# Commercial Solid Core Photonic Crystal Fibers for Sensing Applications

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ABSTRACT In a solid core PCF, structural parameters and the number of rings in the cladding region decide confinement losses, dispersion coefficients as well as bending losses. This paper evaluates some of commercially available solid core photonic crystal fibers .The dispersion coefficient and sensitivity of these fibers is estimated using COMSOL, and compared with the theoretical values wherever available. Based on this study the best commercial solid core PCF is identified for application as a fluid sensor.

KEYWORDS: Solid core PCF, Dispersion, Sensitivity, Fluid sensor

## 1. INTRODUCTION

Photonic crystal fibers (PCFs) are thin silica glass fibers possessing a regular array of microscopic holes that extend along the whole fiber length. The discovery of PCFs has led to several possibilities ranging from guidance of light in vacuum, to achieving unusual dispersion properties from enhancing non linear effects to high confinement of light and minimizing the same non linear effects through very large mode area single mode fibers. In addition, PCFs possess the amazing property of being endlessly single mode and they can remain single mode across all wavelengths.

These unusual properties of PCFs have led to an increasing interest in their applications, in areas such as sensing, signal processing and optical communication systems. Solid core PCFs cross-section presents a periodic array of air holes surrounding a solid core, which are extended invariantly along the fiber length. When using a single material in the fiber manufacturing, this cross-sectional configuration leads to a lowering of the cladding’s effective refractive index given that the solid core is made of the same material. An illustration of a solid core PCF cross section structure is presented in Fig (1).

D = 173 µ m, d =5.15µm, $\Lambda$ = 10.6 µ m.

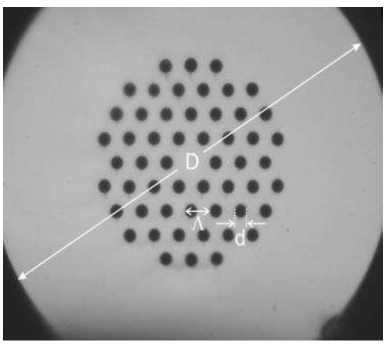


Fig 1(a) -Optical micrograph of the fabricated PCF

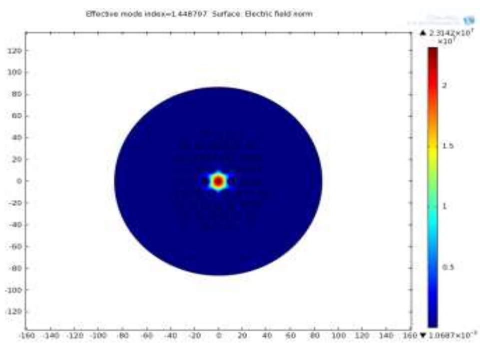

Fig 1(b)-Field confinement at 1550nm

The optical properties of PCFs can be modified in a wide range by just varying the geometrical parameters air hole diameter'd' and spacing between air holes (pitch 'Λ') . If these parameters are fixed one can use another degree of freedom by successively increasing the refractive index of holes from air ($n_l$=1) to that of silica and above. These fluid filled fibers can be used as sensor elements, for tuning of light propagation properties, switching of guide light and spectral filtering.

## 2. OPTICAL CHARECTERISTICS OF SOLID CORE PCF

### 2.1 EFFECTIVE REFRACTIVE INDEX

In homogeneous media, the refractive index 'n' can be used to quantify the phase change per unit length. That phase change is 'n' times higher than it would be in vacuum. The effective index has the same meaning for light propagation in a waveguide and depends not only on the wavelength but also on the mode in which the light propagates. The effective index may be a complex quantity. In that case, the imaginary part describes gain or loss.

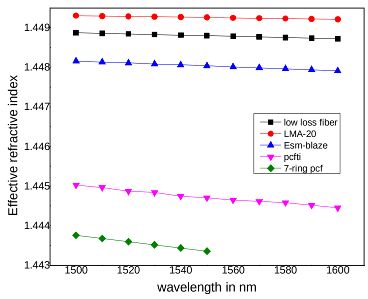


Fig1©: Effective refractive index versus wavelength

### 2.2 DISPERSION

Dispersion is defined as the process of pulse spreading in an optical fiber. As a pulse of light propagates through a fiber, elements such as numerical aperture, core diameter, refractive index profile, wavelength, and laser line width cause the pulse to broaden. This poses a limitation on the overall bandwidth of the fiber. The refractive index of a material depends on the wavelength of the electromagnetic wave interacting with the material. This dependence is referred to as the material dispersion. Dispersion generally increases as the wavelength increases as shown in dispersion versus wavelength graph. In a photonic band gap fiber the material dispersion is very less. The material dispersion is found using the equation:

$$\boldsymbol{D(\lambda)} = -\frac{\lambda}{c}\left(\frac{d^2n}{d\lambda^2}\right)$$

Where λ is the operating wavelength, c is the free space speed of light, $n_{eff}$ is the effective index of the fiber. Solid core fibers possess the attractive property of great controllability in dispersion by varying the hole diameter 'd' and hole to hole spacing 'Λ'.From fig 1(c) it can be noted that zero dispersion point can be achieved at the desired wavelength by changing geometric parameters[9].

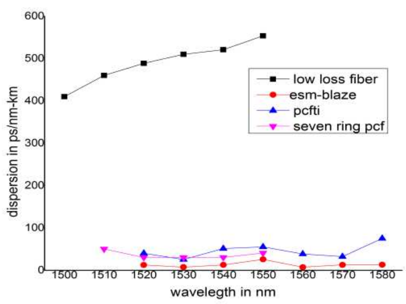


Fig 1(d: Dispersion versus 'λ' for commercial fibers

## 2.3 EFFECT OF STRUCTURAL PARAMETERS ON EFFECTIVE REFRACTIVE INDEX

The first step is it is assumed that the PCF s are made of silica of background refractive index $n_{silica} =$ 1.45 and the holes are filled with air of refractive index of $n_{air} = 1.0$ .The effective index can be controlled with the size of air holes in the first ring of a fiber.

It can be seen from simulation that The effective index decreases with increase in hole diameter and in d/p ratio as shown in fig2 (a) and 2(b).The real part of the refractive index increases with increase in pitch 'p' .The validity of our simulation analysis was verified by comparison of the analysis to that of [9]

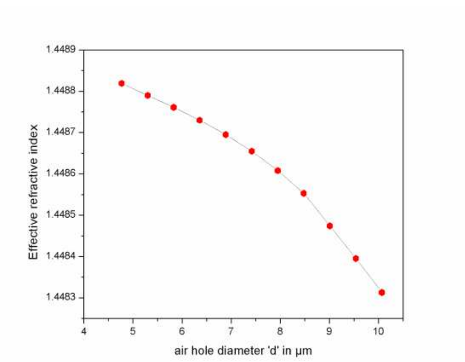


**FIG 2 (a): Effective refractive index versus'd'**

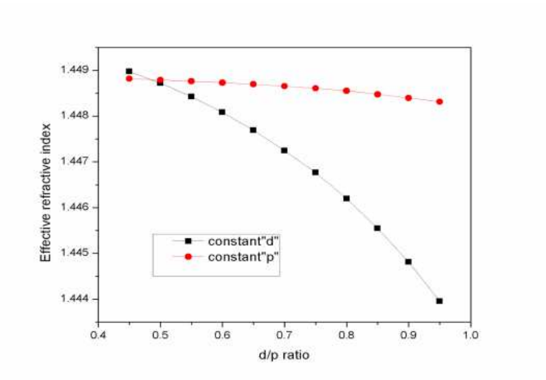


**FIG 2(b): Effective refractive index with d/p ratio**

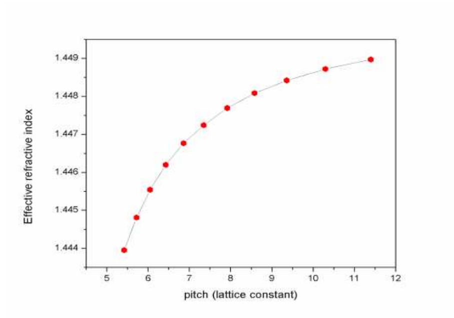


**FIG 2(c): Effective refractive index versus pitch**

**2.4 SENSITIVITY**:

Fiber optic sensing has become one of the key applications of optical fibers in the last decades. Optical sensors have many advantages over their non-optical counterparts, amongst which being Light weight, accurate, compact and immune to electromagnetic, radio-frequency, and microwave interference. Sensitivity is an important parameter in the PCF based sensor. The numerical calculation formula for sensitivity is given by

$$\boldsymbol{r_f = f(\frac{n_r}{n_c})}$$

Where $\boldsymbol{n_r}$ is the refractive index of the fluid, $\boldsymbol{n_c}$ is core refractive index, $\boldsymbol{r_f}$ is relative sensitivity coefficient and '*f*' is the ratio of optical power with in large holes to the total power. The dependency of sensor properties such as the relative sensitivity **on** the fiber structural parameters and working wavelength has been investigated. In commercial fibers with optimized parameters at the wavelength of 1.55 µ m, the relative sensitivity improved.

$$\boldsymbol{f = \int_{holes}(E_xH_y - H_xE_y) / \int_{Total}(E_xH_y - H_xE_y)}$$

### 2.4 USE OF COMSOL MULTI PHYSICS

RF module of COMSOL is used to perform 2D mode analysis of all the test fibers to determine the effective index of the guided modes at wavelengths of interest. Sensitivity of the fibers is evaluated from fraction of evanescent power calculated using line integration of the electric fields. Air holes, running along the length of the fiber, create new abilities for the appropriate interaction between light and gases or liquids through evanescent fields in the hole.

## 3. RESULTS AND ANALYSIS

Several papers have been published on the criterion of the endlessly single mode ness of the ESM-PCF. As small air filling fraction will lead to a high confinement loss, the design of a commercial ESM-PCF will apparently face a trade-off between the endlessly single mode ness and the confinement loss. From simulation, the dispersion at 1550 nm is calculated as 25.8ps/nm-km which is approximately equal to the value 30ps/nm-km given by the manufacturer Blaze photonics ESM-12 [4]. These fibers can be used as fluid sensors and also used in interferometers for dispersion measurements, sensing applications.

**FIG 2(a): SEM photograph of ESM-BLAZE**

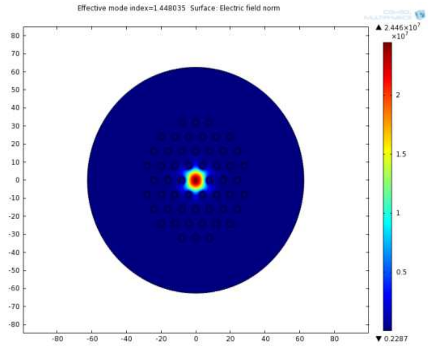

**FIG 2(b): Electric Field Confinement@1550nm**

Solid core PCF or index guiding PCF is a unique class of PCF where its cladding is constituted with multiple rings of air holes while its core is solid silica. Since the PCF cladding are filled with air holes and the refractive index of air is much smaller than silica, it literally renders the PCF cladding region with an average refractive index lower than that in the core, hence allow light to be guided in the core by modified total internal reflection. This kind of light guiding mechanism is similar to that in step-index single mode fiber and for this reason it is natural to analyze the behavior of this PCF using step index fiber approach. In this work, we theoretically investigate and report the dispersion properties of a high air-filling solid core PCF with seven rings with the commercial finite element method solver and compare it with the well-known step index fiber model The seven ring photonic crystal fiber used in our simulation is shown in Fig 3(a).The core is surrounded by seven rings. The core index is taken as $n_c$ =1.45 and the simulations are executed for the fixed d= 5.3μm and for the fixed Λ=6μm with the same d/Λ=0.88 ratio [3].

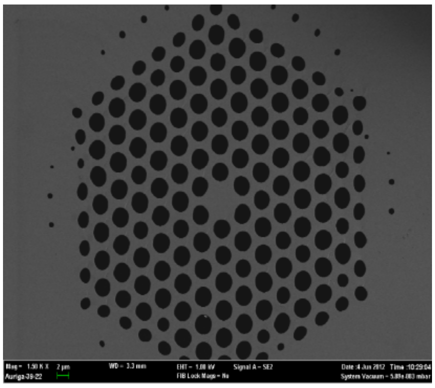

**FIG 3(a): SEM image of 7-ring Solid core PCF**

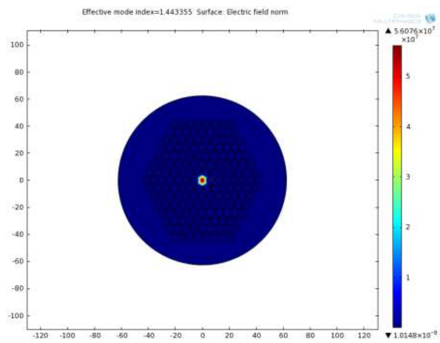


**FIG 3(b): confinement of 7-ring fiber @1550nm**

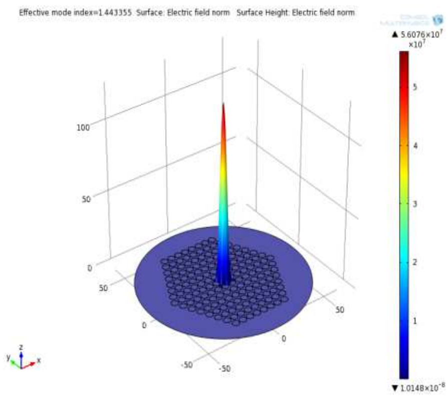


**FIG 3(c): 3-D field pattern for 7- ring PCF**

The commercial single-mode PCF (SM-7.0-PCF, YOFC) consists of a solid core surrounded by five rings of air holes as shown in Fig4 (a). The fiber has a 7 $\mu$m diameter core; the average diameter of voids is 2.57 $\mu$m, and the average separation between the voids of 5.12$\mu$m. In general, it is hard to measure the CD of a strong dispersive PCF at wavelengths far from the ZDW using conventional interferometric technique because the interference fringes become too dense to be resolved. However the spectral density can be easily adjusted by changing the length of the PCF. The measured chromatic dispersion results in tip interferometry method [6] are also compared with that calculated by using Comsol Multiphysics The measured CD coefficient of the PCF was 49.927, 52.169, and 53.954ps/nm·km at wavelengths of 1525.000, 1545.653 and 1565.000nm, respectively as given in table(1). Both measured and calculated results are in good agreement with in the measurement error range.

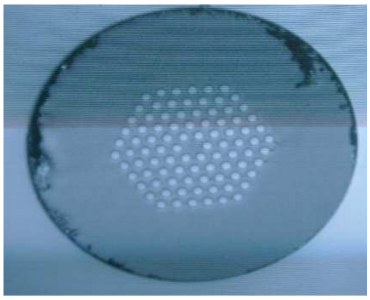

**FIG4 (a): Optical micrograph of YOFC (PCFTI)**

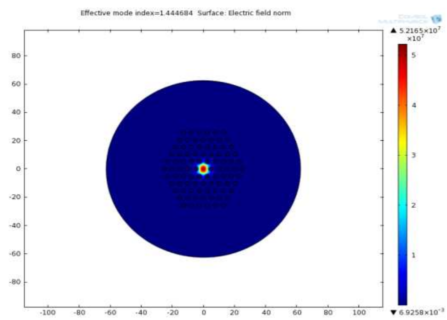


**FIG 4(b): Electric field pattern @1550 nm**

**TABLE (1): variation in chromatic dispersion coefficients for YOFC PCF with wavelengths in C-band**

| CD Coefficient from literature ps/nm-km | CD Coefficient from simulation ps/nm-km | Wavelength in nm |
|---|---|---|
| 49.927 | 40.2 | 1525 |
| 52.169 | 51.5 | 1545 |
| 53.954 | 42.9 | 1565 |

Estimated the effective refractive change for fluids with R.I ranges from 1 to 1.44 in case of PCFTI as 3.573x10^-3 which is highest in value (for 7-ring PCF it is 3.301x10^-3) when compared to other fibers (For LMA-20 it is 3.76x10^-4, in LMA-8 the change observed is 2.534x10^-3, and for ESM-blaze change is 3.36x10^-4) from table (2).

**TABLE (2): Variation in effective refractive index with infiltrated PCF's**

| LMA-20 | LMA-8 | 7-ring PCF | PCFTI | ESM-BLAZE | Refractive index of Fluids | Fluids |
|---|---|---|---|---|---|---|
| 1.449260 | 1.445969 | 1.443295 | 1.444684 | 1.448027 | 1 | Air |
| 1.449262 | 1.445985 | 1.443323 | 1.444732 | 1.448033 | 1.025 | Liquid He |
| 1.449295 | 1.446269 | 1.443799 | 1.445138 | 1.448131 | 1.2675 | Hydrogen cyanide |
| 1.449306 | 1.446363 | 1.443978 | 1.445289 | 1.448163 | 1.305 | Water ice |
| 1.449319 | 1.446448 | 1.444083 | 1.445430 | 1.448197 | 1.330 | Water |
| 1.449322 | 1.446489 | 1.444169 | 1.445474 | 1.448207 | 1.34 | Propane |
| 1.449328 | 1.446536 | 1.444238 | 1.445543 | 1.448223 | 1.35 | Ether |
| 1.449336 | 1.446596 | 1.444326 | 1.445631 | 1.448244 | 1.361 | Ethanol Acetone |
| 1.449346 | 1.446669 | 1.444432 | 1.445739 | 1.448269 | 1.3723 | Sugar solution (25%) |
| 1.449352 | 1.446710 | 1.444474 | 1.445799 | 1.448283 | 1.3776 | Isopropanol |
| 1.449354 | 1.446729 | 1.444502 | 1.445824 | 1.448290 | 1.38 | Alcohol |
| 1.449384 | 1.446944 | 1.444797 | 1.446141 | 1.448363 | 1.4 | Octane |
| 1.449444 | 1.447344 | 1.445297 | 1.446729 | 1.448363 | 1.42 | Diethyl succinate |
| 1.449506 | 1.447738 | 1.445740 | 1.447280 | 1.448363 | 1.43 | Propylene glycol |
| 1.449558 | 1.448052 | 1.446080 | 1.447706 | 1.448363 | 1.435 | Silicon naphthalocyanine |
| 1.449636 | 1.448503 | 1.446596 | 1.448257 | 1.448363 | 1.44 | Chloroform |

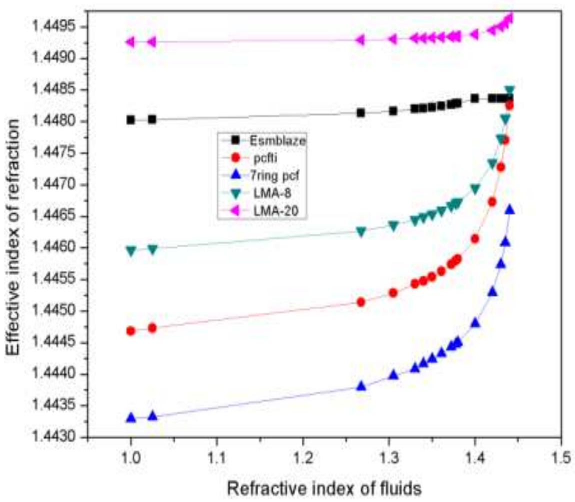


**FIG (5): Effective refractive index versus refractive index of liquids for commercial fibers**

**TABLE (3)**

**Reflective sensitivity dependence on Refractive index of fluids**

| Refractive Index of fluids | Reflective sensitivity |
|---|---|
| 1 | 0.136123 |
| 1.2675 | 0.21993 |
| 1.35 | 0.23694 |
| 1.3776 | 0.288011 |
| 1.4 | 0.371866 |
| 1.43 | 0.608813 |
| 1.44 | 0.806703 |

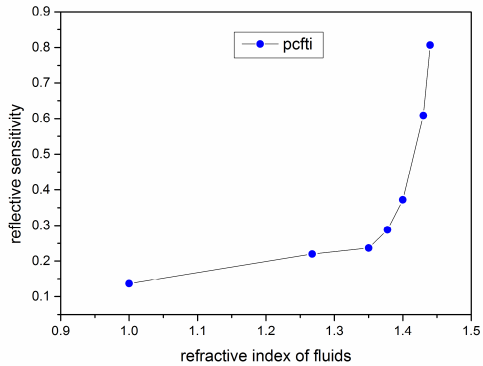


**FIG (6): Refractive index of fluids versus Reflective Sensitivity**

**4. CONCLUSIONS:** This paper observed the effects of structural parameters on their basic properties. Comparative study of different commercial fibers has been carried out. Chromatic dispersion for these commercial fibers is calculated using finite element analysis and verified by comparing with the values mentioned by manufacturer for the fibers. The experimentally measured chromatic dispersion results using tip interferometry method are also compared with that of the simulation results obtained using COMSOL MULTIPHYSICS. The measured CD coefficients of YOFC PCF were 49.9, 52.1, and 53.9ps/nm-km at wavelengths of 1525.0, 1545.65 and 1565.0nm, respectively. Both measured and calculated results are in good agreement within the measurement error range .The sensitivity variation with infiltrated fluids with R.I ranges from1.0 to 1.44 is highest for PCFTI and the results are furnished in table(3). From fig (5) and fig (6) it is found that among all commercial fibers, PCFTI is found to be superior in terms of sensitivity.

## 5. REFERENCES


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