Photonic Crystal Fibres (PCF)

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Abstract- This paper brings light to a new class of optical fibres known as photonic crystal fibres abbreviated as PCF. PCFs are very protean as compared with the traditional optical fibres. This paper also gives a glimpse as to what are photonic crystals with photonic crystals and photonic band-gap. Sensor applications of PCFs are discussed in the paper below. Various technological advancements in PCF is also mentioned.

Keywords: Photonic crystals, band-gap, optical fibres, sensors.

I. INTRODUCTION

Technology has scaled a long way through civilization. We have used copper cables and advanced to optical fibres. Optical fibres scattered all over the world paving a new way to connect the globe. They have been used for many different uses like internet connectivity, inter and intra networking, medical imaging, telecommunication, automobile industry, military purposes etc.

Optical fibres were a stride from a copper cable. It provided a greater bandwidth. This gives us the power to transfer more data over the given network with an increased speed. These fibres are more reliable unlike copper cables which aren't immune to electromagnetic interference. Furthermore, optical fibres are not easily tapped and harder to hack which enhances the security. Certainly, optical fibres are expensive but when all is said and done, they last longer and don't need literally any maintenance.

Optical fibre follows the principle of total internal reflection. Optical fibres are composed primarily of a core and a cladding. Cladding is the outer surface and the core is the inner surface for light transmission. Both these surfaces are made of silica. Light travels through the fibre using the process of total internal reflection. It is dominated by two specific conditions. First, the angle in the denser medium must be greater than the critical angle and the light must travel in the denser medium.

For this reason, the refractive index of the cladding must be smaller than the core. This makes the total internal reflection occurs at the core-cladding boundary.

Although the compatibility, reliability, and sensitivity of optical fibres revolutionized the telecommunication and sensory industry, it carries some setbacks and limitations. Its geometry and refractive index may cause inherent losses, dispersion, non-linearity, birefringence, etc. These drawbacks lead to a special class of optical fibres known as Photonic Crystal Fibres (PCF).

Photonic crystal fibres use a periodic arrangement of hollow holes to confine light. Unlike the traditional optical fibre, PCF doesn't have a glass surface to control the trajectory of light. Instead, they have hollow air holes to confine light and use it for various applications in spectroscopy, imaging, telecommunication, networking, biomedicine etc., opening new fields in non-linear optics, fibre lasers and sensors, particle guidance, and many more.

II. PHOTONIC CRYSTAL FIBRE

Photonic crystal fibres are unique forms of optical fibres that use photonic crystals as a medium or waveguide. These crystals are dielectric in nature and are made of hollow microscopic air holes that run throughout the wire inside a coating. The cladding of the fibres has air holes. Due to the difference in the refractive index of air holes and the material, the refractive index of the cladding has a periodic arrangement.

The manufacturing of PCFs is based on three prime specifications: the diameter of the core, the diameter of the ait hole, the pitch (pitch is the distance between two consecutive air holes). These specifications define the light-guiding characteristic of PCFs. The refractive index of the cladding is also dependent upon the pitch and the diameter. With the flexibility in choosing the material, refractive index, and the geometry of the fibre one gets to achieve different mechanisms for guiding the light beam.

PCFs are classified into two major categories:

- Index guided fibres
- Photonic band-gap fibres

2.1 Index Guided Fibres –

Index guided fibres have a solid high index core at the center of the fibre invariantly extending, along the holes, throughout the fibre. Light is trapped by the modified total internal reflection mechanism. The air holes are made in the cladding. The refractive index of the cladding is variable and dependent on the geometry, material, and radial distance. In these fibres, the refractive index of the cladding is lower than that of the core and is a resultant of the refractive index of air and the material. This condition is similar to that of traditional optical fibres.

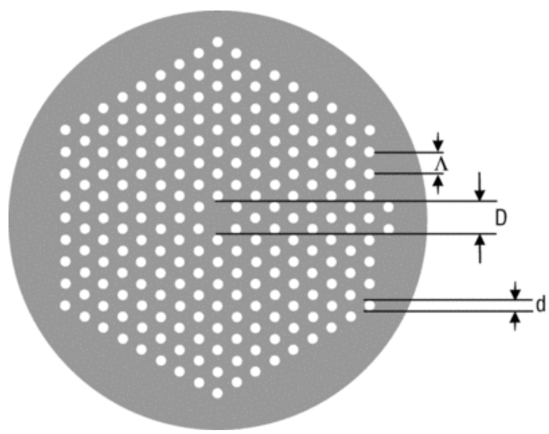

Figure 1. An index guided fibre. The center has a solid core. 'Λ' denotes the pitch, 'D' denotes the diameter of the core and'd' denotes the diameter of the air hole.

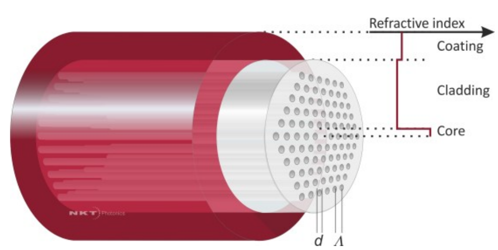

Figure 2. Cross-section of an index guided PCF along with the refractive indices.

2.2 Photonic Band-gap Fibres -

Photonic band-gap fibres have a hollow air hole at the center that runs throughout the fibre. Unlike the index guiding fibre, the refractive index of the core is lower than that of the cladding. Due to this reason, photonic band-gap filters do not follow or are operated by the principle of total internal reflection. To counter this, the concept of a photonic band gap came into light.

Photonic band-gap**:** Some material has dielectric properties which prevent some frequencies of light to propagate through them. There is a range of frequencies and hence it is called a band-gap. These band-gap structures are of 3 types: 1D, 2D and 3D crystals. The 1D type crystals are generally known as Bragg fibres while the 2D crystals make up the photonic crystal fibres.

In hollow-core fibres, a photonic band-gap is achieved by using periodic air holes like that in the index guided fibres, is a low index material. In these types of fibres, light is propagated through the hollow core. There is no Fresnel reflection nor are there any losses due to the bending of light.

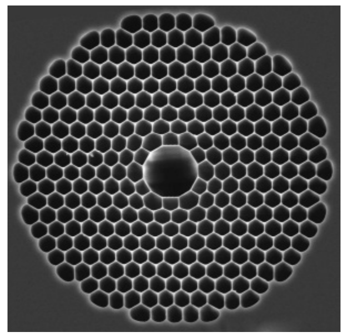

Figure 3. Photonic band-gap fibre (hollow-core PCF)

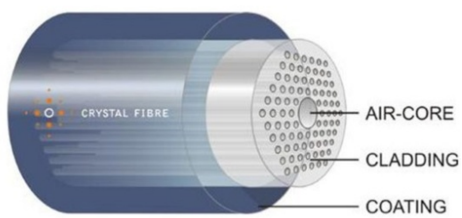

Figure 4. Cross-section of a photonic band-gap fibre.

III. PCF AS SENSORS

A sensor is a device that detects and responds to an aberrant situation. It also works to ensure the safety of a device and to alert whether there is a deterrence from the definite path that is supposed to be followed. Nowadays, sensors are gravitating towards photonic crystal fibres. PCFs provide a protean range of sensors There is a raft of reasons for choosing PCFs. The small size, refractive index, independence from any electrical impedance, remote sensing abilities, etc. are potential properties of PCFs making them ideal for sensing applications. Photonic crystal fibre sensors are broadly characterized in two divisions: physical sensors and biochemical sensors.

Physical sensors cover the fields of temperature, pressure, displacement, curvature, twist, refractive index, etc. Biochemical sensors include sensors like gas, humidity, pH, protein, etc.

3.1 Physical sensors -

PCF-based physical sensors are used to measure various physical parameters like temperature, humidity, pressure, curvature, torrid, displacement, etc. These sensors hold a significant value due to their measuring capabilities. The control and monitoring parameters of these sensors attract a lot of interest in the sensing industry.

Many engineering structures like buildings, drainage, dams, etc. are made use of these sensors for sustainability and avoid any impedance due to an aberration. Properties like remote sensing, in-situ, immunity to effects due to electromagnetic fields and high voltages made them.

3.1.1 Temperature sensor-

Temperature sensors are used in lots of areas. They have a vast scope of medical applications like in thermometers, ultrasound scanners, MRI equipment, etc. They are also used in various home appliances, miming, automobiles, etc.

Optical temperature sensors came out to be very effective. Due to the immunity of PCFs from electromagnetic fields and high voltages, these optical temperature sensors are widely used in fields that are susceptible to such effects.

There has been constant development and improvement in PCF- based optical fibres. Many such sensors include Sagnac interferometer, Bragg fibre grating, long-period fibre grating, etc. These sensors have different temperature ranges based on the substance filled inside the fibre. For instance, Sagnac interferometer-based sensor, proposed by Liu et al, has a temperature range of -25 degree C to 85 degree C. Long-period fibre grating, filled with isopropanol can have a temperature range from -271.1°C to 126.85°C.

3.1.2 Displacement or Strain sensor-

When a body is exposed to a force it tends to deform its shape. The amount of this deformation is known as the strain. Strain sensors detect this deformation. They are obligatory in many industrial fields and even in biomedical equipment. PCF-based strain sensors are used to detect earthquakes, fire, defects in telecommunication equipment, etc. Due to various properties of PCFs like immunity from electromagnetic intervention, remote sensing, flexibility, etc. fibre optic-based strain sensors are widely used. We can use an optoelectronic interrogator to send the light to the sensor and can then determine the strain experienced by it. However, this method is susceptible to temperature changes. This will hamper the correct measurement. So we use interferometers such as Fabry-Perot interferometers. Here, we use the shift in the resonance frequencies in the grating to measure the strain. Likewise, there is a raft of methods to build a strain sensor.

3.1.3 Pressure sensors-

Pressure is the measure of the force applied to a unit area. To detect a change in pressure, there are many pressure sensors available.

Pressure sensors are a useful tool in various industrial applications and even to limit environmental hazards. They are used for monitoring various processes even in severe conditions. Used in turbine engines, buildings, mines, etc, these sensors are exposed to a harsh environment that is not essentially tolerable by conventional pressure sensors. PCF-based pressure sensors are thus great for such grinding conditions because of their various properties. These optical pressure sensors have light trapped in them. Due to a change in the pressure, the light beam is distorted or blocked. This signals to the system that there is some change in the pressure applied. There are many types of pressure sensors available such as model interferometer-based high birefringence PCF, Bragg grating-based high birefringent fibre, Sagnac interference with polarization-based PCF, etc.

3.1.4 Torsion or twist sensor-

Torsion or twist is a very essential factor that requires careful consideration, especially in civil engineering. It is the measure of the twist experienced by the object under force. PCF- based torsion sensors are very efficient and highly used because of their high flexibility, small size, resistivity from any environmental hazards. These sensors measure the twist angle and direction. Many of these sensors are based on Bragg- grating in PCFs or interference. Torsion sensors can also be induced with LPG in the silicon core of the fibre.

3.1.5 Refractive index sensors-

Refractive index is a significant property of a material. It determines the speed of light in any medium. It is an indication of the amount of bending that the ray of light experiences when it is passed through a material. It is measured by the ratio of the sine of incidence angle to the sine of reflected angle. Refractive index is used wildly in many sectors such as biochemical industry, food processing industry and in various medical industries. These sensors will detect variations in refractive index. This indicates a change in the material in which light is propagating. Such detection in variation in refractive index tells a lot about the material or the mixture which is the medium of propagation. There are various methods to fabricate a PCF-based refractive index such as evanescent field, fibre grating, SPR, interference, etc. Numerous types of these optical refractive index sensors are reported such as LPG inscribed PCF sensors, modal interference etc.

3.1.6 Vibration sensors-

Vibrations are caused by imbalance and structural or mechanical failures. These lead to heavy damages and high losses. For these reasons there is a need for constant monitoring of any changes or defects by vibrations to prevent accidents and damages. These sensors are employed in aircrafts, mining, buildings, railway tracks, etc. Generally, vibration sensors are made either intensity based, fibre brag grating or Fabry-Perot interferometer. Vibration sensors detect the vibration amplitude and frequency during a seismic activity.

3.2 Biochemical sensors -

Photonic crystal fibres offer a large range of biochemical sensors. Since chemical and biological industry deals with experiments with living organisms, these biochemical sensors are ideal for such in-vivo experiments. This is because they are small in size, are light in weight, allow remote sensing abilities and most importantly is free from any electromagnetic activity.

Biochemical sensor convert any variation in the a chemical or biological entity into an electrical signal. PCF-based biochemical sensors use a very little amount of the fluid as a sample however, the traditional optical fibres use comparatively large amount of fluid. This imputes to the wide applications and usage of PCF-based biochemical sensors.

Some examples of these sensors are gas sensor, pH sensor, humidity sensor, liquid etc.

3.2.1 Gas sensor-

Many environmental hazards are attributed to gaseous emissions. With the growth of many industries like paper, rubber, pulp, cotton, textile, energy production and the increase in automobiles, the gaseous emissions has also increased leading to pollution and various diseases. Thus, it is very important to monitor the gaseous level and keep a check at it. Gas sensors usually use hollow core PCFs. This hollow core contains the gas. There are many such gas sensors such as acetylene sensor, methane sensor, etc.

3.2.2 pH sensor-

pH is the measure of acidity or alkalinity of a substance, usually in liquid or aqueous state. This is very important factor in determining the properties of a substance. The pH sensor is used to keep a check or detect an abnormality in the acidity and alkalinity of a particular substance or solution. Usually, the pH sensor has a coating or a stub of a pH sensitive layer and a pH meter scale. In a PCF-based pH sensor, this sensing process occurs in the air holes.

3.3.3 Humidity sensor-

Humidity is the measure of moisture in the atmosphere or surroundings. Humidity sensors are greatly used in air-conditioning, agriculture, meteorology, civil engineering, electrical industry, food processing, etc. It works on the principle in which water is attached to a very thin-film interferometer in the holes of PCF. This accounts for a detection in any changes in the humidity of the surrounding.

IV. ADVANCEMENTS IN PHOTONIC CRYSTAL FIBRES

Photonic crystal fibres have made a breakthrough in the field of optical fibres. Although a lot of research has been done regarding PCFs and many applications seem to be molded, PCFs are yet to be out in the market completely. Researchers have been attempting to improve the efficiency of the fibre by employing various shapes of the fibre like hexagonal, octagonal etc.

Recently, the use of PCFs for sensing purposes is attracting a lot of attention of scientists and researchers. This is attributed to the various properties of PCFs like remote sensing, small size, light weight and resistivity to environmental hazards. Various methods are in use to hone the sensing range. For all the above mentioned sensors, there are variations in the air holes and material used to enhance the efficiency of the sensors. Liquid filling also can be effective deployed. Biosensors are capturing many patents due to its advance use especially in the field of medicine.

Photonic crystal fibres are also gaining momentum in many other aspects. PCFs have drawn its attention to lasers. The gain medium is the fibre which provides amplification and gives a more coherent light. PCFs are also paving its way in supercontinuum generation. It provides higher brightness, higher resolution of the images and provides all the characteristics of single mode beam. PCFs are also being used for high power generation.

PCFs are expected to excel in optical computers, highly efficient light appliances, in photonic electronic devices, spectral filters etc.

V. CONCLUSION

Photonic crystal fibres are gaining a lot of attention due to its great efficiency. They offer a raft of applications opening up new methods and technologies. This article has precisely described the growth of PCFs. From the need of PCFs and their types to their growth in sensing, PCFs are still in its embryonic state but shows great prospects in future innovations an developments.

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