

Ultra High Sensitive Disc Core PCF Chemical Sensor



R. Derick, S. Revathi

Abstract— In this article, a PCF sensor is designed and computed to detect chemicals in the refractive indices range of 1.52-1.56. In this proposed design, three and four concentric discs fabricated in the core which provides ultrahigh sensitivity and circular porous cladding pattern confines large fraction of power in core region. This novel proposed design demonstrates ultrahigh relative sensitivity 86.35% and 85.02% for four and three disc models. These sensing discs are filled with different sensing fluid. This proposed PCF design overcomes some experimental challenge such as PCF probe needs some displacement after filling the sensing liquid. These uniform circular sensing discs around the solid core supports better evanescent field matter interaction for sensing application.

Keywords— Lattice, Spiral, Circular Photonic Crystal Fiber (C-PCF), and Optical waveguide

I. INTRODUCTION

In present day the role of photonic crystal fiber (PCF) is of paramount importance. They are one of the most efficient forms for sensing applications and nothing is required other than the analyte itself. PCF has far more advantages compared to that of a conventional fiber. PCF can be grouped into hollow core and solid core fibers. Conventional fibers work on the principle of total internal reflection whereas PCFs also adopts photonic bandgap mechanism (PBG) where the cladding as a greater refractive index compared to that of the core. Also the properties of the PCF are much more flexible as they could easily be changed by varying parameters like the pitch of the airholes, the diameter of the airholes and by having enigmatic designs in the core or cladding like the famous spiral cores, circular cladding which offer very less or no confinement losses too. PCFs can offer a long range of birefringence, can acts as endlessly single mode fibers (hollow core PCF). In these fibers light propagate through the photonic bandgap mechanism. Since only a small part of light can be transmitted through glass, all effects related to interaction between glass and light like scattering, dispersion etc. are highly reduced. PCFs can be designed to sense almost all refractive index range with great accuracy by changing the design of the structure. Airholes shaped to different polygons and circles, further arranging them in enigmatic fashions to get novel results and higher performances. Besides these airholes were later filled in with liquids of different refractive indices for sensing chemicals based on their index profiles. PCF also provides large mode area and enhances the non linearity greatly. The dispersion can also be varied easily.

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Lately, spiral core garnered greater attention due to having brilliant light confinement property leading to low losses. Finite element method (FEM) is a numerical technique to solve the Maxwell equation with proper boundary conditions. The finite element method divides a large system into a system of smaller units with the help of meshing technique. This innovation works based on the different refractive indices of different chemicals. The light interacts with each refractive index differently due to the change in its speed other than vacuum. The sensing of the purity of these chemicals or the presence of the traces of these biochemicals are of paramount importance. This would lead to better treatment of the patient by identifying the chemical and would lead to the discharge of the patients at the earliest. Also this approach is tremendously helpful in finding if the chemical is adulterated. Adulterated chemical would have a different refractive index hence a different value of relative sensitivity. In this paper, a novel porous PCF sensor is designed with a circular porous cladding with multiple concentric discs filled with detecting fluid in the core region. The discs are filled in with the analyte and this provides great light matter interaction in the core region. This disc pattern also ensures minimum confinement loss possible compared to the other patterns like spiral or any other polygon designs. The disc pattern also ensures that the light gets confined in the core region improving the relative sensitivity compared to other structures. Also fabrication of uniform disc pattern is much easier and less cumbersome compared to spiral patterns.

II. PROPOSED DESIGN OF MULTIPLE SENSING DISC PCF

The design of the novel structure is depicted in Fig. 1 along with the zoomed in core that comprises of four sensing discs which are to be filled with the analyte for execution. This structure is engraved with circular airhole cladding with uniform airholes as close as possible for brilliant light confining properties and extremely low or null confinement loss. The core is designed in such a fashion that the discs are 0.3 μm wide to contain the analyte separated by silica material of thickness 0.05 μm . The core of the structure is designed in such a way to fill the entire central void left by the circular cladding in order to achieve excellent light confinement. It has been noted that the disc like structure provides much closure to the light than the usual spiral cores. In this case, the proposed PCF with circular five rings of airholes of diameter 1.33 μm and hole pitch 2.16 μm . The first ring of cladding region has 10 airholes. The number of airholes in consequent rings are 16, 22, 28 and 34 respectively. The distance between the center of the C-PCF and the center of the air holes in the first ring is $R_0 = P = 2.16 \mu\text{m}$. Further, the centers of air holes in the next given rings have a distance $R_i = R_{i-1} + (P \times 0.74)$ from the center of the suggested structure where $i=2, 3, 4, 5$.

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The background of the reported PCF gas sensor is a pure silica with the following Sellmeier equation.

$$n(\lambda) = \sqrt{\left(1 + \frac{B_1\lambda^2}{\lambda^2 - C_1} + \frac{B_2\lambda^2}{\lambda^2 - C_2} + \frac{B_3\lambda^2}{\lambda^2 - C_3}\right)} \quad (1)$$

As mentioned earlier in the section the airholes in the circular cladding are closely packed as possible to provide ultimate light confinement and to prevent leakages of light thus negating confinement losses. It is also much easier to fabricate due to the uniformity of the pattern.

III. NUMERICAL ANALYSIS

The Finite Element Method (FEM) is incorporated and it is the most accurate method for simulating the results. This is implemented with COMSOL Multiphysics where the design is built, meshed and PML applied to the outer ring and results are computed.

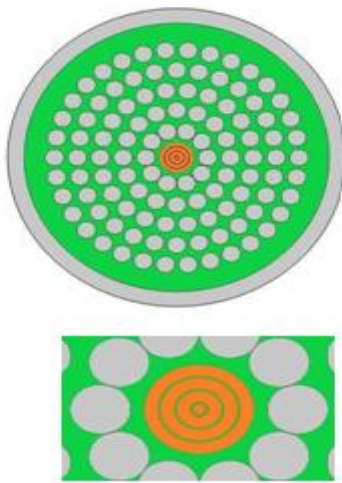


Fig 1. Multiple Disc Core Sensing PCF structure

The design is implemented and PML is applied. After that a normal size is implemented and refined to get results as precise as possible. The mesh consists of 36450 elements. The program is launched for the first six fundamental modes and for all the results the x-polarized mode was considered. After plotting the parameters subdomain integration is done for the sample and later for the entire geometry. Although, the evanescent field absorbed by sensing species and intensity attenuated at output followed the Beer- Lambert law in Eq. (2).

$$A = \log \frac{I_0}{I} = r\epsilon LC \quad (2)$$

Here I_0 and I are intensity of the light incident and transmitted respectively, L is path length, ϵ is molar absorptivity and C is absorbing material's concentration. Relative sensitivity coefficient r at particular wavelength is defined as

$$r = \frac{n_r f}{n_e} \quad (3)$$

$$f = \frac{\int (E_x H_y - H_x E_y) \delta x \delta y (\text{sample})}{\int (E_x H_y - H_x E_y) \delta x \delta y (\text{total})} \times 100 \quad (4)$$

Here n_r denotes the refractive index of the analyte filled in the core, n_e is effective refractive index of guided mode and f is fraction of power located in holes. E_x , E_y , H_x and H_y are transverse electric and magnetic field. The effective mode

area is a quantitative measure of the area which a waveguide or fiber mode effectively covers in the transverse dimensions. It is calculated as

$$A_{\text{eff}} = \frac{(\iint E^2 dx dy)^2}{\iint E^4 dx dy} \quad (5)$$

where E is the electric field of the studied mode.

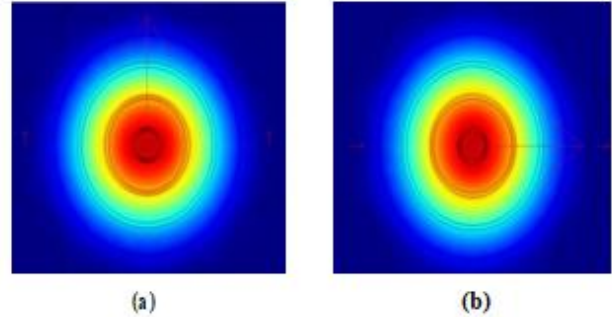


Fig 2. Normalized electric field intensity for the proposed C-PCF (a) y-polarized mode and (b) x-polarized modes at wavelength of 1.3 μm

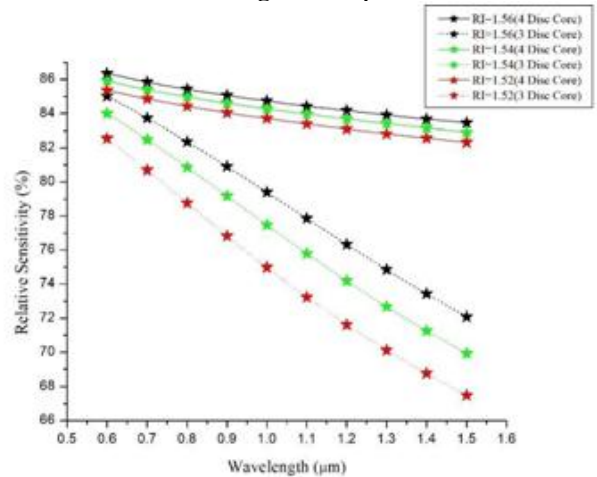


Fig 3. Relative Sensitivity vs Wavelength

IV. RESULTS AND DISCUSSION

The first approach is to obtain both the light confining modes x and y-polarized modes. The x-polarized mode is considered for result obtaining purposes in the wavelength interval (0.6 μm to 1.5 μm). Fig. 2 depicts the observed hybrid mode $HE_{11}^x HE_{11}^y$. It is visualized that the light is completely confined inside the core and no imaginary part is obtained indicating zero confinement loss. Fig. 3 depicts the variation of sensitivity with wavelength for differing number of discs (3 and 4) and for varied refractive indices (1.52, 1.54 and 1.56). It can be observed that the relative sensitivity decreases with increase in wavelength of the light and shows highest sensitivity at 1.56. It reports an excellent relative sensitivity of 86.35% at an operating wavelength of 0.6 μm. Whereas the three disc structure offers a relative sensitivity of 85.02% at the same wavelength. The three disc structure has a greater slope compared to the four disc pattern. In both three discs and four discs, the structure has a disc thickness of 0.3 μm and a disc spacing of 0.05 μm. After tabulating the obtained effective refractive index along the wavelength and plotting,

it can be visualized that the effective refractive index decreases with the wavelength. This can be seen in Fig. 4 and it is also observed that the decrease gets steeper for the three disc core structure.

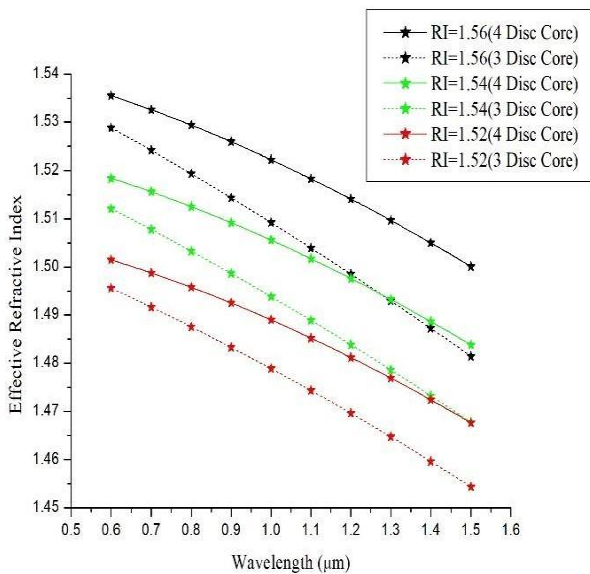


Fig 4. Effective Refractive Index vs Wavelength

Table I. PCF Sensor Performance for Different Biochemical with Four and Three Rings in Core Design

Refractive index	Relative sensitivity [%]	
	4 rings	3 rings
1.52	85.36	82.55
1.54	85.90	84.00
1.56	86.35	85.02

The reason for the decrease in effective mode index is because as wavelength increases it is comparable to that of the airholes in the cladding and hence leakage of light happens. Results also show that three ring has lower effective refractive index as compared to four sensing discs.

The primary objective of this proposed sensor is to attain good relative sensitivity. This parameter shows that most power of the light incident is utilized instead of being wasted. That is the output power is only slightly lesser than the power of the incident light.

Moreover, it is known that relative sensitivity depends upon core design of PCF and refractive index of sensing fluid by referring Eq. (3).

Fig. 3 clearly reveals that relative sensitivity decreases with an increase in wavelength due to equilateral distribution of the photons incident on the sensing discs.

The reported relative sensitivity is the lowest for 1.52 and highest for 1.56 because of relative sensitivity being directly proportional to refractive index of detecting fluid as following Eq. (3).

The three disc model has a comparatively lower performance than the four disc counterpart due to lack of focus in light confinement than the four disc core.

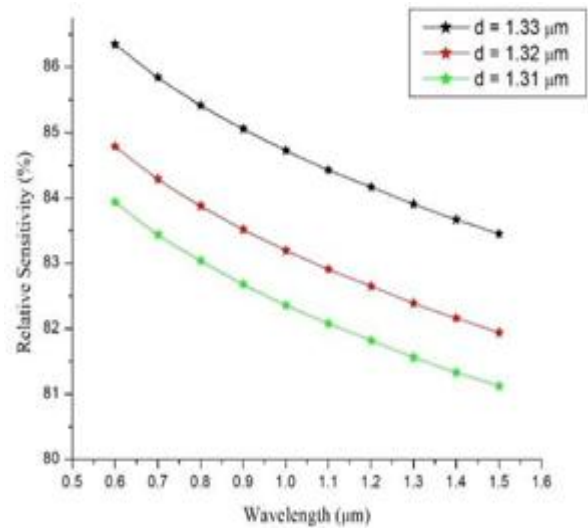


Fig 5. Relative Sensitivity vs Wavelength for varied airhole diameter

Fig. 5 depicts the effect of cladding airhole diameter on the relative sensitivity and it can be interpreted that decrease in the diameter decreases the performance. It is worthwhile to mention that this novel proposed model exhibits ultrahigh relative sensitivity of 86.35% and 85.02% for four and three ring pattern.

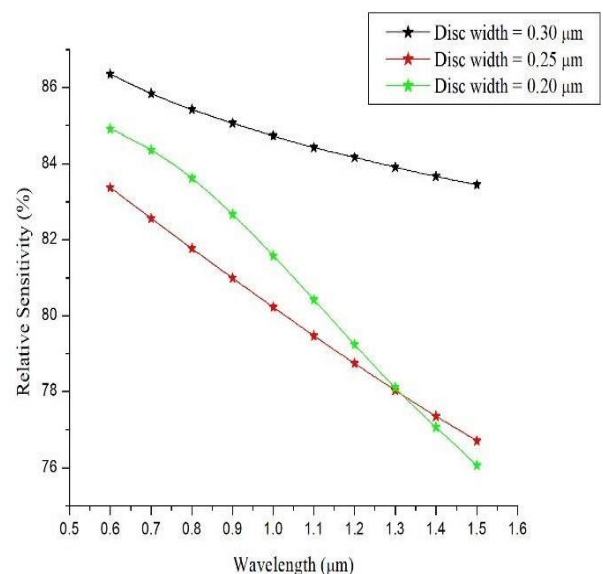


Fig 6. Relative Sensitivity vs Wavelength for varied disc width

Reducing the disc width from 0.3 micrometers to 0.2 micrometers has made the relative sensitivity to drop down and further decreasing the width resulted in no light confinement.

After 1.3 micrometers wavelength the relative sensitivity decreased more abruptly for 0.25 micrometers than that of 0.2 micrometers as shown in Fig. 6.

Maximum relative sensitivity achieved by this proposed sensor for different sensing analytes are listed in Table 1.

The current results are observed with the previously published papers and are compiled in Table 2.

Table 2. Performance Comparison between Proposed PCF and Prior Designs

PCFs	Refractive Index of Analyte	Relative Sensitivity
Ademgil (2015)	1.330	23.75%
Ahmed (2017)	1.350	49.17%
Ahmed (2016)	1.366	58.86%
Proposed (2020)	1.56	86.35%

Further the disc spacing has been doubled from 0.05 μm to 0.1 μm and the result has been deteriorated which can be inferred from Fig. 7. Increasing the disc space further would be costly for the performance of the sensor making it ineffective and unrenderable.

Table 2 tabulates the performance of the existing structures to that of the proposed structure.

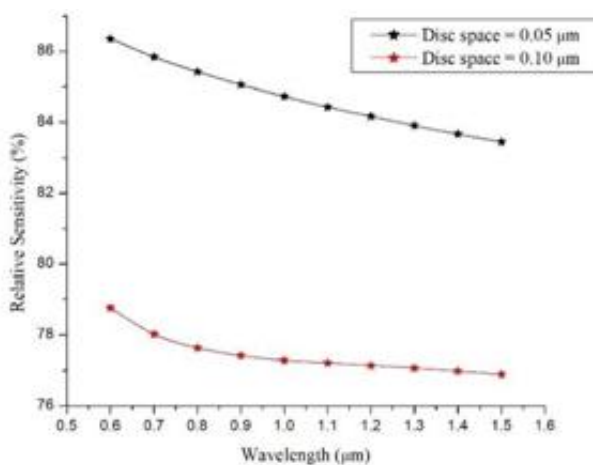


Fig 7. Relative Sensitivity vs Wavelength for varied disc spacing

The sensor reports an effective mode area of 2.56 μm^2 at the wavelength of 0.6 μm and we can see it almost varies linearly with the wavelength with highest value of 2.97 μm^2 at the wavelength of 1.5 μm which can be seen in Fig. 8.

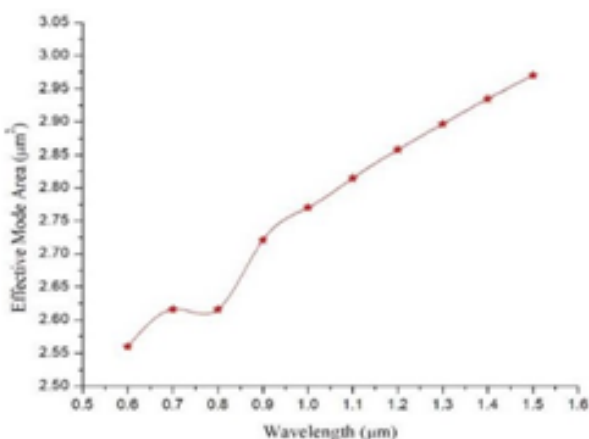


Fig 8. Effective Mode Area vs Wavelength

Lastly this design is very much viable compared to the spiral airhole designs which are more cumbersome from the fabrication point of view. Also this simpler design also amplifies the relative sensitivity considerably than the previously examined and designed PCFs.

V. CONCLUSION

In this paper an extremely sensitive PCF sensor is realized which senses chemicals in the refractive index range of 1.52 to 1.56 efficiently in the wavelength ranges 0.6 μm to 1.5 μm . This PCF sensors provides a high sensitivity of 86.35% and 85.02% with four and three disc core pattern. The reported sensor also boasts an impressive mode area of 2.97 μm^2 . It is also noted that the disc pattern is more efficient than air holes design. This proposed PCF model is strong, adaptable, integrable and conservative in nature and fabricated using advanced extrusion, stack-draw and drilling technique.

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