Recent Trends in Photonic Crystal Fiber

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Abstract: The photonic crystal fiber is new version of optical fiber. These have overcome major limitations of classical fibers. The history of photonic crystal fiber is discussed along with analogy that exists between electron and photon. For this paper we aim at discussing the basic concepts of photonic crystal, light guiding mechanism, important properties and potential applications of PCFs. This paper aims at describing properties, applications, fabrication of photonic crystal fibers. The freedom of changing the diameter of capillaries and lattice constant made possible the widespread use of photonic crystal fiber in many applications.

Keywords: photonic crystal fiber (PCF), photonic band gaps (PBG), Modified Chemical Vapor Deposition (MCVD), vapor axial deposition (VAD) and the outside vapor deposition (OVD), LPFG(long period fiber grating).

Introduction

Light as a mode of information transfer has revolutionized the world since the invention of optical fiber technology. However underlying guiding mechanism of total internal reflection restrain certain features of optical communication which are otherwise possible with a new class of fibers called photonic crystal fibers. This new class of fiber exhibit remarkable properties which depend upon their microstructure rather than material composition. Some of these traits such as endlessly single mode, large mode area, insensitivity to bending configurable dispersion properties, super continuum generator are literally impossible to achieve with conventional fiber because of strict parameters under single mode operation [1].

Photonic bandgap effect makes transmission characteristics sensitive to structural arrangement. With these features, photonic crystal fibers are invariably being used in sensor development, telecommunication, signal processing, optical MEMS, optical integrated circuits. Photonic crystal fibers are also proving helpful in achieving all optical processing viable. For this paper we aim at discussing the basic concepts of photonic crystal, light guiding mechanism, important properties and potential applications of PCFs. Rest of paper is organized as follows. Rest of paper is organized as follows.

History

In 1887, Photonic band gap in one dimension was experimentally discovered by an English Physicist Lord Rayleigh on dielectric stack of multiple layers. The guiding of light in a slab with a refractive index lower than that of the substrate was proposed and analyzed by Yeh and Yariv in 1976. In 1978,Pochiyeh et al discovered that confined modes exist in a fiber with a low-index core, provided the core is surrounded by a suitably designed alternating cladding of high and low refractive indices [2]. The term "Photonic crystal fiber" was invented by Philip Russell. In 1987, E.Yablonovitchandand S.John officially discovered photonic band gap[3]. Considerable work has been done in designing photonic crystal resources having periodic refractive index. Photonic crystal possesses a band gap. If photon is incident in the band gap material, it is reflected or may get confined in the lattice unable to propagate. In 1991, Philip Russell proposed to develop PCF as the concept of stop band prevented its propagation in all direction. In 2-D PBG a large difference between refractive index of core cladding 2.2:1 is desired for photonic band gaps to appear. The idea of PCF with air core was given in the year 1992.The earliest PCF was fabricated at the Optical Fiber Conference (OFC). In 1995, PCF with solid core and 216 air capillaries in the surrounding of the core. In 1996, hexagonal unit cell was made by drilling air hole in silica rod and the flourishing silica-air PCF was firstly demonstrated [4].

(a) First working PCF—the solid glass core is surrounded by a triangular array of 300-nm- diameter air channels, spaced 2.3 μm apart (b) Detail of a low-loss solid-core PCF (interhole spacing~2 μm) (c) First hollow-core PCF. (d) PCF extruded from Schott SF6 glass with a core ~ 2 μm in diameter .

The contour map of the near-field pattern shown in fig e at 632.8 nm was recorded for solid glass core in the picture above (fig a) by imaging the output end of the fiber onto the Videocon camera. The contour map is shown in which the scaled scanning electron microscope picture is superimposed at the fiber output surface that shows the relative orientation of the modal field with respect to the fiber. The light is strongly confined to the core region and the field pattern is dominated by minima occurring at the six nearest air holes. The hexagonal nature of the guided mode is manifest as six symmetrically placed spots o around the central peak, with much weaker spots

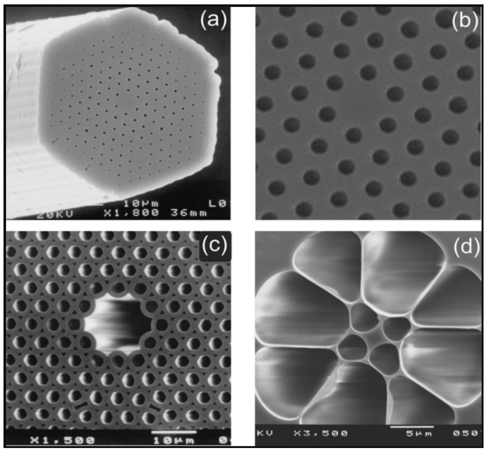

Fig- 1 : Selection of scanning electron micrographs of PCF structures [5]

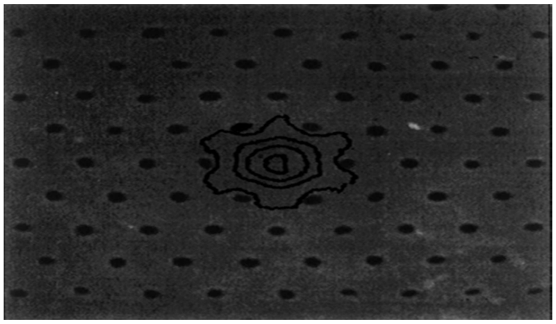

Fig 2: contour plot of near-field pattern[5]

After near field the spatial far-field was photographed on sheet placed at quite a few centimeters and centre part have been overexposed to depict higher order terms[5].

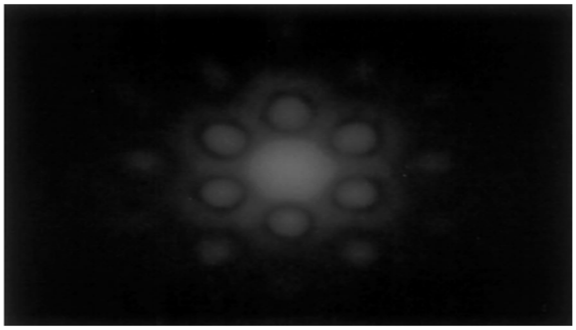

Fig 3: photographed far field pattern at 632.8 nm [5]

The triangular cladding arrangement of PBF was firstly presented in 1999 having super continuum generation i.e. broadening of spectrum w.r.t optical pump pulses a micro structured fiber due to many nonlinear phenomena. This type of air silica fiber with low index core can guide more than 98% of power.For a single mode photonic band gap in which guidance of light is in air, there is propagation constant $\beta<kn$ for which light will propagate whereas for $\beta>kn$(k is wave constant, n is refractive index of core) light is evanescent[6].

Photon vs Electron

Fundamental particle of visible light is photon. The packets of energy or the electromagnetic wave are also known as photon. Electrons consist of negative charge, which move away from other negatively charged particles. Photondoes not consist of positive or negative charges. They have no mass and matter[7].

Equation for photon:

$(E,\vec{P}) = (h\nu, {}^{2\pi}/_{\lambda})$...........(1)

Equation of Electron:

$(E,\vec{P}) = (\frac{h^2k^2}{2m}, hk)$..........(2)

The interaction between the photons is small whereas the interaction between electrons is quite large. Photons follow unguided media, meaning they can propagate outside the guided medium. But the electrons can propagate only inside the medium or on its surface. Photonics and electronics are very important field of studies. Both technologies have important contribution in fields of communication technology, computers, meteorology, medicine and a large fraction of our daily use devices. The field of electronics took a new lead forward with advances of semiconductors, diodes and transistors were made. These components were a lot cheaper, smaller and particularly faster than previously used vacuum tubes. Photonics can be considered as the relatively new branch of science. With the invention of LASER diode in optical fibers in 1970s, the science of photonics took a giant leap forward. Photonics include all technologies that use light, create light and modify light. Nothing goes as faster as speed of light.

Types of Fiber

Out of the two PCF, the index guiding fiber also known as holey fiber having solid core with higher refractive index than in which light travels by total internal reflection at core clad interface. Since PCF defect is formed by eliminating central air capillary the EM wave travels by modified TIR.

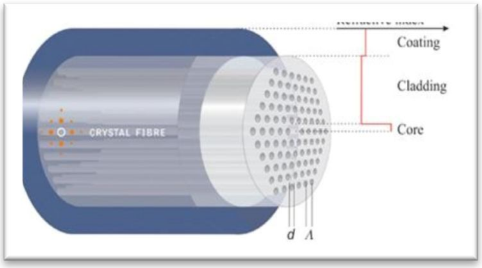

Fig-4 solid core photonic crystal fiber [8]

The other one is the photonic band gap fiber in which light travels in core made of hollow core with lower refractive index. 2D photonic crystal is created by introducing air cores that are distributed periodically in silica Photonic band gapallows a certain range of frequencies to travel inside the defect. A defect is introduced by removing an air core to create a region with optical properties different from that of photonic crystal. The frequencies other than photonic band gap leak out in to the crystal. Only in confined modes can travel in air core even with cladding having greater refractive index than the core. The individuality of photonic band gap fibers was observed by varying lattice constant and diameter of air hole which resulted in extraordinary properties.

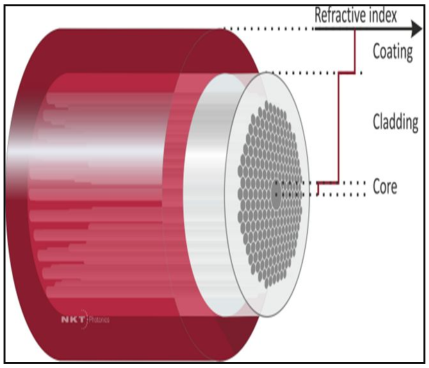

Figure 5: hollow core Photonic crystal fiber[9]

Fabrication Process

The most important aspect of any device is it's fabrication process. Earlier the fibers are usually manufactured by fabricating a fiber preform and then drawing fiber from it with a high tempearatue furnace. Various vapour deposition techniques like the Modified Chemical Vapor Deposition (MCVD), the vapor axial deposition (VAD) and the outside vapor deposition (OVD)are used for the fabrication of circular fiber preforms.

In Photnic Crystal Fibers factors like viscosity, gravity and surface tension are of great importance. As many of the surfaces are close to the fiber core, thus making surface tension relatively much more important. While designing PCF, requires a far higher refractive index contrast differ by 50-100% in comparsion to only 1% in conventional fibers[10]. So the previously described techniques are not applicable to the fabrication of preform for micro structured optical fibers. Two widely used methods for the fabrication if Photonic Crystal Fiber are: Stack and Draw Technique and Extrusion fabrication process.

Stack and Draw Technique

The method was introduced by Birks et al. in 1996. It allows fast, clean, low-cost and flexible method. The PCF is realized by stacking a number of capillary silica tubes and rods to form the desired air-silica structure. With the help of this method a high level of design flexibility as the shape and size of core can be controlled, also the index profile throughout the cladding region is possible. When the stacking process is over, the capillaries and rods are held together by thin wires and fused together during an intermediate drwaing process. After this, 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 [10]. To control the air-hole size during the drawing process, a slight overpressure relative to the surroundings is applied to the inside of the preform.

Due to the effect of surface tension, we should allow the temperature to exceed 1900^0 otherwise it will lead to the air-hole collapse. Various parameters like Dynamics, temperature, and pressure variations should be accurately controlled during the PCF fabrication. At last the PCFs are coated to provide a protective standard jacket, which allows the robust handling of the fibers.

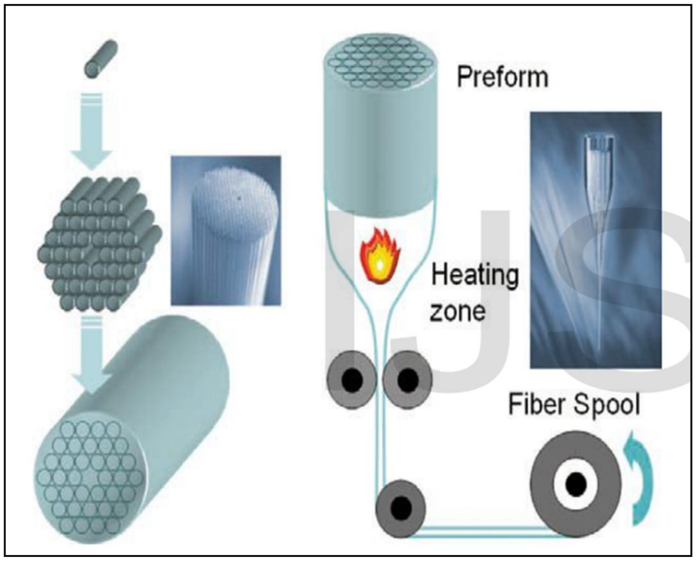

Figure 6: Stack and Draw Technique [10]

Extrusion Fabrication Process

In the Extrusion process a material is pushed or draw through a tool called die which is used to shape materials of desired cross-section. This process is applied to 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. This process allows fiber to be drawn directly from bulk glass, using a fiber drawing tower and almost any structure- Crystalline or Amorphous. It can be used with many materials, including polymers and compound glasses. Sturctured preform of 16mm outer diameter and the jacket tube are extruded. Preform is reduced in scale on a fiber-drawing tower to a cane of about 1.6mm diameter in caning process[10].

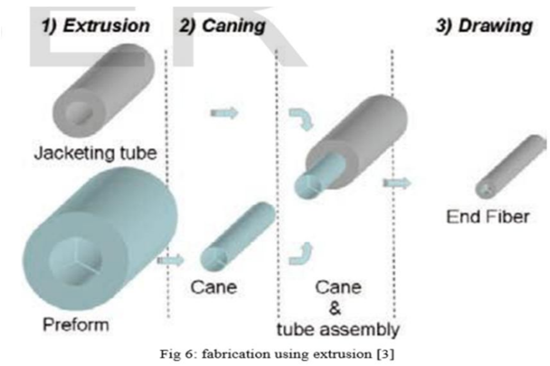

Figure 7: Fabrication using Extrusion[10]

Properties of PCF

By varying hole size, space and distance between the core we can obtain required optical properties for both Index Guiding and Bandgap Guiding PCF.

Endlessly Single mode Fiber

There are two types of fibers based on modes: Single Mode Fiber and Multimode Fiber. Fabricating a Single Mode Fiber is an Expensive task and it is difficult to obtain such a narrow core radius of few micrometers. A Single Mode Fibre with a normalized core-cladding refractive index difference Δ of 0.4%, a core diameter of ρ= 4.5μm, and a very high optical clarity is actually quite limiting for many applications. The main cause of this is the low value of Δ, which causes bend loss. When we increase the value of Δ, the single mode radius become very small and there is an increase in attenuation through increased absorption and Rayleigh Scattering [10].

At first the solid-core PCF which consists of a triangular lattice of air-holes with a diameter d of about 300nm and a hole-to-hole spacing Λ of 2.3um did not ever seem to become multimode in the experiments means it is endlessly single mode. When the value of the ratio of the hole size to hole spacing exceeds certain value, then only single mode propagation is supported.In classical fibers for normalized frequency should be 2.045 for fiber to behave as single mode where as in photonic crystal fiber by varying either hole diameter or the of value lattice constant effective refractive index can be obtained for wider range of wavelength[1]. It was previously observed that for shorter wavelengths travelling modes become concentrated which results in the increase in effective cladding index[11] which will reduce dependence of V on wavelength.

Here,

$V = 2\pi r/\lambda(\sqrt{n1 - n}2$ ....(3)

where n1 is refractive index for core and n2 is refractive index for cladding.

Zero Dispersion in Photonic Crystal fiber

It is very important phenomenon which is needed to be considered and compensated. Two types of dispersion are- Inter-modal 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 reciever at different time. This type of dipersion 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 waveguide dispersion. So the overall dispersion must be zero at some point. For conventional fiber the zero dispersion occurs at 1.3μm [12]. It is possible to compensate chromatic dispersion if zero dispersion wavelengths occur at operating frequency.For Photonic Crystal Fibers with small mode areas, which can exhibit particularly strong waveguide dispersion, the zero dispersion wavelenght can be shifted. As in PCF we can change the size of the air hole size and the position of the air-hole cladding. The zero-dispersion wavelength can be shifted by changing the pitch and air-hole sizes. Zero-dispersion can also be obtained in visible region. If zero dispersion is in this region it can be used as a dispersion compensation in the communication link like in telecommunication lines[14].

Supercontinuum Generations

Non-linear properties can be exhibited by a fiber with very small core area. Fibers with very small effective areas and large non-linear coefficients can be created using very small cores, approx. 1μm of diameter and a high core/cladding index contrast (up to 0.4). When the cladding is filled with 90% of the air, low index cladding can be obtained. So most of the light is confined inside the core only. Non-linear PCF thus becomes an optimal environment for the generation of Raman amplification, Four Wave Mixing, Supercontinuum generation, etc. Supercontinuum was first discovered in 1970. It occurs because of several non-linear phenomenon's occurring together like Raman scattering, phase matching, self-phase modulation and solitons. The pulse in supercontinuum has significant spectral broadening. The main advantage of this property is that it allows the user to convert light to both high and low wavelengths in octave range with low power levels[1].

Large Mode Area

Large mode area can be configured in photonic crystal fiber by increasing size of core. In case of solid silica core air capillaries are removed to increase the size of core to provide large mode area for single mode to travel which results in lesser non linearity's. This can as well be achieved by reducing the size of hollow capillaries[13]. Whereas in conventional fibers their exist a limit on size of core. PCF grants freedom for obtaining single mode for large range of wavelength by changing size air holes and lattice constant thus effective refractive index can be obtained as desired[1].

Applications of PCF

Sensing Application Of Pcf Using LPFG

To sense Temperature, Pressure, Strain, Humidity etc a broad range of sensors can be fabricated using Photonic Crystal Fibers. Fiber Bragg Grating is a 1D Photonic crystal in which different core refractive index either periodic or non-periodic occur in 1D. To use Long Period Fiber Grating (LPFG) as a sensor in Photonic Crystal Fiber, a UV laser exposure method is used.

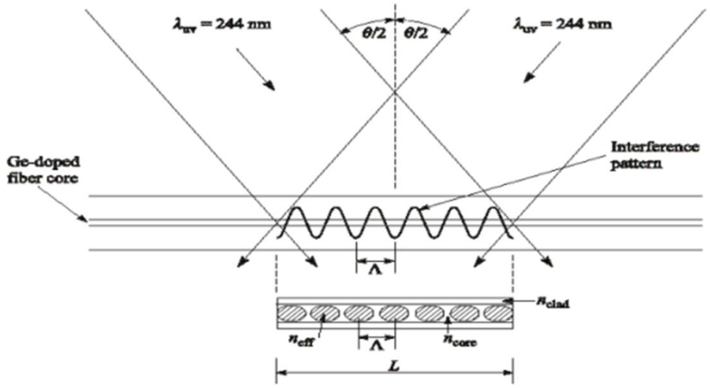

Figure 8: UV Laser exposure[15]

When two UV beams interfere with each other constructively, they create the maximum intensity and a minimum intensity when those ways intersect destructively to each other. A positive sinusoidal peak is shown above when the refractive index of silica fiber is increased and a negative sinusoidal peak is shown when the refractive index of the fiber is not changed [15].

Pressure Sensing Applications

Photonic crystal fibers have been employed in field of pressure sensing due to their unique properties for prediction of Tsunami [16]. Since conventional fibers have certain limitations such as their dependence on temperature whereas using periodically tapered PCF the temperature variations can be compensated. By using SMF-PCF-SMF [17] tapered design makes it less sensitive to changes in temperature which act as noise source. Photonic crystal fibers used in sensors for pressure sensing at bottom of oceans are much reliable than conventional fibers.

Gas Sensing Application

Another important application of PCF is that it can be used to measure diffusion coefficient of gas. One end of photonic crystal fiber in inserted in the gas chamber where diffusion occurs between hollow capillaries of PCF and gas whose diffusion coefficient is to be determined. There will be loss of power due to absorption of light by gas which will be measured using photo detector at the output[18].Photonic crystal fiber is highly non linear. As a result certain non linear effects such as stimulated raman scattering, self phase modulation, cross phase modulation, four wave mixing results in broadening of spectral width. WDM systems using super continuum has reported 200 to 400 Gb/sec[19] .This has increased the capacity of optical communication system many folds. In addition to this photonic crystal fiber can work at zero dispersion for telecommunication by changing diameter of air holes which result in increasing capacities with Pico second pulses[20].

Photonic Crystal Fiber Based Wavelength-Tunable Optical Parametric Amplifier and Picosecond Pulse Generation

Photonic crystal fiber can be used to make fiber optical parametric amplifier (FOPA). It has optimized dispersion and the non-linear properties are also pumped by the mode-locked ytterbium-doped fiber laser. The wavelength can also be adjusted from anomalous to normal dispersion regime. Using this method, we can amplify weak signal which are present in the parametric gain bands. The ranges of optical sources and amplifiers are needed to beincreased for the applications like biomedical imaging and spectroscopy, etc**.[**21**].** The parametric gain bands are generated when the fibers are pumped near zero dispersion wavelengths due to the effect of Four Wave Mixing. In FOPAs the weak and pump signals are pumped simultaneously is a gain fiber. As the weak signals have narrow linewidth. So the maximum energy is concentrated at the narrow spectral linewidth.

Conclusion

In Photonic Crystal Fibers a number of non linear effects such as self phase modulation, stimulated raman scattering, cross phase modulation results in amplification as well as supercontinuum generation. Pcf supports all optic communication.There is no more need for electro-opti conversion. The effects like dispersion, scattering and other non-linear effects are reduced drastically. Also in hollow core fibers unlike conventional fibers, most of the energy is transmitted through air. Therefore the Rayleigh scattering and multiphoton absorption are drastically reduced.With the advancement in fabrication, performance of pcf has been enhanced.The pcf has very wide range of wavelength to work as single mode fiber .The use of various materials and various configuration in design of pcf result in controlled dispersion.The numerical aperture and core area can be increased to get large mode area.

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