Analysis and Comparison of Liquid Sensing using Silica and BK7 Material PCF by 2D FDTD Method

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Abstract

A novel proposed design of hexagonal PCFs choosing two background materials and to compare the high relative sensitivity for liquid sensing. PCF whose both core and cladding are microstructred. Numerical analysis is carried out by implementing full vectorially 2D FDTD method. The proposed structures have been investigated in four different cases ($d_1=d_2=d_3=d_4=2\mu m$, $d_1=d_2=d_3=2\mu m$ $d_4=2.2\mu m$, $d_2=d_3=2\mu m$ $d_1=d_4=2.2\mu m$, $d_1=d_2=2\mu m$ $d_3=d_4=2.2\mu m$ at same lattice pitch of 2.4µm) and it reports that relative sensitivity achieve higher value with increasing the innermost air hole ring in cladding. On the other hand, relative sensitivity effectively increases by introducing a single channel instead of a group of channels. By optimizing configuration of PCF structures with different parameter suggests that relative sensitivity significantly changes with low confinement loss. The relative sensitivity and confinement loss have been investigated against different liquid analyte (water ethanol benzyne) and compared between two background material PCF.

Keyword - *PCF, Liquid sensor, Nonlinear effect, FDTD method*

I. INTRODUCTION

Microstructured Optical Fibre also known as photonic crystal fibre (PCF) when the fibre holes are periodically arranged) is a special kind of fibre with (in general) air holes running parallel to its axis and for all its length [1]. Two types of guidance are possible in these fibres: hollow core fibres guiding by photonic band gap (PBG) or solid core fibres guiding by total internal reflection (TIR). Both approaches offer routes to improved chemical and/or biological sensing of low index materials [2]. MOFs with fluids can be used in three main configurations regarding the guiding mechanism and the location of the material to be probed:

a) Hollow core PBG fibres. These can be completely filled with gas or low refractive index liquid [3] keeping the same guiding mechanism. Potentially they can present near total light-fluid overlap. The fact its transmittance occurs in specific bands that are sensitive to the holes refractive index and the complex manufacturing process reduces its applications in sensing experiments;

b) Liquid core TIR fibres. This approach requires a high air filling fraction cladding and a (selectively filled) liquid core [4]. Again, light-liquid overlap is very strong;

c) Solid core MOFs can have their (cladding) holes filled with the material of interest.

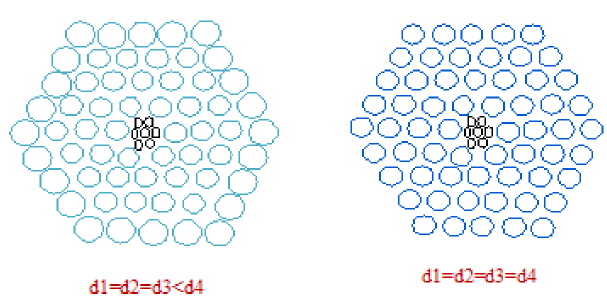
The transmittance window is broad, being limited, in practical terms, just by material loss. In the other hand, usually just a small fraction of power (the evanescent field) travels in the material to be sensed. The usual way to enhance this figure is by using fibres with a core diameter around the size of the wavelength [5]. Sensing in microstructured fibres is a new area, and it is not completely clear yet all implications involved with each of the possible configurations. Due to the low spatial overlap of the light and the fluid there has been little exploration of solid core fibres for fluid sensing.

Highly sensitive chemical (liquid and gas) sensors are playing an important role in the industrial processes [6] especially for detecting toxic and flammable chemicals (e.g., toxic gasses or liquids) to overcome the safety issues. So it has become one of the key challenges to enhance the performance of liquid and gas sensors. In recent years, researchers are keeping much interest on the development of photonic crystal fiber (PCF) based sensors for environmental and safety monitoring [7, 8] issues. Photonic crystal fiber based liquid and gas sensors through the evanescent field show excellent performance in terms of sensitivity, because core of the PCF directly interacts with the material to be analyzed. PCF technologies allow for the accurate tuning of fiber through changing the air hole shape, size, and their position. A wide variety of PCF based sensing techniques have been reported by changing different geometric parameters of the PCF to gain sensitivity at a maximum and confinement loss at a minimum satisfactory level in liquid and gas sensing applications. J. Park *et al*. [9] enhanced relative sensitivity for chemical sensing, using a hexagonal PCF with a hollow high indexed ring defect. In the hollow core PCF, the direct interaction between light and the analyte in the hollow channel is higher than the index-guided PCFs. Recently, the idea of filling core or cladding holes with various liquids or gases has been attracted much to the researchers. Cordeiro *et al*. [10] proposed a microstructure core PCF infiltrated with liquid analyte which enhanced the evanescent field. This concept introduced the sensing potentiality with infiltrated microstructure core. PCF of microstructure core offers to sense low indexed material because of the highly interaction of evanescent fields with the analyst to be sensed. A large number of published papers investigated and enhanced the performance of PCF based gas and liquid sensors with microstructure core [11-14]. In recent study, higher sensitivity and lower confinement loss of microstructure core PCF for liquid sensing have been attempted by using octagonal cladding structure [15, 16]. Reference [16] suggested 5-ring octagonal PCF for higher sensitivity and lower confinement loss; but in practical manufacturing octagonal structure requires extra more capillaries than the hexagonal structure. Keeping large number of capillaries will make high cost to fabricate. In this point of view, liquid sensing using a single infiltrated channel may also reduce the complexity of the core. To the best of our knowledge, no studies have been done in analyzing the sensitivity performance of PCF with a liquid filled core of a single channel.

In this article, we have proposed to design PCF structures choosing Silica and BK7 background material with micro structured core and cladding for liquid sensing. Here sensitivity and low confinement loss are main focus of this article. Further we also demonstrate the effect of single infiltrated channel replacing the microstructure core by proposing another PCF structure, which achieved more sensitivity and very simplicity to design. In fact we don't used any defect of air hole around the hollow core, but enhance the relative sensitivity by making use of ring defect around the core. We have chosen suitable liquid analyte water ethanol and benzyne doped air holes for investigating the relative sensitivity and low confinement loss and compared nearly similar result of two background PCF structure. The above targeted chemical species for characterization of our structure and its mechanism can be applied for all kind of fluids and gases based on the absorption line of targeted sample.

II. STRUCTURAL DESIGN

Four different kind of PCF structure whose transverse cross-sectional view as shown in fig.1. Each proposed PCF contains four air hole ring in their cladding. Taking d_1,d_2,d_3 and d_4 are the diameter of air hole in the innermost ring, 2nd, 3rd and outermost ring respectively and Λ is the distance between centre to centre of two adjacent air holes which is constant for all proposed structure. The field distribution profile of all purposed PCF structure are simulated with wide range of wavelength 0.5 0.75 1.0 1.25 1.5 1.75µm respectively. Initially we consider PCF_1 in which diameter of all air holes are constant, i.e $d_1=d_2=d_3=d_4=2.0$µm and pitch distance setting to $\Lambda=2.4$µm. It is observed that the effect of confinement loss basically depends on the outermost air hole ring diameter and it has greater impact as diameter of outer ring air hole increases. Secondly when we come across PCF_2 as $d_1=d_2=d_3<d_4$. It is seen that the relative sensitivity increase with increase of diameter of inner air holes. In PCF_3, the geometrical parameter of diameter of air holes are set to $d_2=d_3< d_1=d_4$.while PCF_4 the geometrical parameter of diameter of air hole are $d_1=d_2$, $d_3=d_4$ and it is somehow different from other PCFs that it achieves high relative sensitivity by replaceing the group of tiny air holes with single hollow core region is same as the area covered by tiny air holes. It is important to report that, we have designed PCF_1 PCF_2 PCF_3 that the core region is enclosed with some tiny air holes in the circular form which are filled with various liquid analyte like water, ethanol and benzyne. The core air holes are arranged with hole to hole pitch distance represented by 'a'. On the other hand also the diameter of hollow channel $D_2=1.7$µm which is same as diameter of region of holes in the core. Each PCF has two orthogonal sides of the computational region which are assigned two artificial boundary condition such as perfect electric conductor and perfect magnetic conductor. Perfect mateched layer is used as a boundary condition. The thickness of PML is fixed to 10% of radius of proposed PCFs for efficient calculation of confinement loss. We have considered circular perfect matched layer as boundary condition. The cross-section of proposed PCFs are divided into the homogeneous triangular subspace using mesh analysis. The liquid filled air holes region is divided into many sub domains which is either triangular or quadrilateral shape. As wave propagates in z direction, the modal analysis has preformed in the XY plane of PCF structure.



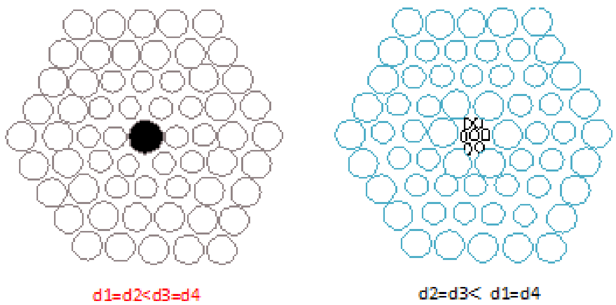


Fig.1 Cross sectional view of PCF_1 PCF_2 PCF_3 and PCF_4 (Silica and BK7)

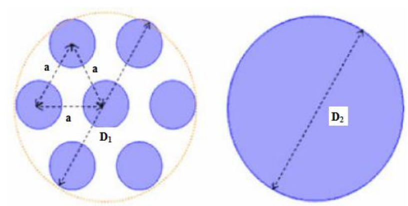


Fig.2 Cross sectional view of core region of PCF_1 PCF_2 PCF_3 and PCF_4 (Silica and BK7)

III. PRINCIPLE OF PCF

It is a special type of optical fiber in which transportation of light is controlled by photonic band gap mechanism. In general PBG can control the guidance of light with certain frequency band. In this research article, PCFs behaves as waveguide in which the purposed analyte and light interact with each other. In order to study the field distribution pattern of purposed PCFs and its propagation mode, by employing 2D-FDTD technique. We have taken circular perfectly matched layer boundary condition and the cross section of purposed PCFs is divided into homogeneous triangular subspace.

IV. NUMERICAL ANALYSIS

In order to study the field distribution of proposed hexagonal PCF structures of two background material(silica BK7), we have used 2D-FDTD technique. Considering the material is isotropic, linear, and lossless, the time dependent Maxwell's equations can be written as

$$\frac{\partial H}{\partial t} = \frac{1}{\mu(r)} \nabla \times E \qquad (1)$$

$$\frac{\partial E}{\partial t} = \frac{1}{\varepsilon(r)} \nabla \times H - \frac{\sigma(r)}{\varepsilon(r)} \mathrm{E} \qquad (2)$$

E, H are electric field and magnetic field.

Where $\varepsilon(r)$, $\mu(r)$, $\sigma(r)$ are permittivity, permeability and conductivity of the material and all are in the function of position.

Equations (1) and (2) can be discretized using Yee's technique. Considering spatial and time discretization, equations (1) and (2) can be written for TE polarization as follows:

$$H^{n+1/2}_{x(i,j)} = H^{n-1/2}_{x(i,j)} - \frac{c\Delta t}{\mu\Delta y}\left(E^{n}_{z\left(i,j+\frac{1}{2}\right)} - E^{n}_{z\left(i,--\frac{1}{2}\right)}\right)$$

(3)

$$H^{n+1/2}_{y(i,j)} = H^{n-1/2}_{y(i,j)} + \frac{c\Delta t}{\mu\Delta x}\left(E^{n}_{z\left(i+\frac{1}{2},j\right)} - E^{n}_{z\left(i-\frac{1}{2},j\right)}\right)$$

(4)

$$E^{n+1}_{z(i,j)} = E^{n}_{z(i,j)} + \frac{c\Delta t}{\varepsilon\Delta x}\left(H^{n+\frac{1}{2}}_{y\left(i+\frac{1}{2},j\right)} - H^{n+\frac{1}{2}}_{y\left(i-\frac{1}{2},j\right)}\right) - \frac{c\Delta t}{\varepsilon\Delta y}\left(H^{n+\frac{1}{2}}_{x\left(i,j+\frac{1}{2}\right)} - H^{n+\frac{1}{2}}_{x\left(i,j-\frac{1}{2}\right)}\right) \quad (5)$$

For stability, the time step

$\Delta t \leq \frac{1}{c\sqrt{\Delta x^{-2}+\Delta y^{-2}}}$, where Δt the time increment, c is the velocity of light,Δx be the lattice increment in x direction, Δy be the lattice increment along y direction.

Considering equation (3),(4) and (5) , we have calculated the field distribution of PCFs in TE polarization mode.

For a nonlinear optical waveguide having Kerr-type non-linearity related permittivity ε_r depends on electric field E_y and can be expressed as

$$\varepsilon_r = \varepsilon_{r.L} + \alpha\left|E_y\right|^2 \qquad (6)$$

Where $\varepsilon_{r.L}$ is the linear relative permittivity and α is the non linear co-efficient. A hybrid implicit FDTD method is used to simulate the field for 2D PCS with nonlinear rods. The overall stability of this hybrid FDTD scheme is determined by the stability in the linear medium regions. Consequently, nonlinearity in the structure does not effect stability and hence the grid size and time step.

The cladding region consists of finite number of air holes so it may cause the leakage of light. This leakage of light from core to exterior material results the confinement loss (dB/km), that can be expressed as:

Confinement loss = $8.686 k_0 I_m$ [n_{eff}] dB/km (9)

Where I_m is the imaginary part, n_{eff} is the effective index of x polarized and y polarized fundamental mode.

The relative sensitivity coefficient measures the interaction between the light and the analyte to be sensed. This interaction is measured through the absorption coefficient at a particular wavelength. According to the Beer-Lambert law, light is attenuated by the intensity of absorption of evanescent wave [17].

$I(\lambda) = I_0(\lambda) \exp[-r\alpha_m l_c]$

The absorbance of the sample to be detected is defined by the following equation [18]:

$$A=\log\left(\frac{I}{I_0}\right)= r\,\alpha_m\, l_c$$

where I and I_0 are the input and output intensities, respectively, and c is the concentration of absorbing material. The length of the channel is l. The function of absorption coefficient is $\alpha_m(\lambda)$, and r is the relative sensitivity coefficient, which can be defined by the following equation [19].

$$r = \frac{n_r}{n_{eff}}\ f$$

where n_r refers to the refractive index of the sample to be sensed, and n_{eff} is the effective index of the guided mode, f is the fraction of total power located in the core, and it is also known as a power distribution function [20] by using Poynting's theorem which can be expressed as the following equation:

$$f = \frac{\int Re\left(E_x H_y - E_y H_x\right)dxdy}{\int Re\left(E_x H_y - E_y H_x\right)dxdy}$$

, where numerator integration for sample and denominator integration for total.

where E_x and H_x are transverse electric field and respectively; E_y and H_x are longitudinal electric field and magnetic field respectively. Using 2D-FDTD technique, the mode field pattern and effective index are obtained. During the simulation, we have considered the material dispersion of silica and BK7 background using the Sellmeier equation [21].

V. RESULT ANALYSIS & DISCUSSION

We have investigated the two proposed PCF structure of two background material (Silica and BK7) for liquid sensing using 2D-FDTD method. Here we report the numerical analysis of propagation characterstics of FM and HOM of two proposed PCF. The core air holes are filled with suitable liquid analyte like water ethanol and benzyne and analyzing it's sensing property. Apart from this, we have considered and investigating the x polarization of FM. The purposed PCFs are designed in four different situation, where PCF_1 has preformed by assuming the geometric parameter like d_1=d_2=d_3=d_4=2.0µm, PCF_2 as d_1=d_2=d_3=2.0µm and d_4=2.2µm, PCF_3 as d_2=d_3=2.0µm and d_1=d_4=2.2µm. Moreover we have made proper selecting the supplementary hole pitch ratio d/a=0.75µm, pitch Λ=2.4µm in cladding and this parameter is kept fixed for all the purposed PCF.

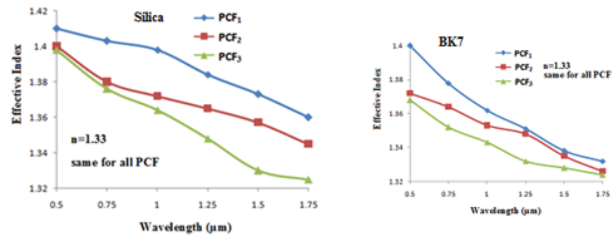
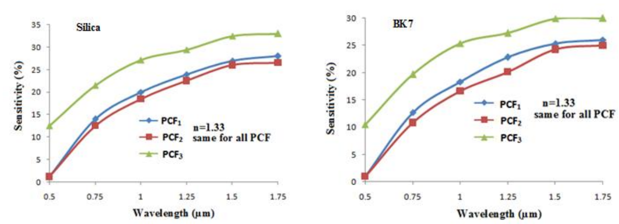


Fig.3 Effective index versus wavelength of FM X-polarization (Silica and BK7)

Fig3. demonstrate the effective index versus wavelength range of PCF_1, PCF_2 and PCF_3 with silica and BK7 as background material is investigated. It is seen that the effective index gradually decrease with increase in wavelength for both background material and found that PCF_1 shows higher effective index as compared to other PCF. But it is little bit small value of refractive index in case of BK7. It is interesting thing that at an operating wavelength of 1.55µm, PCF_1 of silica back ground material is just 0.04 times more than that of BK7 material. So BK7 is also most suitable for any application in optical communication as like silica. This is our comparision.



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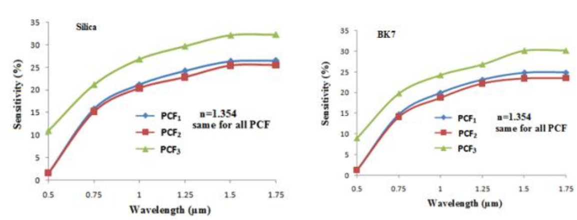

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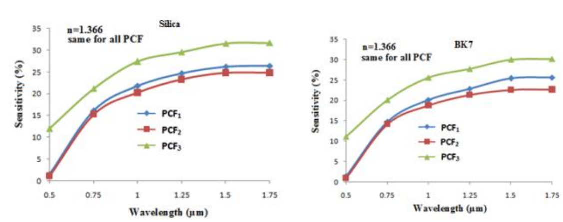


(c)

$$\frac{d_1}{\Lambda} = \frac{d_2}{\Lambda} = \frac{d_3}{\Lambda} = \frac{d_4}{\Lambda} = 0.83 \text{ (PCF}_1\text{)}$$

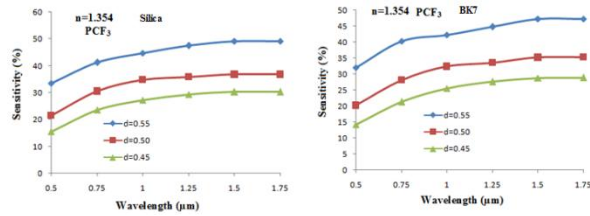
$$\frac{d_1}{\Lambda} = \frac{d_2}{\Lambda} = \frac{d_3}{\Lambda} = 0.83 \quad \frac{d_4}{\Lambda} = 0.93 \text{(PCF}_2\text{)}$$

$$\frac{d_2}{\Lambda} = \frac{d_3}{\Lambda} = 0.83, \frac{d_1}{\Lambda} = \frac{d_4}{\Lambda} = 0.83 \text{(PCF}_3\text{)}$$

Fig.4 Relative sensitivity versus wavelength

Fig.4 represents the relative sensitivity versus wavelength of PCF_1, PCF_2 and PCF_3 for the three different liquid analyte. It reports that, there is no significant change in sensitivity of PCF_1 and PCF_2 for both background materials. So no significant impacts on sensitivity have been observed with increasing diameter of outer rings air holes. But the relative sensitivity of PCF_3 is greatly influenced for both the background material. It is calculated the sensitivity of PCF_3 for water, ethanol and benzyne at an operating wavelength of 1.55µm is 33.42%, 35.15% and 36.64% for silica and 32.12%, 33.82% and 34.24% respectively for BK7 while the confinement loss is $0.82x10^{-2}$dB/km, $0.57x10^{-2}$dB/km and $0.47x10^{-2}$dB/km respectively for silica and $0.7x10^{-2}$dB/km, $0.45x10^{-2}$dB/km and $0.37x10^{-2}$dB/km respectively for BK7.The sensitivity of PCF_3 is enhanced due to the increment of inner air hole ring diameter which leads them closer to the core area and the fraction of evaanscent field penetrates to the air holes increase and so relative sensitivity of PCF_3 increasing effectively. More importantly that higher refractive index material shows higher relative sensitivity. As like silica , BK7 material also shows very important result about relative sensitivity and confinement loss, so BK7 is also most suitable applicable in fiber optics communication as like silica.

Fig.5 represents the performance of relative sensitivity of PCF3 by changing the diameter 'd' of the supplementary air holes in the core region. It reveals the sensitivity gradually increase with increase in wavelength and as well as increment of diameter of supplementary air holes. It is found that highest sensitivity occur when diameter of supplementary air hole is equal to 0.55µm for both PCF (silica BK7). PCF_3 shows the relative sensitivity 49.2% and 48.4% for silica and 47.3%, 46.7% for BK7 background material. In comparison to silica and BK7 PCF , the relative sensitivity of BK7 is no more less than that of silica and hence BK7 material PCF is most suitable for liquid sensing, fiber optics communication like supercontinuum generation, nonlinear fiber optics, birefringence, and many more application as like silica material.



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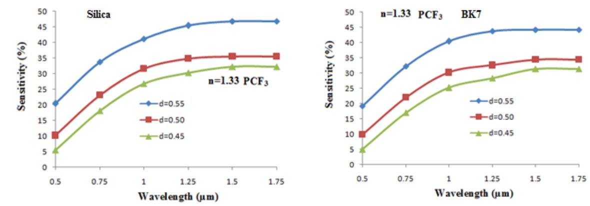
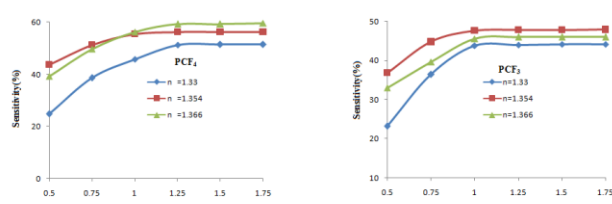


(b)

Fig.5 Relative sensitive versus wavelength at a

$$\frac{d_2}{\Lambda} = \frac{d_3}{\Lambda} = 0.83 , \frac{d_1}{\Lambda} = \frac{d_4}{\Lambda} = 0.93 \text{(PCF}_3\text{)}$$

The next investigation to achieve a very high relative sensitivity, choosing another PCF_4 to implementing a single hollow channel instead of supplementary very tiny air holes and set to diameter of hollow channel is 1.70µm. In order to compare the study of relative sensitivity between PCF_3 and PCF_4 for all liquid analyte as shown in fig.6. It is analyzed that from below fig.6, PCF_4 shows drastically increase in relative sensitivity at an operating wavelength of 1.55µm and it exhibits relative sensitivity about 51.4%, 56.2% , 59.2% and the confinement loss $0.76x10^{-2}$dB/km, $0.52x10^{-2}$dB/km, $0.45x10^{-2}$dB/km for water ethanol and benzyne respectively for silica PCF. Similarily in case of PCF_4 (BK7) also shows the relative sensitivity about 50.6%, 55.2%, 58.4% and confinement loss $0.62x10^{-2}$dB/km, $0.44x10^{-2}$dB/km and $0.32x10^{-2}$dB/km for same liquid analyte. It is interesting thing that, PCF_4(BK7) whose relative sensvity result is not much less than that of silica background material PCF. Hence BK7 PCF_4 is also useful as same as silica PCF_4 applicable.



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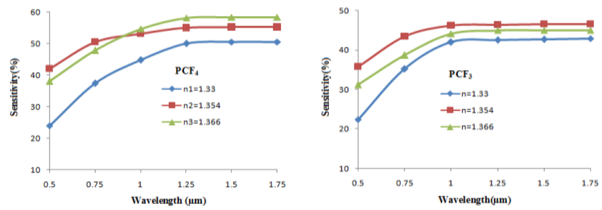
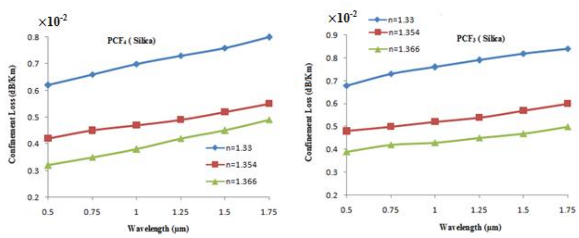


(b)

Fig.6 Relative sensitivity versus wavelength of PCF$_3$ PCF$_4$ for BK7

Finally investigation is carried out between confinement loss versus wavelength of PCF$_3$ and PCF$_4$ shown in fig.7.The simulation result reveals that PCF$_4$ achieves better performance of confinement loss as compared to PCF$_3$ for all liquid analyte. However confinement loss of PCF$_4$(BK7) is slightly less than that of silica PCF$_4$. In fact light is more confined in the core region of both proposed PCF$_4$ as compared to other three PCF structures.



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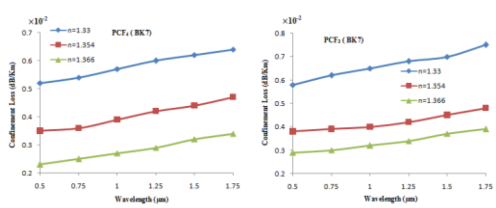

(b)

Fig.7 Confinement loss versus wavelength for PCF$_3$ and PCF$_4$ of Silica and BK7

Light confinement property in both case are nearly same. This seems to be linked that electromagnetic interaction between the liquid analyte and light propagation is more, as a result an increase in relative sensitivity. It is also observed that confinement loss is lower for higher refractive index liquid analyte and hence PCF$_4$ in both this cases show higher value of relative sensitivity and lower confinement loss as compared to PCF$_3$. In addition to simulation result of above fig, it is to be illustrated the field distribution profile of proposed PCF$_3$ and PCF$_4$ as shown in fig.8 at an operating wavelength of 1.55µm.

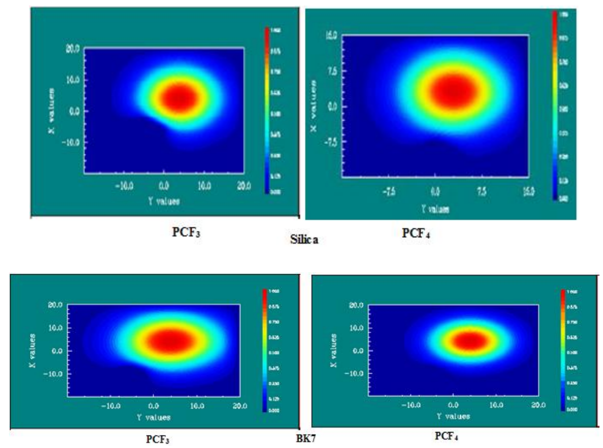

Fig.8 Modal field distribution pattern of PCF$_3$ and PCF$_4$ for X-polarized mode at an wavelength of 1.55µm(for both Silica and BK7 material)

Here air holes of core region is filled with liquid ethanol because of higher refractive index. Apart from this, it is found that the FM of PCFs (PCF$_3$ PCF$_4$), and observe tightly confined in the centre of core region. As discussed in above, it reports that, the purposed design PCF structures show better performance in relative sensitivity with more design simplicity as compared to prior structures (17 18) for liquid sensing. The comparative study between purposed PCFs and the prior PCFs for liquid sensing at an operating wavelength of 1.55µm is shown in below table. Moreover the fabrication feasibility of purposed PCF is an important part, but it is very difficult to fabricate a micro cored region. Due to technological advancement, the fabrication of purposed PCFs are possible. In addition, micro core region is filled with liquid analyte without destruction of fiber integrity. So different type of technology are adopted for filling of PCF air holes with liquid analyte. A unique method for filling the all cladding holes along with core air holes by Huang etal (19). Beside these the fabrication of PCF with inclusion of liquid analyte in air holes can be accomplished with same method (20 21). Apart from this now applying a sol-gel technique (22) in which all kind of difficulty of fabrication of microstructured optical fiber can be solved. In connection to this, the purposed PCFs can be fabricated using 2D-FDTD technique.

Table.1 Comparison between proposed PCFs and prior PCFs for liquid sensing applications at wavelength of 1.55 µm.

PCFs	Sensitivity (%) Ethanol (n=1.354)	Benzyne (n=1.366)	Shape of structure
Ref [24]	23.42	24.23	Octagonal 3rings
Ref [25]	47.82	48.12	Octagonal 5 rings
Proposed			
PCF$_3$ (Silica)	49.20	51.22	Hexagonal 4 rings
PCF$_3$(BK7)	48.24	49.60	Hexagonal 4 rings
PCF$_4$(Silica)	56.20	59.6	Hexagonal 4 rings
PCF$_4$(BK7)	55.24	58.40	Hexagonal 4 rings

VI. CONCLUSION

It reports the performance of two novel proposed PCF for liquid sensing which have been investigated. The two proposed PCF are based on microstructrued core, hollow core and infiltrated with the liquid to be sensed. It is found that, the proposed PCFs have more guiding capability and useful for the current research like nanofabrication technique. In addition, it also provides higher relative sensitivity with tighter confinement of optical field. Like silica, BK7 PCF structure is also applicable for liquid sensing choosing suitable parameter. It is successfully overcome the critical trade off between confinement loss and relative sensitivity for two proposed PCF offer great potential for toxic chemical and gas detection in industrial safety purposes**.**

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