic bandgap guiding the core consist of air hole and there are no suitable low-loss materials with a refractive index lower than air at optical frequencies. Thus, light is guided due to the presence of bandgap. We know that the photonic crystal allows only those photons which have bandgap greater than that of PCF cladding bandgap. So, all those photons with band higher than PCF bandgap evanescent in cladding and the rest propagate in air core.

The first hollow-core PCF had a simple triangular lattice of air-holes, and the core was formed by removing seven capillaries in the center of the fiber cross-section. In this type light is guided by using the bandgap i.e. only a particular portion can enter in cladding and rest reflect back and lost in air or hollow core. When white light is launched into the fiber core, colored modes are transmitted, thus indicating that light guiding exists only in restricted wavelength ranges, which coincide with the photonic bandgap.

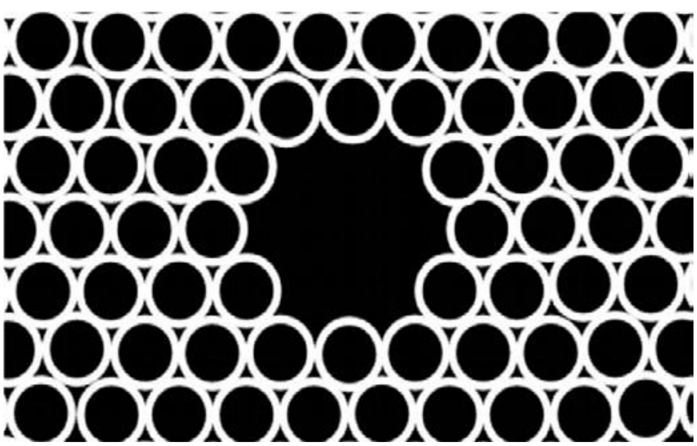

Fig 4: cross-section of the first hollow-core PCF, with hole-to-hole spacing of 4.9 µm and core diameter of 14.8 µm [2]

V. FABRICATION PROCESS

One of the very important aspects of any device is its fabrication process. Traditional optical fibers are usually manufactured by fabricating a fiber preform and then drawing fiber from it with a high-temperature furnace in a tower setup. The different vapor deposition techniques, for example, the modified chemical vapor deposition (MCVD), the vapor axial deposition (VAD), and the outside vapor deposition (OVD), are used for the fabrication of symmetric circular fiber performs. Thus, the deposition can be controlled in a very accurate way only in the radial direction without significant modifications of the methods.

In case of PCF, several forces like viscosity, gravity, and surface tension are of great importance. These forces are due to the much larger surface area in a micro structured geometry, and to the fact that many of the surfaces are close to the fiber core, thus making surface tension relatively much more important. Also in conventional optical fiber core and cladding materials with similar refractive index values, which typically differ by around 1%, whereas designing PCFs requires a far higher refractive index contrast, differ by perhaps 50–100% [4].Hence all the techniques previously described are not directly applicable to the fabrication of preform for micro structured optical fibers, whose structure is not characterized by a circular symmetry.

There are two methods for the fabrication of photonic crystal fiber: stack and draw technique and Extrusion fabrication process.

A. Stack And Draw Technique

This method introduced by Birks et al. in 1996, has become the preferred fabrication technique. Since it allows relatively fast, clean, low-cost, and flexible perform manufacture. The PCF preform is realized by stacking a number of capillary silica tubes and rods to form the desired air–silica structure. This way of realizing the preform allows a high level of design flexibility, since the control of core shape and size, as well as the index profile throughout the cladding region is possible. After the stacking process, the capillaries and rods are held together by thin wires and fused together during an intermediate drawing process, where the preform canes are drawn from preform. Then, the preform is drawn down on a conventional fiber-drawing tower, greatly extending its length, while reducing its cross-section, from a diameter of 20 mm to 80–200 μm [3]. In order to carefully control the air-hole size during the drawing process, it is useful to apply to the inside of the preform a slight overpressure relative to the surroundings, and to properly adjust the drawing speed.

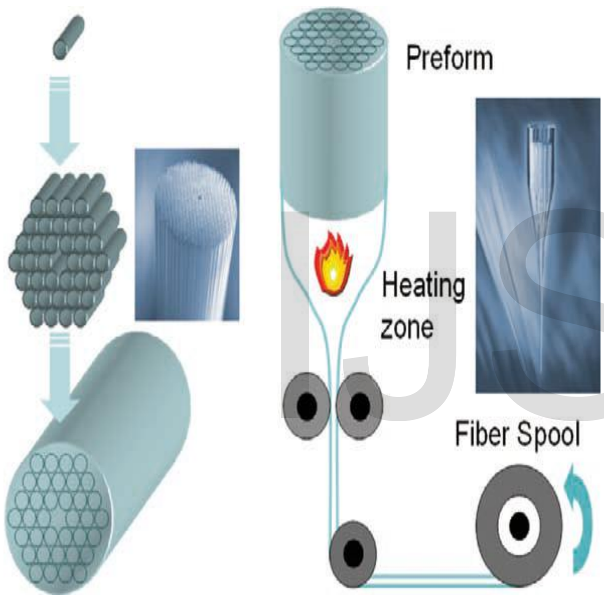

Fig 5: Stake and draw technique [3]

Temperature should not exceed 1900^0 C [3] since the surface tension can otherwise lead to the air-hole collapse. Dynamics, temperature, and pressure variations are all significant parameters which should be accurately controlled during the PCF fabrication. Finally, the PCFs are coated to provide a protective standard jacket, which allows the robust handling of the fibers. Stacking method requires the handling very carefully, and the control of air-hole dimensions, their positions, and shapes in PCFs makes the drawing significantly more complex than that of conventional optical fiber.

B. Extrusion Fabrication Process

Silica–air preforms have also been extruded, enabling the formation of structures not readily attainable by stacking capillaries. In extrusion a material is pushed or draw through a tool called die which is use to shape materials of desired cross-section. Extrusion process is applied to the glasses other than silica which are not readily available in the form of tubes. In this fabrication process a molten glass is forced through a die containing a suitably designed pattern of holes. Extrusion allows fiber to be drawn directly from bulk glass, using a fiber-drawing tower, and almost any structure, crystalline or amorphous, can be produced. It works for many materials, including polymers, and compound glasses. The structured preform of 16 mm outer diameter and the jacket tube are extruded. The preform is reduced in scale on a fiber-drawing tower to a cane of about 1.6 mm diameter in caning process. The cane is inserted within the jacket tube. This assembly is drawn down to the final fiber.

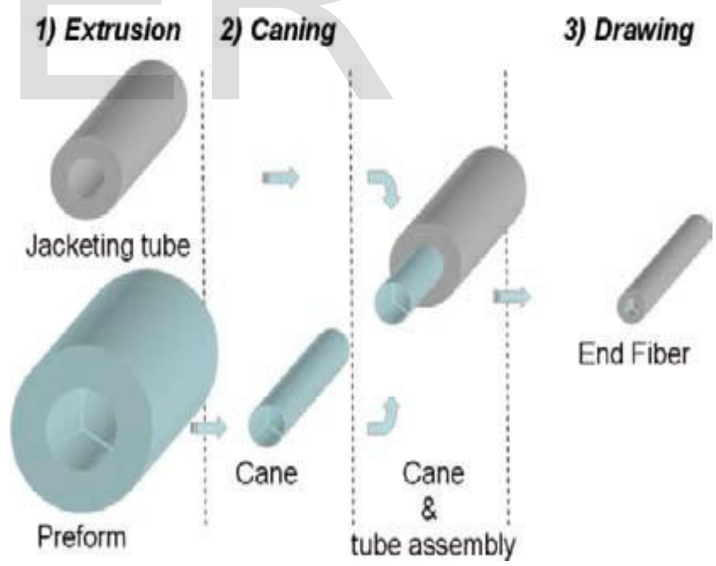

Fig 6: fabrication using extrusion [3]

This method can also be applied to other commercial glasses, including some with higher nonlinearity and slightly lower intrinsic loss. In particular, a tellurite PCF with an outer diameter of 190 µm and a core diameter of 7 µm has been realized [3].

VI. APPLICATIONS OF PCF

For both index guiding and bandgap guiding PCF by varying hole size, space and distance between the core we can obtain required optical properties.

A. Endlessly single mode fiber

On the basis of modes optical fiber are of two types: single mode fiber and multimode fiber. In single mode fiber only one mode can propagate and in multimode fiber many modes can travel simultaneously. Producing single mode fiber is an expansive and it is difficult to obtain such a narrow core radius of few micrometers. But using single mode fiber we can compensate the problem of intermodal dispersion. So it is need to have an endlessly single mode fiber at comparatively greater radius.

The first solid-core PCF which consist of a triangular lattice of air-holes with a diameter *d* of about 300 nm and a hole-to-hole spacing Λ of 2.3 µm [1]as shown in fig.2 did not ever seem to become multi-mode in the experiments means it is endlessly single mode. Variation in the design includes three, five or seven missing holes are also found to be endlessly single mode. It is found that when the value of the ratio of hole size to hole spacing exceed certain value then only single mode propagation supported. Very small to very large core size can be supported regardless of wavelength. So it is possible to construct a fiber with tens of micron core size.

B. Zero Dispersion Photonic Crystal

Dispersion is a very important phenomenon which is needed to be considered and compensated. There are basically two types of dispersion: inter model and intra modal or chromatic dispersion.

Intermodal dispersion occurs due to the fact that multiple modes travel inside the fiber and each mode travel with different velocity and hence reach the receiver at different time. This type of dispersion can be compensated using single mode fiber i.e. we can use endlessly single mode fiber. Chromatic means color, this type of dispersion occurs because different colors of light travel with different speed. It is of two types: material and wave guide dispersion. Waveguide dispersion has negative dispersion coefficient so the overall dispersion must be zero at some point. For conventional fiber the zero dispersion occurs at 1.3µm. It is possible to compensate chromatic dispersion if zero dispersion wavelengths occur at operating frequency.

Due to the high refractive index difference between silica and air in PCF's , and to the flexibility of changing air-hole sizes and patterns, a much broader range of dispersion behaviors can be obtained with PCFs than with standard fibers. By proper designing of photonic crystal fiber it is possible to design such a fiber which gives zero dispersion wavelengths at operating wavelength.

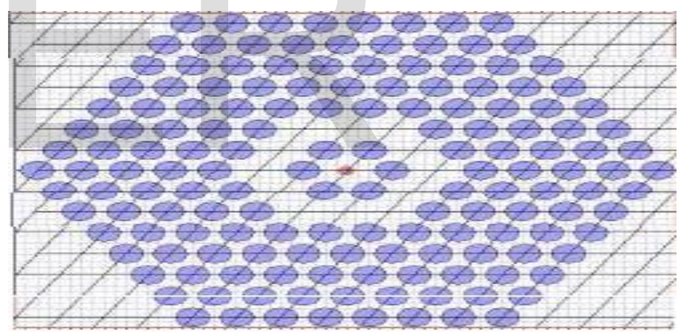

Fig 7: structure with second missing ring [4]

Configuration of PCF	Zero dispersion wavelength
Layer 3	……
Layer4	…….
Layer 5	1.55 µm
Layer 6	1.45 µm
Layer 7	1.2 µm

Table 1: Zero dispersion wavelength at different wavelengths [4]

By using a PCF with a missing air hole in solid core and a missing second ring as shown in the fig. 7 we can obtain zero dispersion at different wavelengths. Hence by using different layers we can obtain zero dispersion at different wavelengths.

C. Sensing application of PCF using LPFG

A broad range of sensors can be fabricated using photonic crystal fiber to sense temperature, pressure, strain, humidity etc. It is possible to achieve better linearity using long period fiber grating (LPFG) as a sensor in PCF. LPFG provides periodicities of several hundred wavelengths as compared to fiber Bragg grating having the periodicity of few wavelengths. Fiber Bragg grating is a 1D photonic crystal in which periodic or non periodic variation in refractive index of fiber core occurs in one dimension. To construct the LPFG in different types of optical fiber, various fabrication method such as UV laser exposure, CO_2 laser irradiation, electric arc discharge are used.

UV laser exposure- This is the first method used for fabrication of LPFG. Generally, it constructs periodic variation in the refractive index of fiber core. First two ultraviolet (UV) beams incident on the GeO_2-doped silica fiber i.e. a photosensitive optical fiber. Two UV beams having the wavelength 244 nm [5]. When these two UV beams constructively interfere to each other, then create the maximum intensity & there will be minimum intensity when two UV beams destructively interfere to each other. Refractive index of silica fiber is increased at the place of maximum intensity i.e. shown by positive sinusoidal peak & at the place of minimum intensity there is no change in the refractive index of the fiber core shown by negative sinusoidal peak. It forms a periodic index variation along the axis of the fiber that is GRATING.

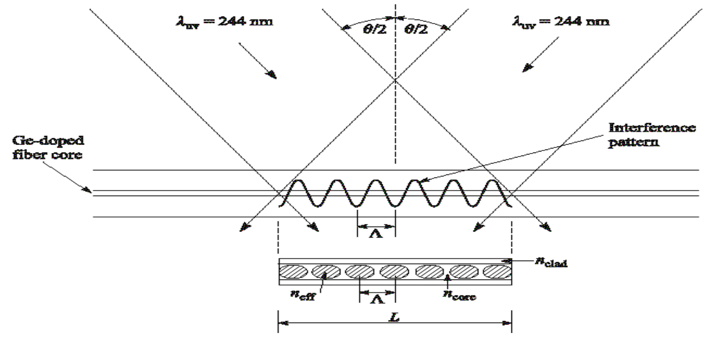

Fig 8: UV laser exposure [5]

CO_2 laser irradiation- It is superior to UV laser exposure because it provides unique number of features such as:

- Much more flexible, because flexibility is controlled by irradiation of CO_2 laser beam.
- Low cost because it doesn't require photosensitivity and any other pretreated processes are to write a grating in the glass fibers.
- The CO_2 laser irradiation process can be processed under control to generate complicated grating profiles via the point-to-point technique without any expensive masks.
- Highly efficient technique for grating fabrication.

CO_2 laser irradiation can be used to write high-quality LPFGs in different types of optical fibers without photosensitivity, including solid-core PCFs and air-core PBFs. CO_2 laser irradiation provides near zero insertion loss. The continuous irradiation of CO_2 laser beam on the solid core PCF increases the temperature on the fiber surface. Due to it, there is periodic collapse of air holes & the gasification of SiO_2 on the fiber surface take place. It induces periodic refractive index modulations along the fiber axis & creates LPFG with periodic grooves in the solid core PCF. Through the scanning mirror CO_2 laser beam is shifted to the next grating period to create the LPFGs.

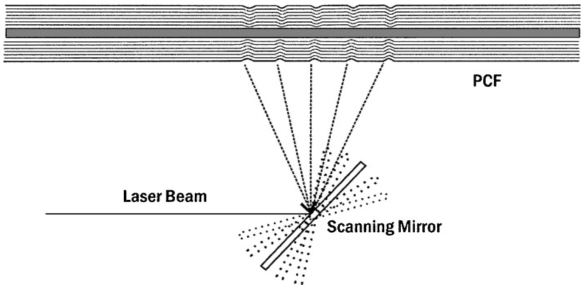

Fig 9: First LPFG written in a pure-silica solid-core PCF [5]

LPFG can also be fabricated in photonic bandgap fiber by using the same method as that used in solid core PCF. Since almost 100% of the light [5] propagates into the air holes of the core, not in the glass, PBF based grating offer a unique number of the features:-

- Better linearity
- Large strain sensitivity.
- Unusual mode coupling.
- New possibilities for long distance light-matter interactions when additional materials are present in the air holes.
- Very large polarization dependent loss.

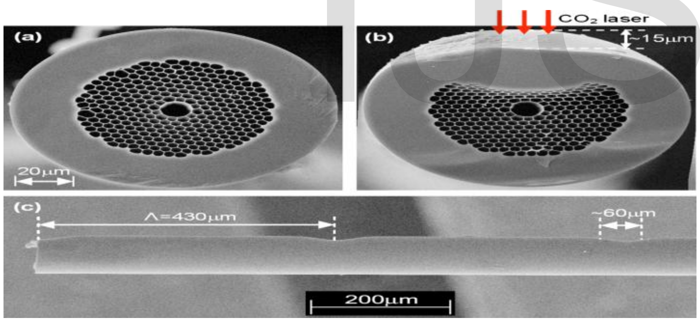

Fig 10: Cross-section image of an air-core PBF (a) before (b) after CO_2 laser irradiating (c) side image of a LPFG written in the air-core PBF, where about two periods of the LPFG are illustrated [5]

Temperature Sensor- Transmission spectra of the CO_2-laser-induced LPFGs shift linearly with the change in temperature and are stable when subjected to a very high temperature of up to 1200°C [5]. Therefore, the CO_2 laser induced LPFGs are excellent temperature sensing elements, especially high temperature sensors. In contrast, the sensors employing a UV-laser-induced grating usually have to work under a temperature of about 300 °C [5].

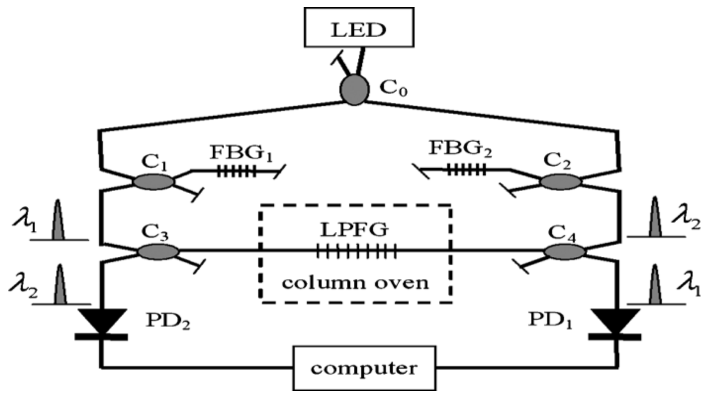

Fig 11: Temperature sensor system based on intensity modulation [5]

Here, a practical temperature sensing system is shown that is based on intensity modulation. It uses a CO_2-laser induced LPFG with periodic grooves as a sensing element. Two FBGs are employed to select two different single wavelengths that differ by intensity. After selecting the wavelengths, it is passed through the LPFG. LPFG is a temperature sensor that changes the intensity of passing wavelength according to the temperature. By calibrating the variation in intensity of passing wavelength, temperature can be measured. Thus intensity modulation is used in this temperature sensing system.

Strain Sensor- When tensile strain is applied to CO_2-laser-induced LPFGs with periodic grooves, it exhibits unique optical property. When a CO_2-laser-induced LPFG with asymmetric grooves is stretched, then periodic micro bends are induced. Such stretch-induced micro bends effectively enhance refractive index modulation in the gratings. By determining the enhancement in refractive index modulation, applied stress can be measured. As a result, such a LPFG have an extremely high strain sensitivity of −102.89 nm/μ€ [5] which are two orders of magnitude higher than that of other CO_2-laser-induced LPFGs without physical deformations in the same type of fibers.

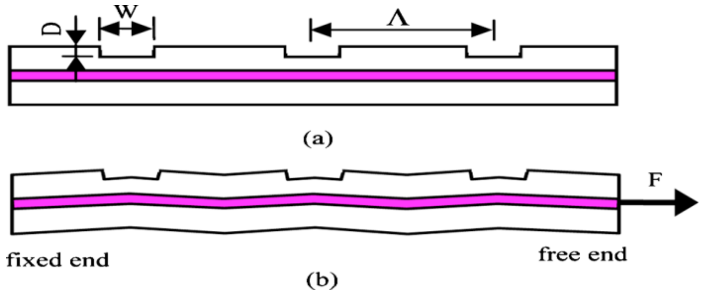

Fig 12: Schematic diagram of the CO_2-laser-carved LPFG with asymmetric grooves (a) before and (b) after a stretching force is applied to the grating [5]

VII. CONCLUSION

In this paper, first we studied about the basics of photonic crystal fiber, its fabrication & guiding mechanisms. We came in contact of various limitations of optical fiber transmission media. To overcome these limitations, we have reviewed a special PCF design. Here PCF enables endlessly single mode fiber, zero dispersion at different operating wavelengths, & in sensing applications using LPFG constructed by CO_2 laser irradiation technique.

ACKNOWLEDGEMENT

We are highly grateful to Mrs. Rekha Mehra, Associate professor & head of ECE department, Govt. Engineering College, Ajmer, for providing us the opportunity to carry out this work.

REFRENCES

[1] J. C. Knight, "Photonic crystal fibres", *Nature*, vol. 424, pp. 847–851, Aug. 2003.

[2] P. St. J. Russell and R. Dettmer, "A neat idea photonic crystal fibre" , *IEEE Review*, vol. 47, pp. 19–23, Sept. 2001.

[3] J.C.Knight, T.A.Birks, P.St.J. Russell, D.M.Atkin, Opt. Lett. 21, pp. 1547, 1996.

[4] Vineet Agrawal, Ravindra Kumar Sharma, Ashish Mittal, "Designing Zero Dispersion Photonic Crystal Fiber With Concentric Missing Ring", IJECT Vol. 4, Issue Spl - 4, April - June 2013.

[5] Yiping Wang, "Review of long period fiber gratings written by CO 2 laser", Journal of Applied Physics 108, 081101, 2010.