Investigating the effect of waist diameter on sensitivity of the etched plastic optical fiber based ethanol sensor

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The ability to sense low concentration of ethanol rise an urge, especially in food industry. This paper reported the sensing performance of low concentration of ethanol solutions (0.5% to 3.5%) by varying the length (1, cm, 3 cm and 5 cm) and waist diameter (0.5 mm and 0.8 mm) of etched plastic optical fiber. Plastic Optical fiber with waist diameter of 0.5 mm with unclad length of 3 cm give an optimum performance in ethanol detection. Smaller waist diameter will increase the absorption coefficient value and affecting the sensor's sensitivity. The sensitivity obtained by this sensor is 0.0671 a.u/% with linearity of 98% and limit of detection of 1.29%.

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1. Introduction

Fiber Optic Evanescent wave spectroscopy (FEWS) is one of the popular analytical methods in Infrared (IR) absorbance spectroscopy. This method is based on attenuation principle of total internal reflection [1]. Over the years, there is continuous development of this fiber optic sensor. The interaction of FEWS with the sample is enhance by removing a small portion of fiber optic clad in the sensing region and relate to the output power of the light transmitted through the fiber. This application of evanescent wave is widely applied in biology in order to detect the position of one cell from the surface of fiber. This advantage used in order to study the solid-liquid interfaces, rate of chemical reaction, detection of liquid and gas and also in biological field [2,3]. Development of POF enhanced the ability of SOF in sensing area but they still share a common characteristic in sensing field small and light, electromagnetic interference free influence and ability in multiplexing. Advantages POF over SOF in sensing area are like flexible and have high strain limit, less fragile, higher flexibility in bending. Moreover, the excellent performance in order to combine with organic material gives POF a great potential in the medical application [3]. Fiber sensors is suitable in order to monitor people that exposed to unhealthy atmospheres in civil and industrial fields, and for monitoring the pollutants in gaseous mixtures [4]. Hence, detection of ethanol based on fiber optic had been study by the researchers over the years such as by using photonic crystal fiber [5], POF [6,7], fiber bragg grating [8] and others. Ethanol had given a big contribution in the industry such as food, biotechnology field, and also medicine [6]. As known, ethanol is popular in the manufacture of alcoholic beverage production. In the scope of optical fiber sensor, ethanol concentration can be detected in beverages by evanescent wave optical sensing. It based on the absorption spectra of light in an optical fiber by the liquid. In this paper, the optimum parameter of uncoated POF fiber for low concentration of ethanol detections is examined by varying the unclad length and waist diameter of the fiber optics.

2. Materials and method

The POF used are from Mitsubishi Rayon Co. LTD with black Polyethylene jacket. The cladding is made from fluorinated polymer and core is made from polymethyl-methacrylate resin with refractive index (RI) 1.40 and 1.49 respectively. Meanwhile, the diameter of the cladding and fiber is stated as 20 μm and 980 μm and this multimode POF performs a step-index profile. The purpose was to investigate the optimum performance of unclad POF sensor by varying the unclad length and its waist diameter. The unclad length around 1 cm, 3 cm and 5 cm is etched at the middle of the fiber. The unjacketed POF was immersed in the 100% of pure acetone solution for 2 seconds in room temperature. The etching region was wiped with Kewpie tissue to peel the cladding skin and wash with distilled water (DI) to stop the reaction. Immerse the fiber in distilled water in order to remove acetone completely. The region was continually refined with sandpaper to get 0.5 mm and 0.8 mm waist diameter. The diameter of the etching region was measured by using vernier caliper. The fiber's surface will be observed by using optical microscope.

This experiment used a pair of optical light source with 650 nm wavelength and optical power meter connected at the both end of coated POF as shown in Fig. 1. For analyte preparations, absolute ethanol was dilute in DI water according to the concentration ranging from

0.5% to 3.5% respectively and their refractive index is measured by using ATAGO, PAL-1 refractometer. The responce and recovery time is observed in order to determine the repeatability performance.

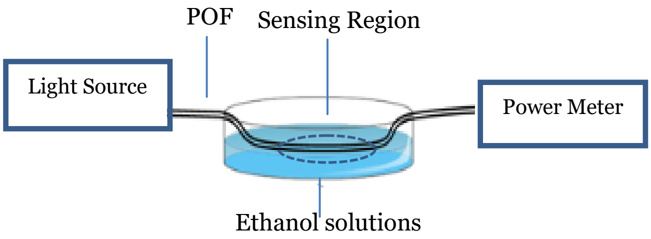
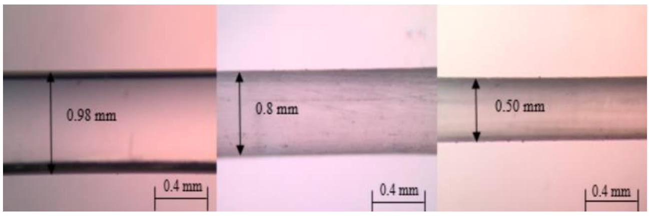


Fig. 1. Experimental setup for coated fiber sensor

3. Results and discussion

Fig. 2 shows the comparison of microscope image with 10X magnification for (a) bare fiber, (b) 0.8 mm and (c) 0.5 mm waist diameter of POF sensor respectively. The different between the bare fiber and etching fiber can be observe in term of their roughness where the etched surface is rougher than the bare fiber. Fig. 3 shows the RI of ethanol concentrations from 0.5% to 3.5%. From the graph, it clearly shows that the RI increases from 1.3328 to 1.3336 when adding the percentage of ethanol concentration.



(a) (b) (c)

Fig. 2. Microscope image of (a) Bare POF and unclad waist diameter POF of (b) 0.80 mm and (c) 0.50 mm

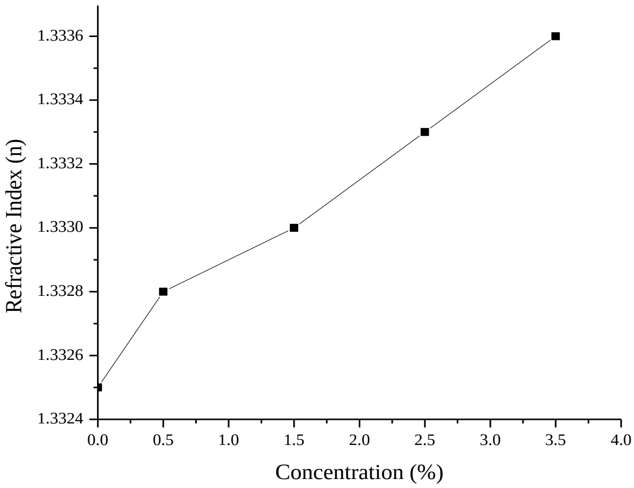
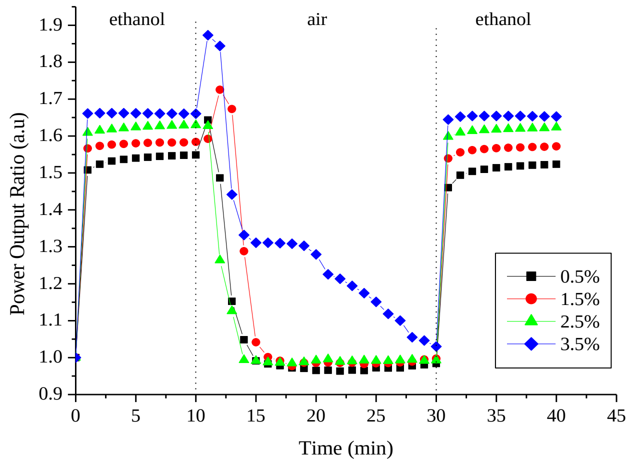


Fig. 3. Refractive index of varies ethanol concentration

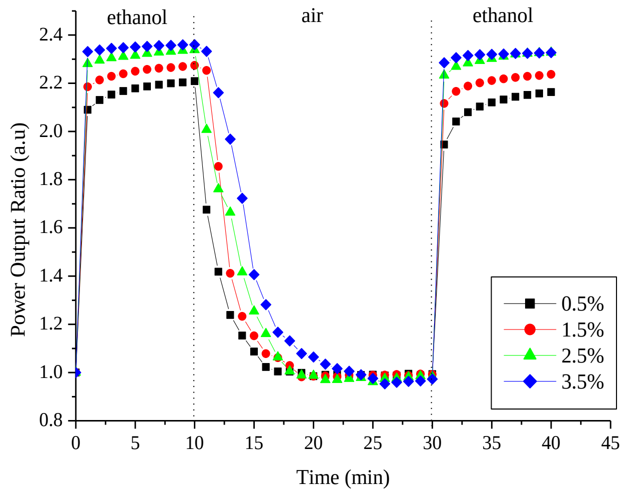
Fig. 4 shows response and recovery rate of POF with 0.5 mm waist diameter and 1 cm, 3 cm and 5 cm unclad length. Fig. 4(a) and (b) demonstrated a distinct power output ratio compared to unclad fiber with 0.8 mm waist diameter. Smaller radius of the core produces larger evanescent wave penetration depth [9]. Power output ratio increase when the ethanol concentration varying from 0.5%, 1.5%, 2.5% and 3.5%. The refractive index difference between the core and surrounding medium drops since the refractive index of the solutions increases with concentration percentage. Therefore, less leakage is observed from the light that propagates inside the unclad region to the surrounding, which results in the increasing of power output ratio. Thus, when the concentration of ethanol solution increases, the power output will also be raised.

In aqueous medium, minimum radius of the core should be 68% smaller than the original size to avoid V-number losses [8]. In this case, 0.5 mm waist diameter is 68% smaller than the original size. Meanwhile, at concentrations ethanol of 3.5%, it took longest time to recover due to the higher number of ethanol molecule attach on the POF surface. Fig. 4 (c) shows fluctuated pattern of response and recovery rate when immersed in ethanol solutions. This may due to the higher power output ratio loss since the exposing region of core to the analyte is the highest. The light tends to propagate outside of the fiber when increase the length of unclad fiber [10]. Rather allowing interaction between analyte with the absorbance light, this length of unclad is not suitable since it allows unstable light leakage.

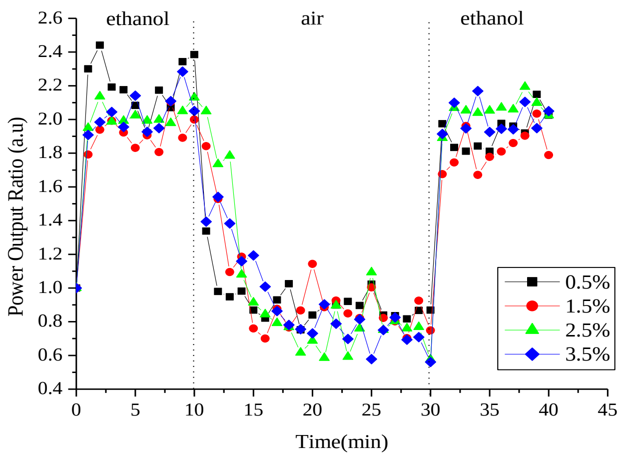
Fig. 5 shows the response and recovery rate of 1 cm, 3 cm and 5 cm unclad length with 0.8 mm waist diameter in ethanol solutions. The pattern shows indistinct power output ratio response to different ethanol concentration that might due to V-number mismatch [9]. As a portion of fiber cladding was removed, the propagation of the light mode is increase as the light interacts with surrounding medium. When the light mode propagates from unclad medium to cladding medium, the light mode will lose as the supported number of modes in the cladding region is reducing. V-number in unclad region is larger than the cladding region. Because of this mode difference, light that propagates from sensing region is lost as it enters the cladding region [12]. Figs. 4(a) and 5(a) demonstrated spiky signal appeared at minutes 11 before they decrease gradually until achieved saturated power output ratio reading. This is due to the existence of solute in water left on the surface of fiber [13].



(a)

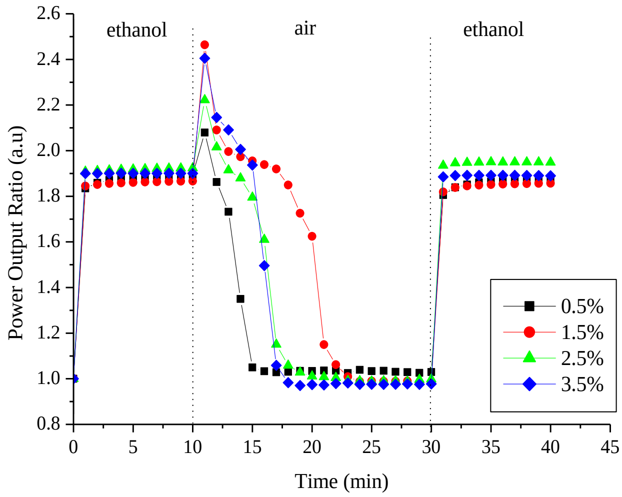


(b)

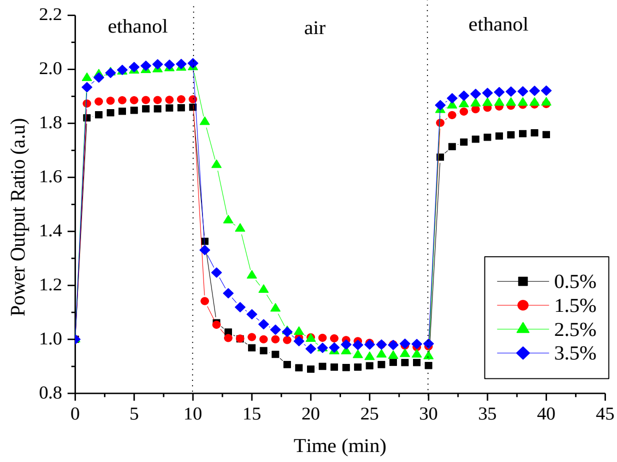


(c)

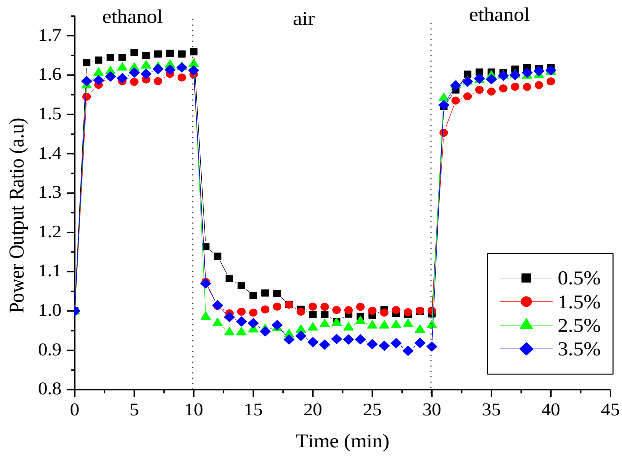
Fig. 4. Response and recovery rate of sensor with 0.5 mm waist diameter and (a) 1 cm, (b) 3 cm, (c) 5 cm unclad length (color online)



(a)



(b)

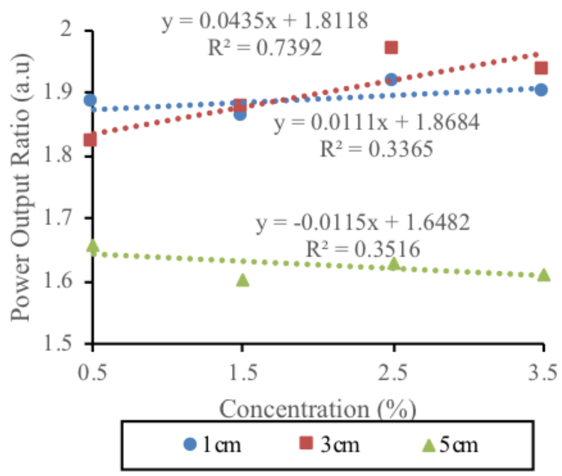


(c)

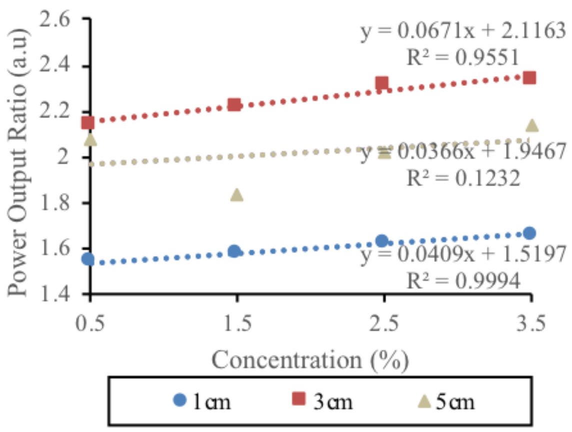
Fig. 5. Response and recovery rate of sensor with 0.8 mm waist diameter and (a) 1 cm, (b) 3 cm, (c)5 cm unclad length (color online)

Although unclad length is not considerate as parameters of V-number mismatch, they contributed a significant effect on the performance of unclad POF sensors. Therefore, in this section the optimum length of unclad POF is investigated. The sensitivity of the sensor is represented by the gradient of the linear curve in Fig. 6 and Fig. 7. Fig. 6 (a) shows the sensitivity of 1 cm, 3 cm and 5 cm unclad length with 0.8 mm waist diameter where 1 cm is 0.0111 a.u/%, 3 cm is 0.0435 a.u/% and 5 cm is 0.0115 a.u/% with slope linearity 58%, 99% and 59% respectively. For 0.8 mm waist diameter, 3 cm show the highest sensitivity while 5 cm shows the lowest sensitivity.

Fig. 6 (b) presents the sensitivity of 1 cm, 3 cm and 5 cm unclad length with 0.5 mm waist diameter. 1 cm unclad length has sensitivity of 0.0409 a.u/% with slope linearity of 99%. Meanwhile, the sensitivity of 3 cm unclad length is 0.0581 a.u/% with slope linearity of 99% and for 5 cm unclad length, the sensitivity obtained is 0.0366 a.u/% with linearity of 35%. Therefore, 3 cm unclad length exhibit higher sensitivity compare to 1 cm and 5 cm unclad length for 0.5 mm waist diameter. This is due to the increasing interaction between evanescent wave field with ethanol solution that act as cladding [14]. The sensitivity obtained is the highest which is 0.0671 a.u/% with linearity of 98% and limit of detection of 1.29%.



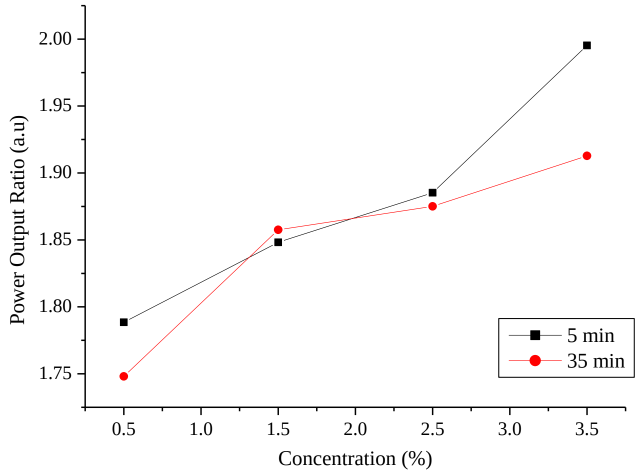
(a)



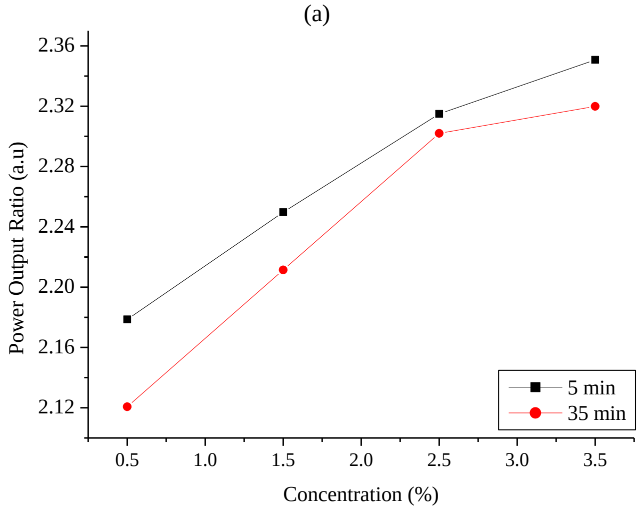
(b)

Fig. 6. Sensitivity of various unclad length with (a) 0.8 mm and (b) 0.5 mm waist diameter (color online)

Fig. 7 shows a comparison of 3 cm length of unclad fiber at 5 min and 35 min of response time. Both of the sensor shows good repeatability performance since the patterns obtained are uniform and the data almost the same. The fiber optic need a longer recovery times in order to have better repeatability performance.



(a)



(b)

Fig. 7. Repeatability of 3 cm unclad length with (a) 0.8 mm and (b) 0.5 mm waist diameter POF (color online)

The evanescent wave absorption coefficient can be calculated by using equation (1), where P_0 is the power transmitted through the fiber in the absence of analyte and P is the transmitted power when the cladding has been replaced by an analyte. L is the length of the unclad region and γ is the evanescent wave absorption coefficient.

$$P = P_0 \exp(\gamma L) \tag{1}$$

POF with 3 cm unclad length shows highest sensitivity compared to others length. Fig. 8 shows the evanescent wave absorption coefficient of 3 cm unclad length fiber with 0.5 mm as well as 0.8 mm waist diameter. We observe that the absorption coefficient increases linearly with ethanol concentrations. Absorption coefficient for POF sensor with waist diameter of 0.5 mm is higher than 0.8 mm. Thus, higher is the value of γ, the more will be the sensitivity of the sensor. As a result, the optimum parameters of the POF sensor is by using 3 cm unclad length with 0.5 mm waist diameter.

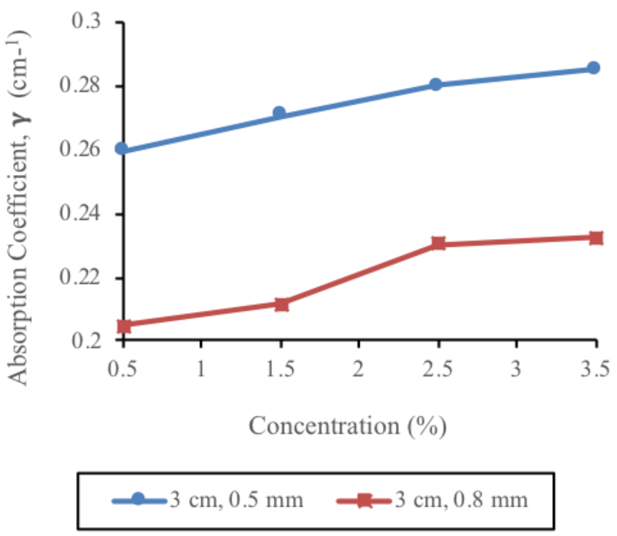


Fig. 8. Absorption coefficient of 3 cm unclad length with 0.5 mm and 0.8 mm waist diameter (color online)

4. Conclusion

In conclusion, 3 cm length of unclad POF with waist diameter of 0.5 mm shows an optimum performance when tested under 0.5% until 3.5% concentration of ethanol solution. The sensitivity obtained by this sensor is 0.0671 a.u/% with linearity of 98%. When the length of unclad length increased, more light will be propagated outside the fiber and the power output will be fluctuated. Absorption coefficient increases linearly when the refractive index of ethanol increase. The sensitivity of the sensor is depending on the fiber optic parameters such as waist diameter, fiber's length and the shape of the fiber.

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References

[1] Messica, A. Greenstein, A. Katzir, Applied Optics **35**(13), 2274 (1996).
[2] Jianqing Lu, Zhenyi Chen, Fufei Pang Fufei Pang, Tingyun Wang, Wang Tingyun, 2008 China-Japan Joint Microwave Conference 1–5 (2008).
[3] A. R. A. Rashid, N. A. F. Shamsuri, A. H. Surani, A. A. N. Hakim, K. Ismail, Optoelectron. Adv. Mat. **13**(1-2), 63 (2019).
[4] A. R. A. Rashid, P. S. Menon, S. Shaari, Journal of Nonlinear Optical Physics & Materials. Vol. 22, No. 03, 1350037 (2013).
[5] Jakeya Sultana, Md. Saiful Islam, Kawsar Ahmed, Alex Dinovitser, Brian W.-H. Ng, Derek Abbott, Appl. Opt. 57, 2426 (2018).
[6] A. R. M. Kamil, H. Saad, International Journal of Engineering and Technology (UAE) **7**(4), 147 (2018).
[7] A. R. A. Rashid, A. A. Nasution, A. H. Suranin, N. A. Taib, W. M. Mukhtar, K. A. Dasuki, A. A. Ehsan, EPJ Web of Conferences **162**, 01015 (2017).
[8] P. Kumar, S. Kumar, J. Kumar, G. S. Purbia, O. Prakash, S. K. Dixit, Measurement Science and Technology **31**, 025109 (2020).
[9] H. Yang, X. Qiao, M. M. Ali, R. Islam, K. Lim, J. Light. Technol. **32**(9), 1777 (2014).
[10] M. Ahmad, L. L. Hench, Biosens. Bioelectron. **20**(7), 1312 (2005).
[11] A. R. A. Rashid, W. M. Mokhtar, K. A. Dasuki, A. A. Ehsan, S. Shaari, Solid State Phenomena **268**, 413 (2017).
[12] J. P. Golden, G. P. Anderson, S. Y. Rabbany, F. S. Ligler, IEEE Trans. Biomed. Eng. **41**(6), 585 (1994).
[13] S. Azad, R. Parvizi, E. Sadeghi, International Journal of Optics and Photonics **12**(2), 109 (2018).
[14] P. S. Kumar, C. P. G. Vallabhan, V. P. N. Nampoori, V. N. S. Pillai, P. Radhakrishnan, J. Opt. A Pure Appl. Opt. **4**(3), 247 (2002).

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