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Effect of Surface Roughness on Sensitivity of Unclad Fiber-Optic Sensors

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Abstract. This work presents the effect of surface roughness's effect on transmission characteristics and the sensitivity of unclad fiber optic sensor (FOS). A total of three samples with different surface roughness were fabricated using the chemical etching technique using different chemical solutions which are 49% hydrofluoric acid (HF), 5:1 Buffered Oxide Etchants (BOE), and 7:1 BOE to analyze the spectrum behavior and the performance of these samples. All samples were fabricated by immersing the 4 cm of sensing zone inside the chemical solution according to the etching rate of that solution. Every sample fabricated will be measured using five different concentrations of glucose which were 5g, 10g, 15g, 20g, and 25g as an experiment medium. From the measurement, the results obtained will be analyzed and the graphs were plotted. The power loss for all solutions were analyzed and the least recorded power loss is 32.49 dB exhibited by FOS fabricated in the 49% HF solution while the best sensitivity in terms of power loss is FOS fabricated in the 5:1 BOE solution with the highest sensitivity of 9.526 dB/g at 5g of glucose concentration.

Keywords – Unclad fiber sensor, sensitivity, surface roughness, chemical etching, BOE.

1. Introduction

Fiber optic sensor (FOS) are being quickly developed into commercial solutions to perform measurements in niche sectors as part of the global telecommunications revolution [1]. FOS has many benefits, including high sensitivity, light weight, small size, high temperature performance, and immunity to electromagnetic interference. The waveguide property is altered by applying a suitable process, such as chemical etching to remove the cladding, to make the FOS more sensitive to the outside environment. Numerous FOS researchers have proposed various fabrication processes and strategies for the sensing zone on optical fiber elements [2]. The use of unclad fiber has raised wide interest in global communication for the high sensitivity sensors among the other FOS. The preparation of unclad fiber is quite easy and can be done by using several methods, especially using the chemical etching technique. Chemical etching techniques are usually utilized to measure, reduce, and remove the subsurface in optical components, which makes it significant to fabricate the FOS by using this technique [3-5]. The FOS's surface roughness has been altered in order to take advantage of the fact that it is possible to test the sensitivity of the FOS when the nature of the sensors is altered. The FOS's benefits are its cost-effectiveness, compact size, strong sensitivity to the environment, and high immunity to electromagnetic interference [6].

In this type of sensor, the evanescent wave's attenuation on the unclad fiber surface directly affects the sensitivity of its sensing region and the surface roughness of the etched fiber core significantly affects the transmission properties and sensitivity of the sensors [7]. To fabricate a high-quality evanescent-field fiber, chemical etching technology has been investigated and tested [8-9]. However, during the etching process, the etching products will be adsorbed on the surface and unevenly distributed. Therefore, chemical etching cannot be used to obtain a smooth surface on the etched optical fiber without agitation [10]. Ultrasonic waves are widely used to improve the surface roughness of silica optical fibers [11]. To fabricate an etched fiber core with smooth and different surface roughness, a simple etching approach that combines ultrasonic agitation with the use of buffered hydrofluoric acid (BHFA) solution and hydrofluoric acid (HFA) solution etchant are used [12]. The optical reflectivity of the interface between the fiber and the surrounding environment will be affected by the surface roughness of the unclad fibers; this is very important for the construction of high-sensitivity sensors [7].

2. Theory

Surface roughness of the FOS is the condition where the core of the fiber has an uneven surface which contain a depth on it caused by the chemical reaction during fabrication of FOS by using chemical etching technique. The surface roughness of the unclad fibers directly affects the optical reflectivity of the interface between the fiber and the surrounding environment [13]. The sensitivity of unclad FOS depends on the attenuation of the evanescent waves, which is affected by their effective intensity, decay coefficient, penetration depth, and optical path length on the unclad fiber surface. $2\delta/\Delta$ is average pit parameters measure from the surface non-uniformity of fiber core which represent the surface roughness of the fiber core, δ is the average pit depth on the fiber surface which is defined in terms of a field of peaks and valleys, Δ is the average pit diameter which is defined as the distance between two adjacent peaks, hi is the local pit depth and Di is the local pit diameter, and N is the number of pit units. The average pit parameters are a measure of the surface nonuniformity, which represents a field of varying depth and diameter.

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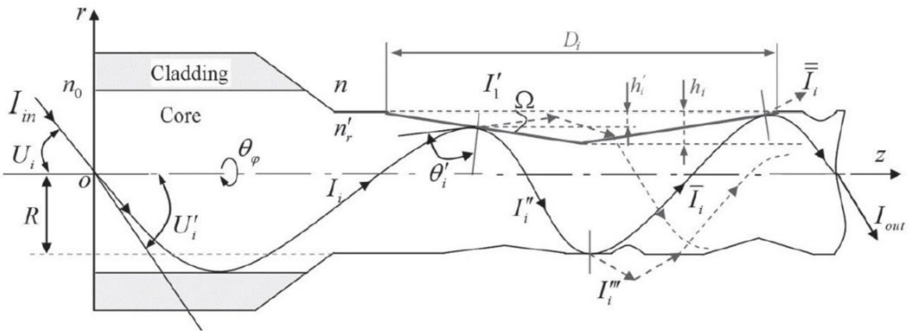

Figure 1 The light transmission in rough surface FOS (adapted from [13])

Figure 1 shows the propagation of light in the FOS with a rough surface. The angle of incidence angle is different compared with the smooth surface since there is surface pits on the core of the FOS caused by the fabrication using the chemical etching technique. From Equation (1), the output intensity of the smooth surface can be calculated using this equation, and Equation (2) shows the output intensity of the rough surface on the FOS [13]. These parameters of $2\delta/\Delta$ can be obtained from the Scanning Electrons Microscopy (SEM) image in the observation region (0.3–0.4 mm from the microscope photographs at the magnification ×400) [14].

$$I_{out} = I_{in}\ \exp\left[-\frac{\alpha\lambda L}{r\pi n_r^2}\left(n + \frac{n^3}{n_r^2}\right)\cos\theta_i cot\theta_i\right] \quad (1)$$

$$I'_{out} = I_{in}e^{-\xi'(n)L} \cdot \frac{U_{max} - \arcsin\{\frac{n_{max}}{n}\sin[\frac{\delta}{2r}\arctan(\frac{2\delta}{\Delta})]\}}{U_{max}} \quad (2)$$

The relationship between the measurement system's output and input is known as sensitivity. In a perfect world, sensitivity would be unaffected by environmental factors like humidity or temperature and would remain constant over the whole operating range. Fading is the term for sensitivity variation for a specific system, however, transducer design or system operation can be changed to modify the sensitivity value for other systems. For this project, the sensitivity was calculated by using the recorded value of the power loss and the concentration of glucose.

3. Experimental details

The FOS structure in this project is designed using a single type of fiber optic, multimode fiber (MMF). To monitor the refractive index of the different concentrations of the glucose solution, three samples of the fiber with different surface roughness along the sensing zone are used. To fabricate all three samples, 49% HF is needed with 40% Ammonium Fluoride (NH4F) composed of 80g of Ammonium Fluoride powder and 120ml of Deionized (DI) water. To prepare the Buffered Oxide Etchants (BOE) solution, 40% NH4F was mixed with 49% HF according to the ratio needed. This sensor's design is very simple, with FOS fabricated on the sensing zone of the multimode fiber (MMF) that needs to be cleaned with DI water.

3.1. Fabrication process

The fabrication process for this FOS was simple, but precise. It only required a few steps. The first step was to use a stripper to remove the coating of the sensing zone on the multimode fiber. After the coating of the sensing zone was removed, the fiber needs to be cleaned using the task wiper with the ethanol to make sure all the dust on the fiber were removed. The second step was to prepare the chemical solution such as 49% HF, 5:1 BOE and 7:1 BOE solution. To prepare the BOE solution, 40% NH4F is needed with 49% HF. To prepare 40% NH4F, 80g of Ammonium Fluoride powder was weight using analytical balances and then was mixed with 120 ml of Deionized (DI) water. The process of preparing the BOE solution required a precise measurement to make sure the BOE solution made is high quality.

The sensing zone was then immersed in hydrofluoric acid at a concentration of 49% as shown in Figure 3, to achieve the desired diameter. The experiment shows that after two minutes in hydrofluoric acid, the actual diameter of the MMF decreases by 10μm. The diameter of the sensing zone of FOS after 10 minutes immersed in the different ratios of BOE solution was measured using the microscope RaxVision Y100 to determine the etching rate for the BOE solution. The etching rate for the 5:1 BOE was 2.5μm/10 minutes after measurement with the microscope, while the etching rate for the 7:1 BOE was 1.25μm/10 minutes. The total time required to fabricate the FOS using the chemical etching technique for 5:1 BOE was 4 hours and 40 minutes to remove the diameter of MMF for 70μm while the time required to remove 70μm for 7:1 BOE was 9 hours and 20 minutes.

MMF fiber-end surface was cleaved in a straight line with a cleaver to form a fiber-end face mirror, reducing traveling light losses. The hetero-core interface the excited high-order cladding modes. The fiber-end face mirror would reflect both the cladding and core modes, causing them to interfere with the hetero-core interface.

3.2. Surface roughness experiment process

The surface roughness measurement equipment was setup as Figure 2. The first end of 1m FOS was linked up to the ASE C-banding light source with maximum peak power of 100Mw while the lead out

FOS was linked up to the optical spectrum analyzer (OSA). The sensing zone of the FOS was placed in the glass container so that we can see clearly the glucose solution used as a medium.

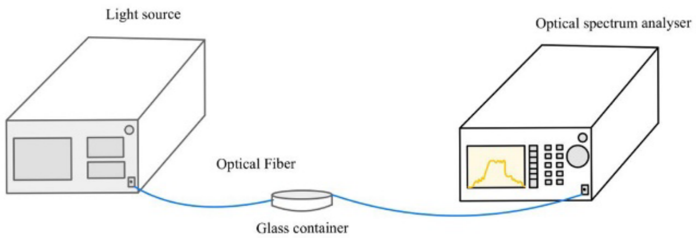

Figure 2 The experiment setup for the measurement process

To start the measurement, the first end of the FOS was cleaved using a cleaver and then will spliced using a splicer with the connector to link with the light source and repeat the process for the other end of the FOS and linked it to the OSA. The process of splicing required a very precise step in order to make sure the fiber spliced do not have any flaw such as the fiber being too dusty, there was a bubble during the splicing process, the cleaved angle being too big or small, and got loss after the splicing process.

Next, when all the setup was done, a few drops of the glucose solution started with 5g were dropped on the sensing zone in the glass container. The sensing zone was made sure to be fully immersed in the glucose solution and measurement was taken approximately after 5 minutes the sensing zone was fully immersed in the glucose solution. To get better results, the measurement was taken three times for each glucose concentration. The procedure was repeated for other glucose concentrations of 10g, 15g, 20g, and 25g. After all the measurements for all glucose concentrations were done, the process was repeated for the other two samples fabricated in the 5:1 BOE and 7:1 BOE solution.

To make sure the data obtained from the measurement were consistent, the process of changing the different solutions in the glass container contained the fabricated FOS was using the dropper. To make sure the data obtained is reliable, the measurement process must be done without any disturbance such as vibration on the table and the measurement must be done in one go for all glucose concentrations.

4. Results and discussion

Using an optical spectrum analyzer (OSA), the behavior of the transmission spectrum of these fiber optic sensors with various levels of surface roughness was observed during the experiment. Three distinct FOS surface roughness's were utilized in this experiment to assess the sensors' sensitivity to immersion in five different concentrations of glucose, starting at 5g, 10g, 15g, 20g, and 25g. The OriginPro 8.5 software will then be used to observe and analyze the transmission spectra, power, and wavelength of the FOS presented by the OSA.

The transmission spectrum behavior for the FOS, which was constructed inside the 49% HF chemical solution using a chemical etching process with a diameter set at 55μm. The measurements for the 5g, 10g, 15g, 20g, and 25g of glucose have been completed. This research clearly investigates the variable behavior of the transmission spectra on the OSA screen caused by the various glucose concentrations used as the refractive index (RI), demonstrating that the surface roughness of the FOS was sensitive to the various glucose concentrations employed. When the FOS was used at varying concentrations, the surface roughness of the FOS caused changes in the transmission spectrum.

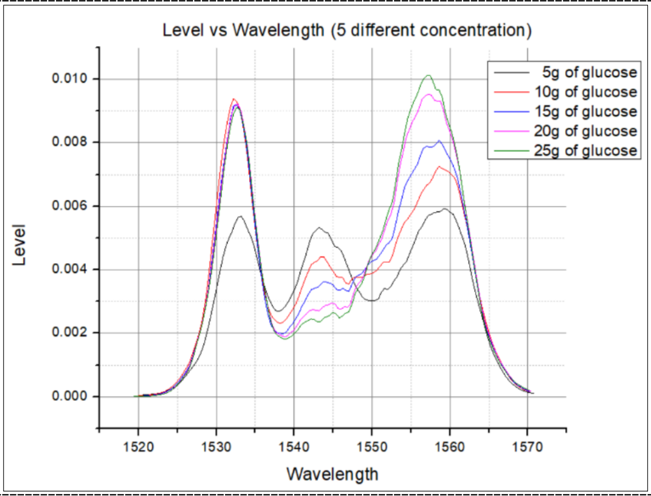

Figure 3 Transmission spectrums for all concentrations using FOS fabricated in 49% HF solution

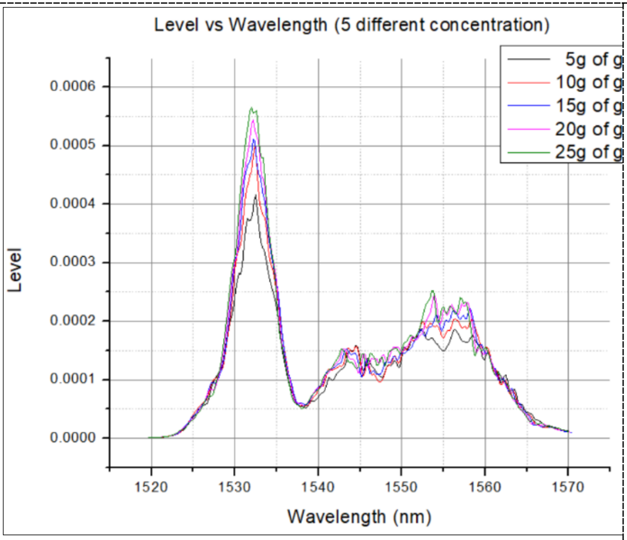

Figure 4 Transmission spectrums for all concentrations using FOS fabricated in 5:1 BOE solution

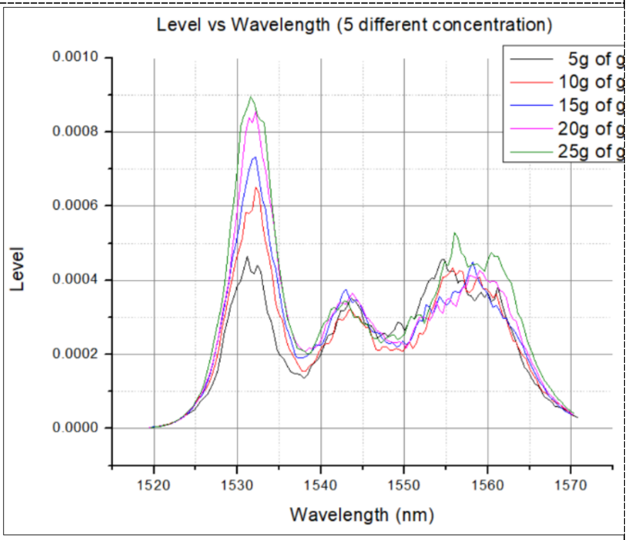

Figure 5 Transmission spectrums for all concentrations using FOS fabricated in 7:1 BOE solution.

Figures 3, 4 and 5 show the transmission spectrums for all concentrations using FOS fabricated in 49% HF solution, 5:1 BOE solution, and 7:1 BOE solution respectively. The range of the wavelength spectrum was observed from 1520nm to 1570nm. From these figures above, the difference in power can be seen clearly from the transmission spectrum. When the glucose concentration become more concentrated, the power received will be increased based on the transmission spectrum obtained from the OSA.

Table 1. Results obtained for FOS fabricate using 49% HF at λ = 1557nm

Solution	Glucose concentration (gram)	Level	Power (dBm)
1	5	0.00564	-22.49
2	10	0.00667	-21.76
3	15	0.00789	-21.03
4	20	0.00950	-20.22
5	25	0.01012	-19.95

Table 2. Results obtained for FOS fabricate using 5:1 BOE at λ = 1557nm

Solution	Glucose concentration (gram)	Level	Power (dBm)
1	5	1.7275	-37.63
2	10	1.9264	-37.15
3	15	2.0258	-36.93
4	20	2.1998	-36.58
5	25	2.3987	-36.20

Table 3. Results obtained for FOS fabricate using 7:1 BOE at λ = 1557nm

Solution	Glucose concentration (gram)	Level	Power (dBm)
1	5	3.9937	-33.99
2	10	4.2281	-33.74
3	15	4.3843	-33.58
4	20	4.5015	-33.47
5	25	4.6968	-33.28

The analysis of the level and power received observed at λ = 1557nm was tabulated in the above tables for different solution used to fabricate the FOS with different surface roughness. It was clear from the tables above that when the glucose solution becomes more concentrated, the power received increases which means the power loss decreased with a high concentrated glucose solution.

To assess the sensitivity, a few parameters can be employed. Power loss is used in this research to test the sensitivity. According to the analysis of the tables above, as the power transmission is increased, the glucose solution increases with its concentration. Therefore, using the transmission spectrum as the parameter, the liquid with the highest concentration of glucose, or 25g of glucose, has the best power received. However, comparing the sensitivity of three different surface roughness samples is the primary goal of this project. Figure 6, which compares and plots the power received against each varied concentration of glucose solution, makes it easy to understand.

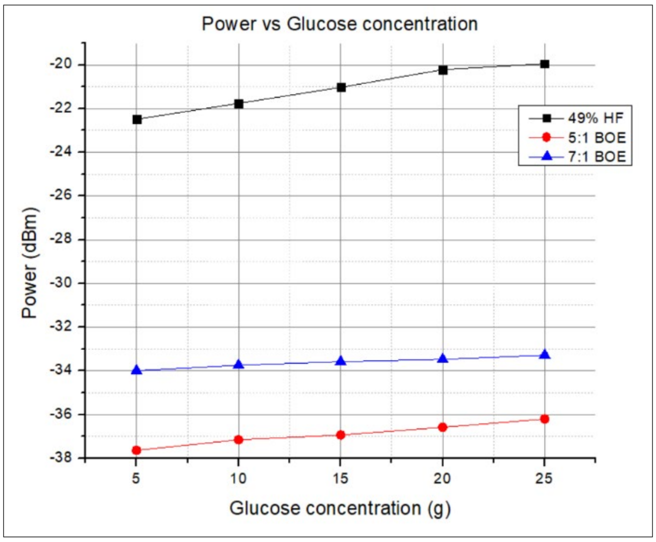

Figure 6 Power transmission of FOSs with different concentrations of glucose

Figure 6 shows the power transmission for all sensors fabricated in 49% HF solution, 5:1 BOE solution, and 7:1 BOE solution. From the graph above, the power transmission increases as glucose concentration increases. When the concentration of glucose changed from 5g to 25g, the power transmission for all sensors was increased respectively. Also, from the graph above, the sensor fabricated in 49% HF has a better power transmission compared with the other two samples fabricated in 5:1 BOE solution and 7:1 BOE solution.

Table 4. Results of power loss for all solutions at λ = 1557nm

Solution	Glucose concentration (gram)	Power Loss (dB)		
		49%HF	7:1BOE	5:1BOE
1	5	32.49	43.99	47.63
2	10	31.76	43.74	47.15
3	15	31.03	43.58	46.93
4	20	30.22	43.47	46.58
5	25	29.95	43.28	46.20

Table 5. Sensitivity in terms of power loss for all solution

Solution	Glucose concentration (gram)	Sensitivity (dB/g)		
		49%HF	7:1BOE	5:1BOE
1	5	6.498	8.798	9.526
2	10	3.176	4.374	4.715
3	15	2.067	2.905	3.129
4	20	1.511	2.174	2.329
5	25	1.198	1.7312	1.848

From Table 4, it is shown the power loss for all the sensors. To calculate the power loss for all the sensors, the input power was needed which is from the light source, the power supply is 10 dBm. The value of the power supply was used to subtract the power received to get the value of power loss. From Table 5, when the concentration of the glucose increased, the sensitivity in terms of power loss for all sensors decreased and among these three sensors, the sensor fabricated in 5:1 BOE solution had better sensitivity compared with the other two samples fabricated in 49% HF solution and 7:1 BOE solution. As can see clearly from the table above, sensor fabricated in 5:1 BOE solution exhibits the highest sensitivity in every concentration of glucose compared with other sensors. For 5g of glucose concentration, 5:1 BOE solution recorded the highest sensitivity of 9.526 dB/g compared to 7:1 BOE and 49% HF solutions with sensitivity of 8.798 dB/g and 6.498 dB/g respectively.

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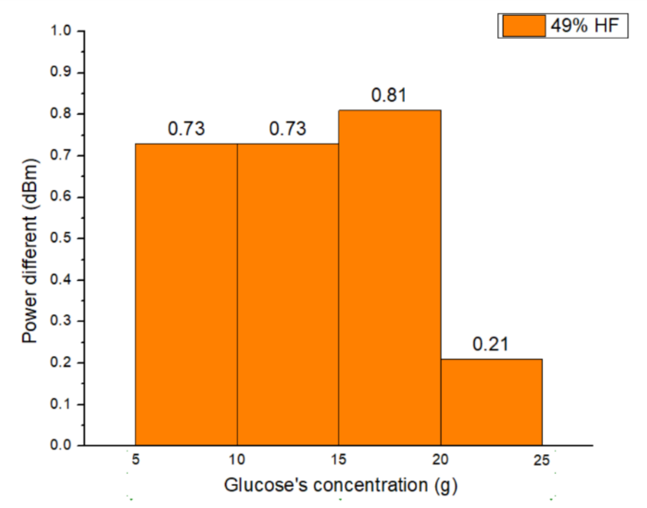

Figure 7 Power variation when changing the glucose concentration using FOS fabricated in 49% HF solution

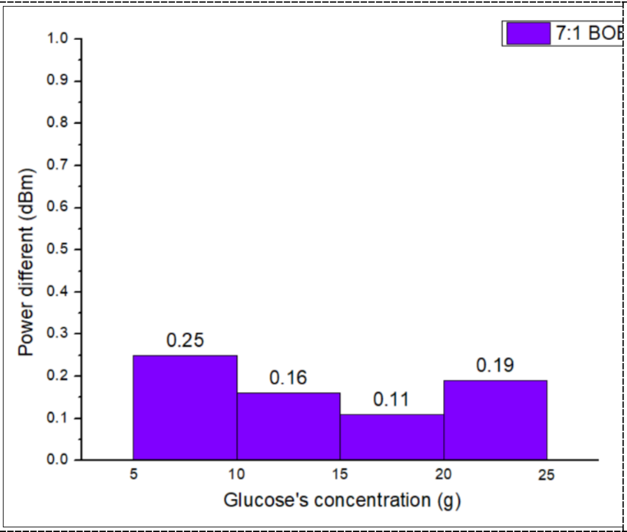

Figure 8 Power variation when changing the glucose concentration using FOS fabricated in 7:1 BOE solution.

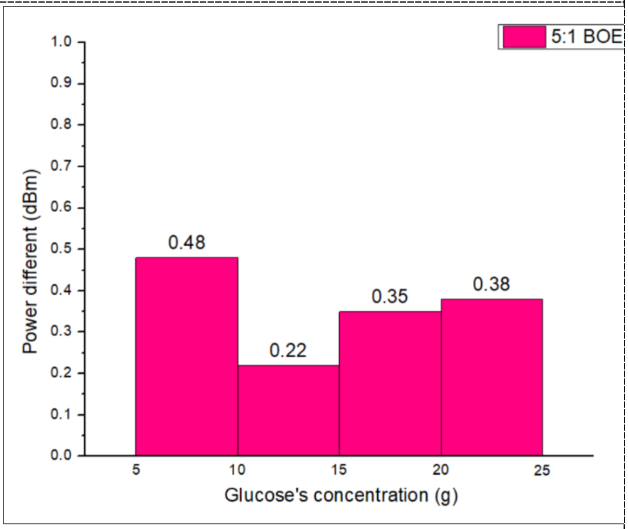

Figure 9 Power variation when changing the glucose concentration using FOS fabricated in 5:1 BOE solution.

Figures 7, 8, and 9 show the power difference when changing the glucose concentration using FOS fabricated in 49% HF solution, 7:1 BOE solution and 5:1 BOE solution respectively. The power difference was calculated by getting the difference between two concentrations of glucose. As can been seen clearly from these figures, all power difference for all three sensors were less than 1 which is good. It is better if the power difference remains constant or slightly different when changing the glucose concentration. When the power difference is changed, the sensitivity also changed because both power difference and sensitivity in terms of power loss were dependant with the power loss parameter.

5. Conclusion

The sensitivity of the FOS with different surface roughness was investigated by fabricating the FOS using chemical etching technique and analyzed their effects when the different glucose concentration was used as a medium. In this study, the investigation method was carried out to determine whether the surface roughness has any bearing on the sensitivity of the sensing zone. According to the research conducted, the sensor that was constructed in 5:1 BOE solution exhibits the highest sensitivity than other solutions. The project's findings revealed that the FOS fabricated in 5:1 BOE provides better sensitivity in terms of power loss when the power loss is significantly higher than for other samples. The sensitivity at 5g of glucose concentration for 49% HF, 7:1 BOE and 5:1 BOE are being recorded as 6.498 dB/g, 8.798 dB/g and 9.526 dB/g respectively. The presented results significantly highlight that the different surface roughness of sensing element contributed to different level of sensitivity.

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