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Optimized Hexagonal Photonic Crystal Fibre Sensor for Glucose Sensing

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Authors' contributions

This work was carried out in collaboration between all authors. Author MBH designed the study, performed the statistical analysis, wrote the protocol, and wrote the first draft of the manuscript. Authors EP and AA managed the analyses of the study. Author AAM managed the literature searches. All authors read and approved the final manuscript.

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ABSTRACT

Aims: This paper presents an optimised hexagonal photonic crystal fibre (PCF) geometry for investigation of relative sensitivities for 20%, 30%, 40%, 50% and 60% of glucose solution in water at a wavelength ranging from 1200 nm to 1600 nm. This work also shows an active area and confinement loss variation of the optimised hexagonal PCF when the core is filled with different concentrations of glucose solution.
Study Design: Here, optimised hexagonal photonic crystal fiber (PCF) geometry is chosen where COMSOL Multiphysics software is used for simulation.
Place and Duration of Study: Department of Electronics and Communication Engineering at Khulna University, Khulna-9208, Bangladesh and Study duration was between March 2017 and December 2017.
Methodology: At first, 20%, 30%, 40%, 50% and 60% of glucose solution in water with different refractive indexes are inserted through the core of the modified Hexagonal PCF. Then, the simulation is done by varying wavelength from 1200 nm to 1600 nm. Here, Comsol Multiphysics is

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used for simulation and MATLAB is used to plot the desired optical properties of the proposed PCF geometry.

Results: From this work, the relative sensitivities are obtained approximately 28.6, 33.09, 36.97, 40.37, 44.81 in percentage at wavelength 1200 nm and 35.27, 37.63, 41.15, 44.98, 47.87 in percentage at wavelength 1600 nm for 20%, 30%, 40%, 50% and 60% of glucose solution in water respectively. Again, the effective areas are found approximately 16.306 μm^2, 17.285 μm^2, 18.207 μm^2, 19.209 μm^2, 19.729 μm^2 at wavelength 1200 nm and 18.823 μm^2, 19.495 μm^2, 20.21 μm^2, 20.739 μm^2, 20.954 μm^2 at wavelength 1600 nm for 20%, 30%, 40%, 50% and 60% of glucose solution in water respectively. The confinement losses are approximately 2.1×10^{-8} dB/Km, 0.78×10^{-8} dB/Km, 0.15×10^{-8} dB/Km for 20%, 30%, and 40% of glucose solution in water respectively at wavelength 1500 nm but for 50% and 60% of glucose solution, the confinement loss is approximately zero from 1200 nm to 1600 nm.

Conclusion: High sensitive Glucose sensor is achieved with optimised Hexagonal PCF structure which was the main target of this research.

Keywords: Photonic crystal fiber; relative sensitivity; effective area; confinement loss; COMSOL multiphysics.

1. INTRODUCTION

Optical fibres development in 1966 revolutionised the field of telecommunication [1-3]. The invention of photonic crystal fiber (PCF) has enlarged the fibre optic field with faster communication overcoming many limitations of traditional optical fibre [4-5]. Nowadays, PCF has been used for a large number of optical applications because of its design flexibilities as well as exclusive physical features [6-7]. Various guiding properties of PCF can be achieved by changing geometric parameters such as air holes diameter, lattice pitch and number of air holes layer. The periodic arrangements of air holes surrounding the core guide the light from one end of fiber to another end [8]. The core also may solid or hollow. Even more, these fibres offer also the possibility of a light guiding in a hollow core [9-10].

One of the most important fields of PCF application is the sensing application [11]. PCF has already used for numerous sensing applications such as biosensing, gas sensing, chemical sensing and temperature sensing. Biosensing as well as chemical sensing has enlarged the medical science, and that's why a large number of researchers are paying their keen attention to increase the sensitivity of liquids, chemicals as well as gases [12-15].

It is very tough to get a PCF geometry which will provide high sensitivity as well as low confinement loss [16-18]. So, researchers are working on it. There are a large number of published papers which present the concept of filling liquids in the core region for liquid or chemical sensing applications [19-22]. For example, Cordeiro et al. (2006) introduced a PCF geometry for liquid sensing. After that, Ademgil et al. (2014) confirmed the improvement of relative sensitivity for liquid sensing and recently, Asaduzzaman et al. (2015) introduced another PCF geometry with higher sensitivity than all the previous result. Though some of the research papers in the field of liquid sensing are showing higher sensitivity, they are practically impossible to implement. So, still, there are scopes of designing a high sensitive liquid sensor with optimised PCF structure.

In our research, we have designed a hexagonal PCF geometry in Comsol Multiphysics, and we have changed the core holes diameter where we have inserted into different concentrations of glucose solution. Again, we have changed the air holes diameter and pitch in the cladding region, and after that, we have selected an optimised structure which can be practically implemented as well as which provides high sensitivity for the glucose sensor. The primary goal of this research is the investigation of relative sensitivity, active area and confinement loss of the proposed PCF geometry by varying the concentrations of glucose solution.

2. METHODOLOGY

In this thesis, we have designed an optimised hexagonal PCF structure in COMSOL Multiphysics. The fibre background material is made of silica glass and three layers of air holes (outside three layers) with diameter, d1 = 1.6 μm and pitch, Λ = 2.1 μm have covered cladding region. The central hole with diameter, d = 1.8

μm and another eight holes surrounding the central hole with diameter 1.2 μm are filled with different concentrations of glucose solution. The perfectly matched layer (PML) of 1 μm is used after three layers of air holes. The optimized hexagonal PCF structure is shown in Fig. 1.

For this research we have taken 20%, 30%, 40%, 50% and 60% of glucose solution in water as sensed liquid. The refractive indexes of glucose solution concentrations for 20%, 30%, 40%, 50% and 60% of glucose solution in water are 1.3538, 1.3708, 1.3890, 1.4084 and 1.4298 respectively at wavelength 1200 nm. This optimized hexagonal PCF structure is investigated for analyzing the relative sensitivity, effective area and confinement loss at wavelength range from 1200 nm to 1600 nm.

The relative sensitivity can be calculated by using the following equation [9]:

$$r = \frac{n_r}{n_{eff}} f \tag{1}$$

Where n_r is the refractive index of sensed material and n_{eff} is the modal effective refractive index which is obtained from Comsol Multiphysics simulation. Again, f is the power ration in percentage which is shown below [9]:

$$f = \frac{\int_{sample} \mathrm{Re}(E_x H_y - E_y H_x) dxdy}{\int_{total} \mathrm{Re}(E_x H_y - E_y H_x) dxdy} \times 100 \tag{2}$$

Here, Ex, Ey and Hx, Hy are the transverse electric field and magnetic field in x and y axis respectively. Where, f can be obtained from Comsol Multiphysics simulation directly, then putting the values of n_r, n_{eff} and f in MATLAB, we can get relative sensitivity curve with respect to wavelength.

Another important parameter is effective area of fiber which can be calculated directly from COMSOL Multiphysics and it is obtained from the equation [9-10]:

$$A_{eff} = \frac{(\iint |E^2| dxdy)^2}{\iint |E^4| dxdy} \tag{3}$$

Here, A_{eff} is the effective area in μm^2 and E is the electric field.

MATLAB is used to plot the effective area curve with respect to the wavelength ranging from 1200 nm to 1600 nm.

Confinement loss is one of the barriers of optical fiber transmission and it can be calculated from the following equation [10]:

$$L_c = 8.686 K_o I_m (n_{eff}) \times 10^6 \tag{4}$$

Where, $K_0 = 2\pi/\lambda$ and $Im\ (n_{eff})$ is the imaginary part of modal index which is obtained from Comsol Multiphysics simulation directly.

Then, MATLAB software is used to plot the confinement loss curve by using equation (4).

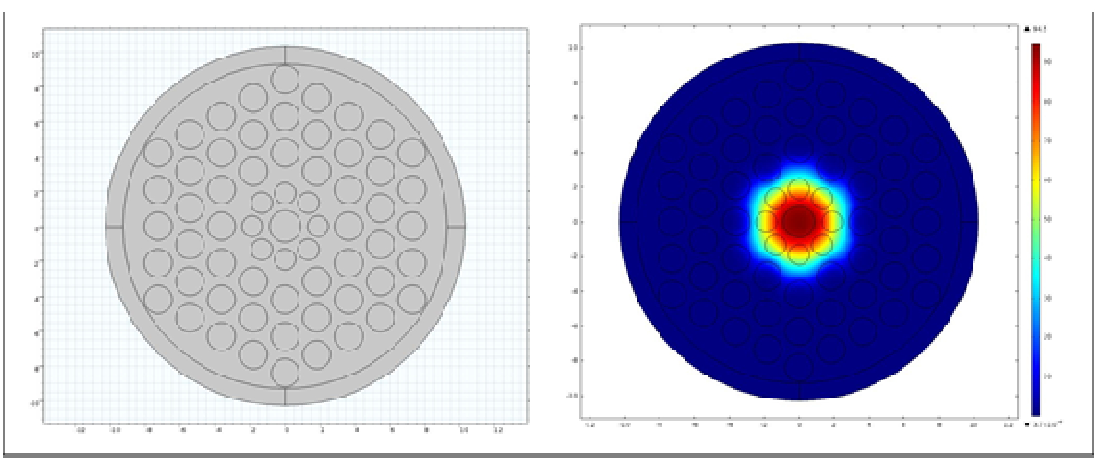

Fig. 1. The Optimized Hexagonal PCF geometry and fundamental mode field

3. RESULTS AND DISCUSSION

To investigate the relative sensitivity of glucose solution, effective area as well as confinement loss of the proposed hexagonal PCF structure, COMSOL Multiphysics simulation software is used. The PCF core region is filled with 20%, 30%, 40%, 50% and 60% of glucose solution in water. For each amount of concentration of glucose solution, the simulation is run at wavelength ranging from 1200 nm to 1600 nm. The main focus of this research is the effect of variation of glucose solution concentrations on relative sensitivity, effective area and confinement loss.

The relative sensitivity is increasing with the increase of wavelength and it is also increasing with the increase of concentrations of glucose solution. The relative sensitivities are obtained approximately 28.6, 33.09, 36.97, 40.37, 44.81 in percentage at wavelength 1200 nm and 35.27, 37.63, 41.15, 44.98, 47.87 in percentage at wavelength 1600 nm for 20%, 30%, 40%, 50% and 60% of glucose solution in water respectively.

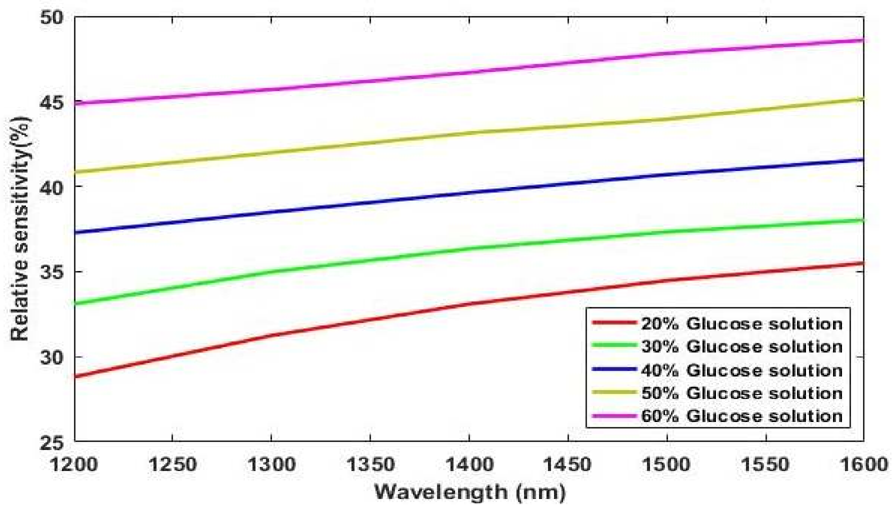

Fig. 2. Relative sensitivity curve for different concentrations of glucose solution with respect to wavelength for optimized hexagonal PCF geometry

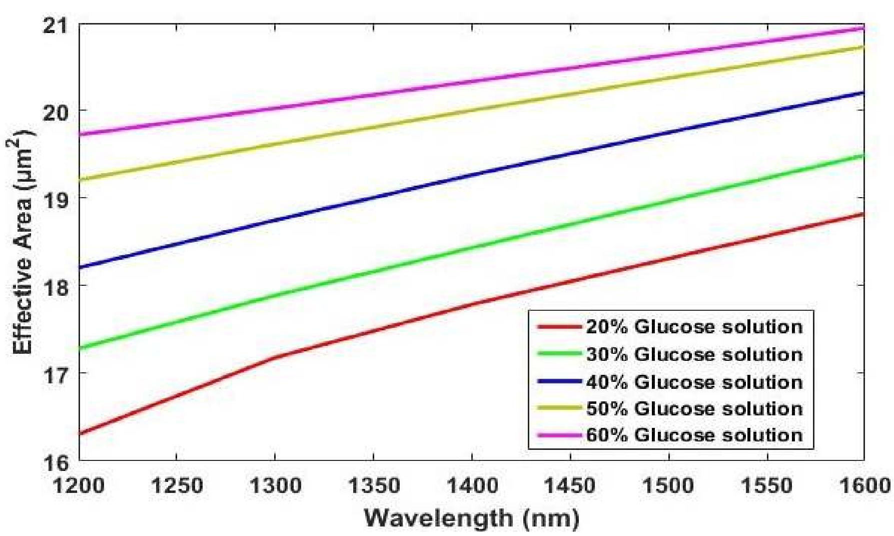

Fig. 3. Effective area curve for different concentrations of glucose solution with respect to wavelength for optimized hexagonal PCF geometry

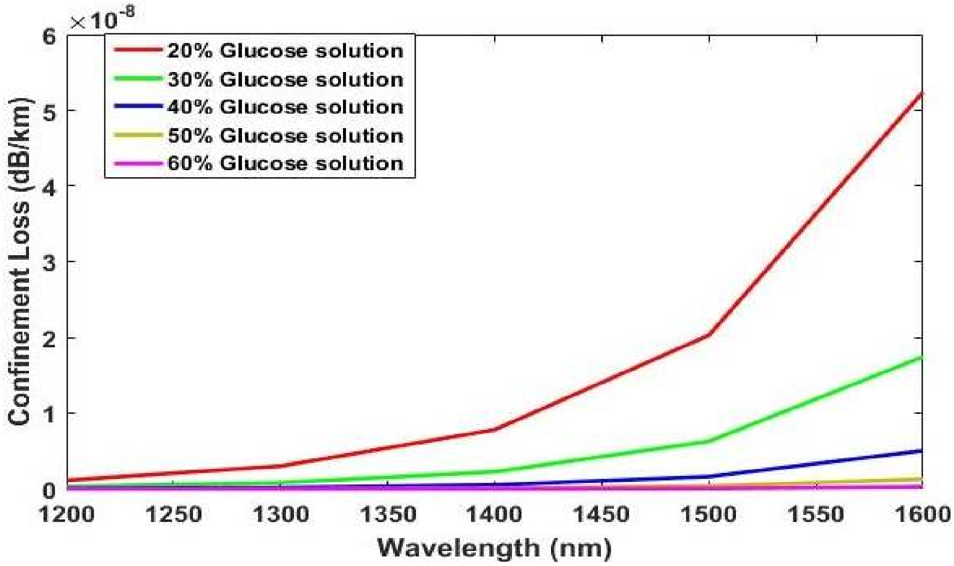

Fig. 4. Confinement loss curve for different concentrations of glucose solution with respect to wavelength for optimized hexagonal PCF geometry

The effective area is increasing with increasing concentration of glucose solution as well as wavelength. The effective areas are found approximately 16.306 μm^2, 17.285 μm^2, 18.207 μm^2, 19.209 μm^2, 19.729 μm^2 at wavelength 1200 nm and 18.823 μm^2, 19.495 μm^2, 20.21 μm^2, 20.739 μm^2, 20.954 μm^2 at wavelength 1600 nm for 20%, 30%, 40%, 50% and 60% of glucose solution in water respectively.

The confinement is increasing largely with increasing wavelength for 20% and 30% of glucose solution in water, while for 40% of glucose solution initially confinement loss is approximately zero and it starts to increase after 1400 nm. The confinement loss is approximately 2.1×10^{-8} dB/Km, 0.78×10^{-8} dB/Km, 0.15×10^{-8} dB/Km for 20%, 30%, and 40% of glucose solution in water respectively at wavelength 1500 nm. But for 50% and 60% of glucose solution, the confinement loss is approximately zero form 1200 nm to 1600 nm.

4. CONCLUSION

In this research work, an optimised hexagonal photonic crystal fiber (PCF) geometry has been designed in Comsol Multiphysics. The main focus of this research is the variation of relative sensitivity for the variation of the concentration of glucose solution as well as with the variation of wavelength. This paper also investigates effective area and confinement loss of the optimised PCF structure when 20%, 30%, 40%, 50% and 60% of glucose solution in water which is filled in the core region. From this work, the relative sensitivities are obtained approximately 28.6, 33.09, 36.97, 40.37, 44.81 in percentage at wavelength 1200 nm and 35.27, 37.63, 41.15, 44.98, 47.87 in percentage at wavelength 1600 nm for 20%, 30%, 40%, 50% and 60% of glucose solution in water respectively. Again, the effective areas are found approximately 18.823 μm^2, 19.495 μm^2, 20.21 μm^2, 20.739 μm^2, 20.954 μm^2 at wavelength 1600 nm for 20%, 30%, 40%, 50% and 60% of glucose solution in water respectively. The confinement losses are approximately 2.1×10^{-8} dB/Km, 0.78×10^{-8} dB/Km, 0.15×10^{-8} dB/Km for 20%, 30%, and 40% of glucose solution in water respectively at wavelength 1500 nm but for 50% and 60% of glucose solution, the confinement loss is approximately zero form 1200 nm to 1600 nm.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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