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Photonic Crystal Fiber for Sensing Food Additives

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Abstract*: Photonic Crystal Fiber (PCF) have recently found extensive use in sensor applications. The design of PCFs is crucial for optimal sensing performance. In this work, an index guided Hollow Core Photonic Crystal Fiber (HC-PCF) with hexagonal shaped cladding is proposed for sensing harmful food additives. Using COMSOL software we performed extensive simulations and have shown that our proposed PCF design achieves a very high sensitivity > 90% for typical food additives like Saccharin, Sorbitol, and Butyl Acetate. We have also compared our proposed design and shown that it significantly outperforms the current PCF designs. The presence of hexagonal airholes in the entire cladding layer of the proposed PCF design enhances sensitivity in comparison to the previous designs. Also, the increase in size of the circular core supports the increased sensitivity.

Keywords*: Hollow core photonic crystal fiber, PCF, Relative sensitivity, Food additives.

I. INTRODUCTION

Photonic-crystal fiber (PCF) is a class of optical fiber based on the properties of photonic crystals. Its main ability is to confine light in hollow cores or with confinement characteristics not possible in conventional optical fiber [1, 2]. They have a much higher effective-refractive index contrast between core and cladding, and therefore can have much stronger confinement for applications in non-linear optical devices and polarization-maintaining fibers [1, 2].

PCFs have some exceptional properties. It will focus the most conversant sensing application areas with their consistent parameters and perception. PCF is now finding applications in fiber-optic communications, fiber lasers, non-linear devices, high-power transmission, highly sensitive gas sensors, and other areas [2, 3, 4-15]. In recent years, many promising advancements have been reported in the field of PCF based sensing. Numerous PCF sensors are available in day-to-day world. Researchers and technologists are working on PCFs with more than 15-20 application areas [2-15].

Optical sensors using photonic crystal fiber (PCF) technology are newly adopted beyond conventional optical fibers (OFs).

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Due to their unique geometric structures, there are several challenges in the design of the PCF for sensor applications. In [9] the authors have explored sensing capabilities of two variations of the proposed suspended ring-core PCFs which were investigated experimentally by detecting absorption lines of acetylene gas. It was shown that improvement in both sensitivity and response time of the suspended ring-core PCF can provide larger gas diffusion.

A highly sensitive vibration frequency and acceleration sensor application was demonstrated in [10] using a liquid-filled photonic crystal. The proposed vibration sensor was shown to possess merits of extended working range, extremely high sensitivity, and promising potential in various fields such as monitoring real time signal alternations and sensing of extremely weak vibrations such as human breathing and finger movements.

In [11], the authors have designed a single-mode spiral photonic crystal fiber for gas sensing applications. The geometrical parameters of the PCF have been altered, by varying the pitch and radius, to optimize the structure and improve relative sensitivity through increased core area. They have shown that their PCF design enables sensing of toxic gases like methane and hydrogen fluoride.

Design of the PCF geometry is also studied for several other applications. A novel cancer sensor based on dual-core photonic crystal fiber for the detection of cancer cells in cervical, breast, and basal parts is explored in [12]. They have shown that the sensing performances for detecting the cancer cells can be improved by optimizing the PCF design. Further, the authors in [13] have designed a circular pattern solid core PCF to detect various liquids. They have studied and designed the PCF to detect several liquids at wavelengths ranging between 1.4μm and 1.65 μm. Various numerical computations were used to optimize the design for sensing glycerol and toluene, achieving 65.16% and 64.05% sensitivity respectively. Finally, the authors in [14] have designed and presented three different structures of index guided hexagonal shaped Hollow Core Photonic Crystal Fiber (HC-PCF) for sensing harmful food additives like Saccharin, Sorbitol and Butyl Acetate. In their work they have tried to optimize the cladding layer structures and spacing to achieve sensitivities of 88.75%, 87.37% and 86.72% for Saccharin, Sorbitol, and Butyl Acetate respectively. The authors in [15] have explored PCF designs for harmful chemicals in Poultry Feed. In this work, we further explore the design in [14] and propose a modified PCF design for sensing harmful food additives. We evaluate its performance using extensive simulations on COMSOL. We show that the PROPOSED PCF achieves high sensitivity of 94.21%, 93.10% and 91.84% for Saccharin, Sorbitol, and Butyl Acetate respectively. In the next section, we describe the design and geometric structure for the PROPOSED PCF. Further, we describe the simulation setup and the corresponding results obtained in the later sections. Finally, in the last section, we conclude with some future directions.

II. PCF DESIGN

The design goal is to work on sensitivity and effective area of the photonic crystal fiber. To achieve high sensitivity of the PCF, we manipulate the geometrical and structural parameters of the crystal. The core and the cladding layers are designed to maximize relative sensitivity of a photonic crystal fiber. The designs for these structures are implemented on COMSOL Multiphysics [16]. In our design we use a circular core. The cladding layer is composed of a unique hexagonal lattice structure with three rings. The airholes in this cladding layer are hexagonal structures. The size of the airholes in the cladding region are optimized for PCF performance. The cross-sectional view of this design as developed on COMSOL is illustrated in Fig. 1. The geometrical parameters of this proposed design are presented in Table 1. Further, three basic structures from [14] are also implemented on COMSOL to investigate and perform a comparison with our design. The cross sectional view of these designs are as shown in Fig. 2, 3 and 4. These designs use differently shaped (circular/hexagonal) core airhole and innermost cladding airholes.

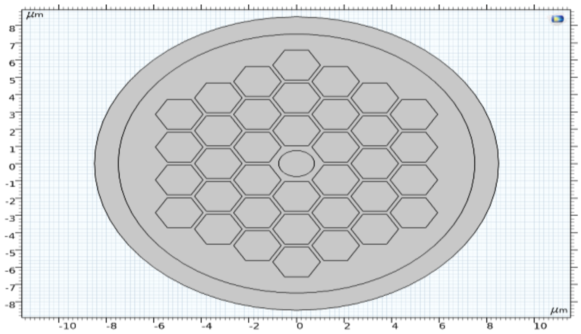

Fig. 1: Geometrical structure of PROPOSED PCF

Table 1: Design parameters of PROPOSED PCF

Structural Parameters	Value
Core	1.8 µm
Cladding	2 µm
Pitch	1.9 µm
Overall Diameter	17 µm

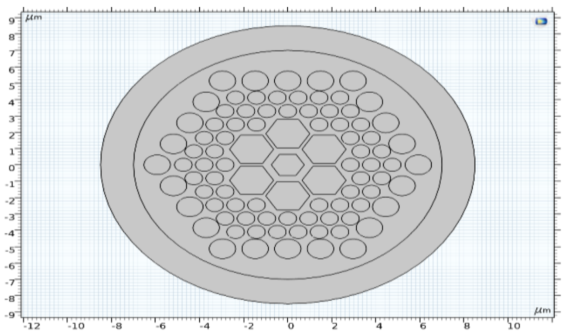

Fig. 2: Geometrical structure of PCF - 1

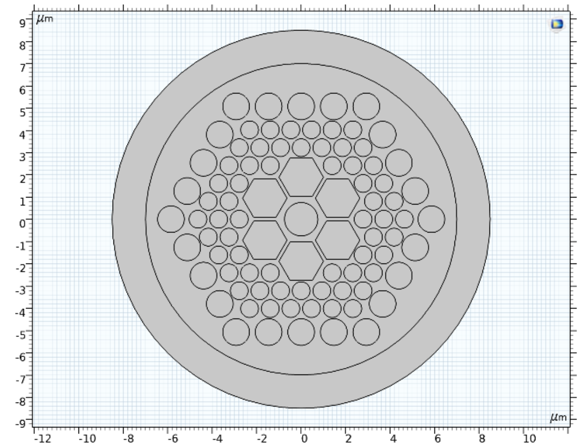

Fig. 3: Geometrical structure of PCF - 2

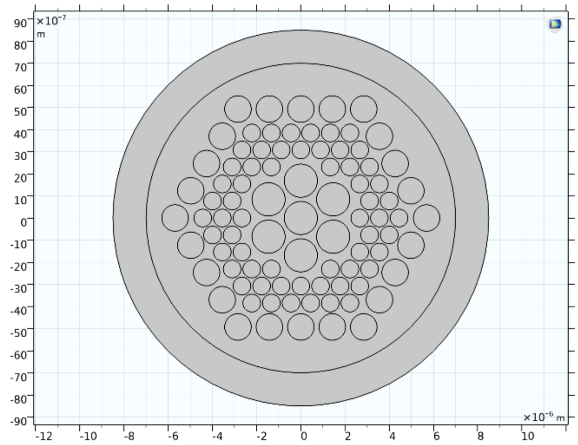

Fig. 4: Geometrical structure of PCF – 3

We need to calculate the relative sensitivity of the photonic crystal fiber by changing some parameters like pitch, refractive index, and diameter of the dielectric. The simulation method and results achieved are presented in the following sections.

III. SIMULATION

In order to evaluate the designs, COMSOL Mutliphysics software is used. COMSOL Mutliphysics is a tool used for engineering design in specialised applications [16]. The PCF designs are implemented in COMSOL Multiphysics and finite element method (FEM) is used to obtain several properties of PCF. A Perfectly Matched Layer (PML) and appropriate boundary conditions are used in the simulations.

The light confinement analysis is used to understand the effectiveness of the PCF to guide the light without any loss of power. It is critical for any PCF design to follow good confinement of light for use in practical sensing applications. We study the confinement considering the corresponding refractive indices of the food additives as our sample in the core. The typical food additives under consideration as presented in [14] are Butyl Acetate, Saccharin and Sorbitol [17-22]. Under these considerations, the PCF designs are analysed by varying 200 effective mode indices to evaluate the light confinement.

Using Saccharin as sample the light confinement obtained for the proposed PCF design is illustrated in Fig. 5. We also illustrate the light confinement obtained for the existing PCF designs 1, 2 and 3 in Fig. 6, 7 and 8.

A magnified view of the core of these light confinement illustrations is shown in Fig. 9-12. Good light confinement characteristics is observed for all of the PCF designs. Although we observed good light confinement characteristics even for the other food additives, we have not illustrated those light confinement figures due to space limitations.

We next proceed to analyse the relative sensitivity of the proposed PCF design since we observed favourable light confinement characteristics. As discussed in previous works [14] the relative sensitivity for a PCF can be computed using the two following equations.

$$f = \frac{\int_{sample} Re(E_x H_y - E_y H_x)\, dx\, dy}{\int_{total} Re(E_x H_y - E_y H_x)\, dx\, dy} \quad (1)$$

$$r = \frac{n_r}{\mathrm{Re}(n_{eff})} f \quad (2)$$

where, n_r is the refractive index of the sample and n_{eff} is the effective refractive index and f is the fraction of power as computed by the Poynting theorem.

We use three different food additives as the samples placed in the core. The refractive indices of these samples, namely, Saccharin, Sorbitol and Butyl Acetate are 1.43, 1.41 and 1.39, respectively.

We study the PCF structures on the COMSOL software using Finite Mode Analysis by varying the wavelength from 0.8µm to 1.8µm.

We then compute the relative sensitivity of the proposed PCF for these samples on the COMSOL software using subdomain integration. The sensitivity analysis from simulations are discussed in the next section.

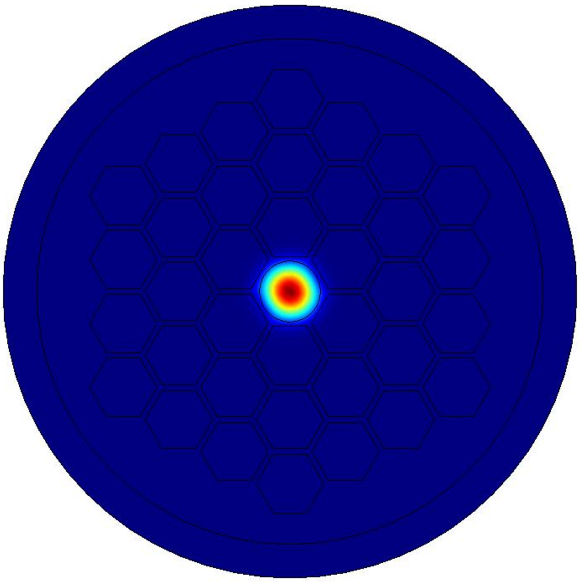

Fig. 5: Confinement of light in PROPOSED PCF using saccharin as sample at 1.55µm (complete view of the PCF)

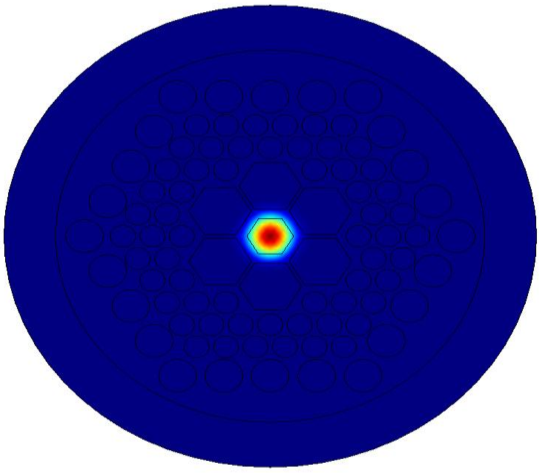

Fig. 6: Confinement of light in PCF-1 using saccharin as sample at 1.55µm (complete view of the PCF)

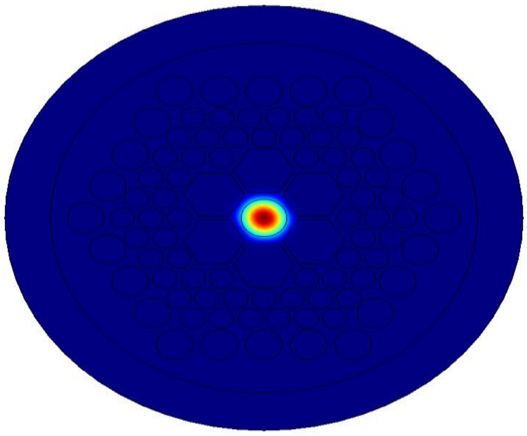

Fig. 7: Confinement of light in PCF-2 using saccharin as sample at 1.55µm (complete view of the PCF)

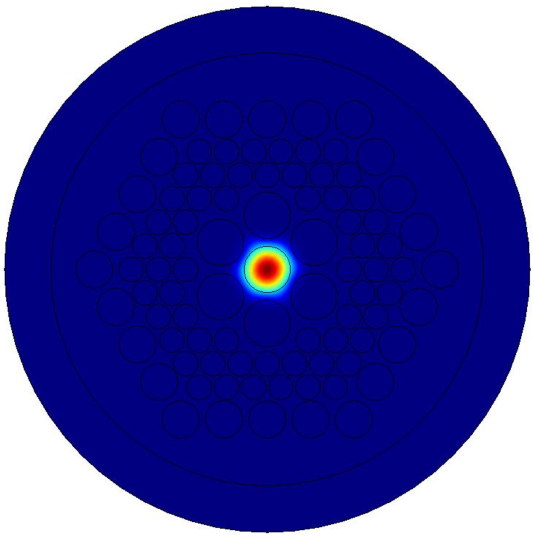

Fig. 8: Confinement of light in PCF-3 using saccharin as sample at 1.55µm (complete view of the PCF)

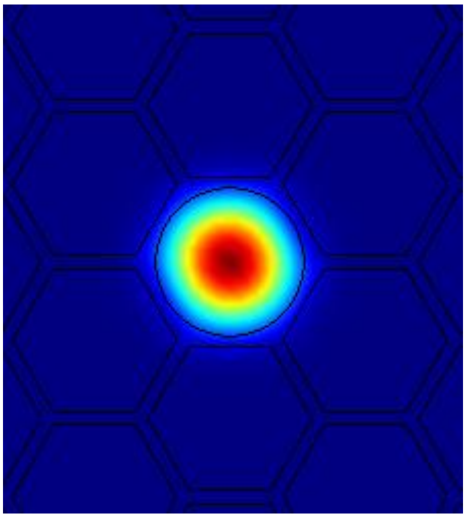

Fig. 9: Confinement of light in PROPOSED PCF using saccharin as sample at 1.55µm (view of the core of the PCF)

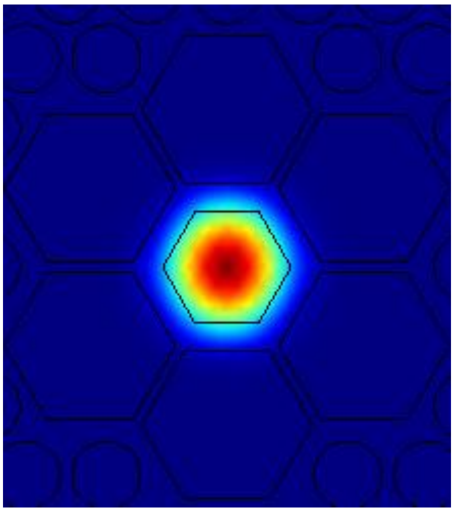

Fig. 10: Confinement of light in PCF-1 using saccharin as sample at 1.55µm (view of the innermost cladding of the PCF)

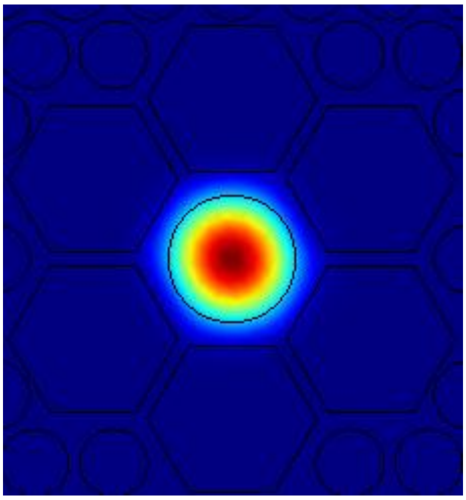

Fig. 11: Confinement of light in PCF-2 using saccharin as sample at 1.55µm (view of the innermost cladding of the PCF)

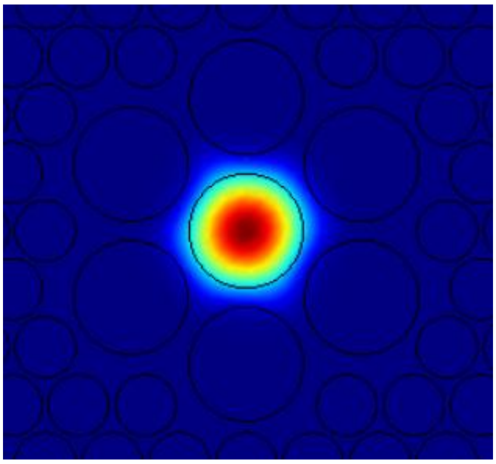

Fig. 12: Confinement of light in PCF-3 using saccharin as sample at 1.55µm (view of the innermost cladding of the PCF

IV. RESULTS AND DISCUSSION

The sensitivity analysis performed using COMSOL for the PROPOSED PCF design is compared with the relative sensitivities of PCF–1, PCF–2 and PCF–3. This analysis carried out for the three different food additives are plotted in Fig. 13, 14 and 15. In each of these plots the relative sensitivity is plotted by varying the wavelength from 0.8µm to 1.8µm, where the y-axis denotes the relative sensitivity in percentage (%) and the x-axis denotes the wavelength in µm. The analysis is also carried out at special wavelengths of 850nm, 1310nm and 1550nm [23] (typically used wavelengths for operation) and these results are plotted in Fig. 16, 17 and 18. Some of these results are also presented in Tables 5, 6 and 7.

It is observed that the PROPOSED PCF design has significantly improved sensitivity compared to the other designs for all the three samples. It is noted that the PROPOSED PCF design achieves > 90% sensitivity in the region of study. These results show that the presence of hexagonal airholes in the entire cladding enhances sensitivity in comparison to the previous designs which have hexagonal airholes only at the innermost cladding layer. Also, the increase in size of the circular core supports the increase in sensitivity. The proposed PCF, therefore, achieves a relative sensitivity of 94.21%, 93.10% and 91.84% for Saccharin, Sorbitol, and Butyl Acetate respectively.

We also compare the relative sensitivity values of the PROPOSED PCF design with the values of the other PCF designs provided in [14] at the wavelength of 1.33µm. This comparison is presented in Table 2, 3 and 4 for the three different samples. It is noted that we have directly used the values from [14] for the other designs since it contains the optimized values for those PCFs, whereas in our simulations we have not optimized the pitch value for these PCFs. It is clear from the tables that the PROPOSED PCF design has an improved high sensitivity. With regards to the designs PCF - 1, PCF – 2 and PCF – 3 we observe similar trend as in [14]. We see that PCF – 1 and PCF – 2 perform better than PCF – 3 in terms of sensitivity.

This has been attributed to the difference in the structure of the innermost cladding layer in these PCFs designs. We also note that the confinement loss for all the different PCF designs are negligible and therefore this did not play a central role in the comparison.

Therefore, it is clear from the detailed simulations that the PROPOSED PCF design outperforms the existing PCF designs. Hence, we have been able to achieve an highly sensitive PCF design that works effectively for detecting several food additives.

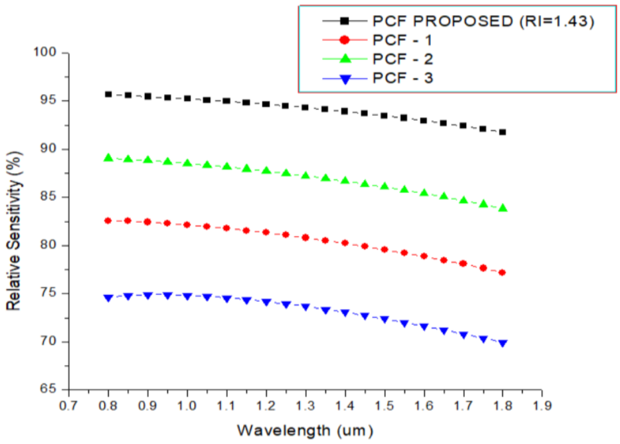

Fig. 13: Relative Sensitivity of PROPOSED PCF, PCF-1, PCF-2 and PCF-3 for Saccharin

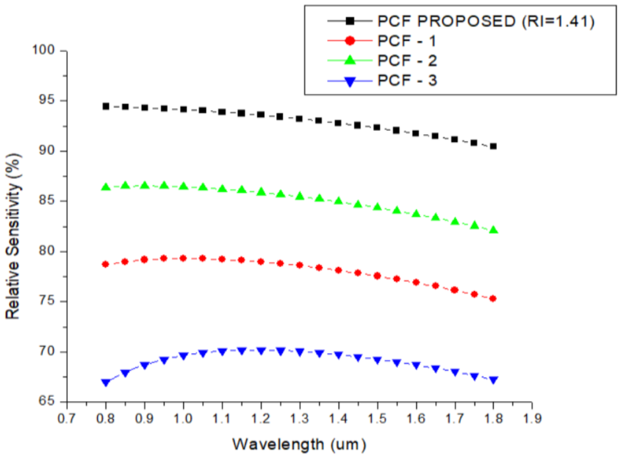

Fig. 14: Relative Sensitivity of PROPOSED PCF, PCF-1, PCF-2 and PCF-3 for Sorbitol

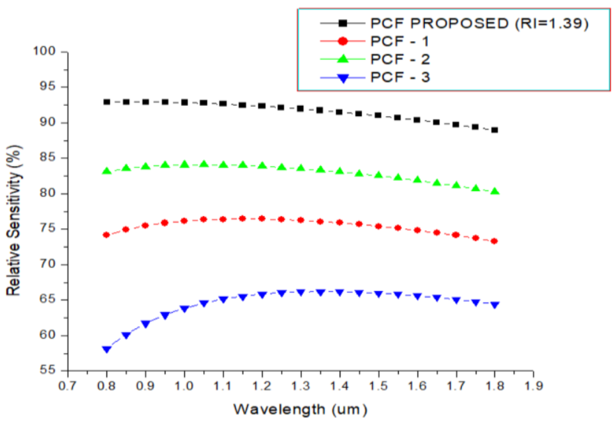

Fig. 15: Relative Sensitivity of PROPOSED PCF, PCF-1, PCF-2 and PCF-3 for Butyl Acetate

Table 2: Relative sensitivity at 1.33 µm for Saccharin (RI=1.43)

Structure	Relative Sensitivity
PROPOSED PCF	94.21%
PCF - 1	85.40%
PCF - 2	88.75%
PCF - 3	79.45%

Table 3: Relative sensitivity at 1.33 µm for Sorbitol (RI=1.41)

Structure	Relative Sensitivity
PROPOSED PCF	93.10%
PCF - 1	83.70%
PCF - 2	87.37%
PCF - 3	76.91%

Table 4: Relative sensitivity at 1.33 µm for Butyl Acetate (RI=1.39)

Structure	Relative Sensitivity
PROPOSED PCF	91.84%
PCF - 1	81.85%
PCF - 2	86.72%
PCF - 3	74.14%

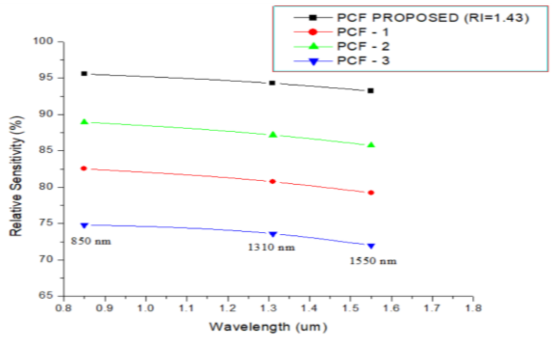

Fig. 16: Relative Sensitivity of PROPOSED PCF, PCF-1, PCF-2 and PCF-3 at 850nm, 1310nm and 1550nm for Saccharin

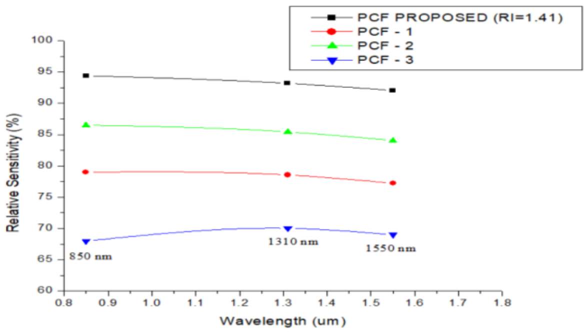

Fig. 17: Relative Sensitivity of PROPOSED PCF, PCF-1, PCF-2 and PCF-3 at 850nm, 1310nm and 1550nm for Sorbitol

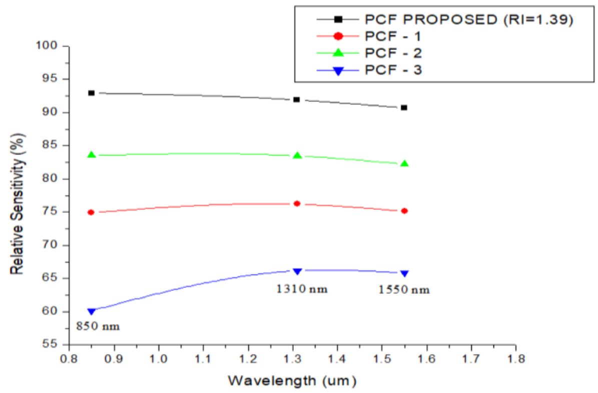

Fig. 18: Relative Sensitivity of PROPOSED PCF, PCF-1, PCF-2 and PCF-3 at 850nm, 1310nm and 1550nm for Butyl Acetate

Table 5: Relative sensitivity at 1310 nm for Saccharin (RI=1.43)

Structure	Relative Sensitivity
PROPOSED PCF	94.29%
PCF - 1	80.75%
PCF - 2	87.18%
PCF - 3	73.61%

Table 6: Relative sensitivity at 1310 nm for Sorbitol (RI=1.41)

Structure	Relative Sensitivity
PROPOSED PCF	93.18%
PCF - 1	78.55%
PCF - 2	85.43%
PCF - 3	70.03%

Table 7: Relative sensitivity at 1310 nm for Butyl Acetate (RI=1.39)

Structure	Relative Sensitivity
PROPOSED PCF	91.93%
PCF - 1	76.20%
PCF - 2	83.50%
PCF - 3	66.18%

V. CONCLUSION

In this work, we have designed an index guided Hollow Core Photonic Crystal Fiber (HC-PCF) with hexagonal shaped cladding for sensing harmful food additives like Saccharin, Sorbitol and Butyl Acetate. We have used the COMSOL software to study our designs and to perform finite element method simulations. Through these extensive simulations, we have shown that our proposed PCF design achieves a very high sensitivity of 94.21%, 93.10% and 91.84% for Saccharin, Sorbitol, and Butyl Acetate respectively at the operating wavelength of 1.33 μm. We have also compared our proposed design and shown that it significantly outperforms the current PCF designs. These results show that the presence of hexagonal airholes in the entire cladding enhances sensitivity in comparison to the previous designs which have hexagonal airholes only at the innermost cladding layer. In the future we would like to study similar PCF designs for related applications. We would also like to point out the extensive scope to explore PCFs for various applications.

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REFERENCES

1. Photonic Crystal Fiber Wiki, [Online]. Available: https://en.wikipedia.org/wiki/Photonic-crystal_fiber
2. F. Poli, A. Cucinotta, S. Selleri, "Photonic Crystal Fibers: Properties and Applications," Springer Science & Business Media, 2007 Aug 17.
3. A. Bjarklev, J. Broeng, S. E. Barkou Libori, E. Knudsen and H. R. Simonsen, "Photonic crystal fiber modelling and applications," OFC 2001. (IEEE Cat. 01CH37171), Anaheim, CA, 2001, pp. TuC1-TuC1.
4. Tianyu Yang, Erlei Wang, Haiming Jiang, Zhijia Hu, and Kang Xie, "High birefringence photonic crystal fiber with high nonlinearity and low confinement loss," Opt. Express 23, 8329-8337 (2015).
5. Petru Ghenuche, Silke Rammler, Nicolas Y. Joly, Michael Scharrer, Michael Frosz, Jérôme Wenger, Philip St. J. Russell, and Hervé Rigneault, "Kagome hollow-core photonic crystal fiber probe for Raman spectroscopy," Opt. Lett. 37, 4371-4373 (2012).
6. R. Ragni, S. Cicco, D. Vona, G. Leone, and G. M. Farinola, "Biosilica from diatoms microalgae: smart materials from bio-medicine to photonics," Journal of Materials Research, vol. 32, no. 2, pp. 279–291, 2017.
7. Yimin Wang, Yonghua Zhao, J. S. Nelson, Zhongping Chen, and Robert S. Windeler, "Ultrahigh-resolution optical coherence tomography by broadband continuum generation from a photonic crystal fiber," Opt. Lett. 28, 182-184 (2003).
8. K. Saitoh and M. Koshiba, "Highly nonlinear dispersion-flattened photonic crystal fibers for supercontinuum generation in a telecommunication window," Opt. Express 12, 2027-2032 (2004).
9. S. H. Kassani, R. Khazaeinezhad, Y. Jung, J. Kobelke and K. Oh, "Suspended Ring-Core Photonic Crystal Fiber Gas Sensor With High Sensitivity and Fast Response," in IEEE Photonics Journal, vol. 7, no. 1, pp. 1-9, Feb. 2015, Art no. 2700409.
10. H. Yu, Z. Luo, Y. Zheng, J. Ma, X. Jiang and D. Jiang, "Vibration Sensing Using Liquid-Filled Photonic Crystal Fiber With a Central Air-Bore," in IEEE Journal of Lightwave Technology, vol. 37, no. 18, pp. 4625-4633, 15 Sept.15, 2019.
11. Md. I. Islam, K. Ahmed, S. Asaduzzaman, B. K. Paul, T. Bhuiyan, S. Sen, Md. S. Islam, S. Chowdhury, "Design of single mode spiral photonic crystal fiber for gas sensing applications," in Sensing and Bio-Sensing Research, Volume 13, 2017, Pages 55-62, ISSN 2214-1804.
12. N. Ayyanar, G. Thavasi Raja, M. Sharma and D. Sriram Kumar, "Photonic Crystal Fiber-Based Refractive Index Sensor for Early Detection of Cancer," in IEEE Sensors Journal, vol. 18, no. 17, pp. 7093-7099, 1 Sept.1, 2018.
13. Senthil, R., Soni, A., Bir, K. et al. "Circular-Pattern Photonic Crystal Fiber for Different Liquids with High Effective Area and Sensitivity," Plasmonics 14, 1783–1787, 2019.
14. S.M. Atiqullah, Apu Palit, Mohammad Istiaque Reja, Jobaida Akhtar, Saleha Fatema, Rubaya Absar, "Detection of harmful food additives using highly sensitive photonic crystal fiber," in Sensing and Bio-Sensing Research, Volume 23, 2019, 100275, ISSN 2214-1804.
15. M. Niger, M. I. Reja, J. Akhtar, N. Jahan, R. Absar and S. Fatema, "Modified Dodecagonal PCF Sensor with High Sensitivity for Detecting Harmful Chemical Compounds used in Poultry Feed," 2019 5th International Conference on Advances in Electrical Engineering (ICAEE), Dhaka, Bangladesh, 2019, pp. 530-535.

16. COMSOL Multiphysics® software, [Online]. Available: http://www.comsol.co.in/comsol-multiphysics
17. S. Chattopadhyay, U. Raychaudhuri, R. Chakraborty, "Artificial sweeteners–a review," J. Food Sci. Technol. 51 (4) (2014 Apr 1) 611–621.
18. H. Mitchell (Ed.), "Sweeteners and sugar alternatives in food technology," John Wiley & Sons, 2008 Apr 15.
19. U.S. National Library of Medicine, NCBI, [Online]. Available: https://pubchem.ncbi.nlm.nih.gov/compound/Butyl_acetate.
20. Report on Carcinogens, Fourteenth Edition, [Online]. Available: https://ntp.niehs.nih.gov/ntp/roc/content/appendix_b.pdf.
21. Sorbitol Side Effects, medically reviewed on Jul 4, 2018, [Online]. Available: https://www.drugs.com/sfx/sorbitol-side-effects.html.
22. Butyl Acetate Reviews, [Online]. Available: https://reviewguts.com/butyl-acetate, (June 09, 2018).
23. Understanding Wavelengths In Fiber Optics, [Online]. Available: https://www.thefoa.org/tech/wavelength.htm

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