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Design and Optimization of Mach-Zehnder Interferometer Sensor for Dye Sensing by Using Central Composite Design Coupled with Surface Response Method

Su Sin Chong [1], A. R. Abdul Aziz [1,*] and Sulaiman W. Harun [2], Hamzah Arof [2]

[1] Department of Chemical Engineering, Faculty of Engineering, University of Malaya, 50603 Kuala Lumpur, Malaysia; E-mail: susin_2117@yahoo.com; azizraman@um.edu.my

[2] Department of Electrical Engineering, Faculty of Engineering, University of Malaya, 50603 Kuala Lumpur, Malaysia; E-mail: swharun@um.edu.my; ahamzah@um.edu.my

* Author to whom correspondence should be addressed; E-mail: azizraman@um.edu.my; Tel.: +603-7967-5300; Fax: +603-7967-5319.

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Abstract: Color concentration detection is one of the main monitoring processes in textile industry. Highly sensitive sensors and less cumbersome procedure in monitoring color concentration are required. Potential for using fiber optics sensor in such measurement is promising because of its high sensitivity and faster response. In this study, concentration of Remazol Black B (RBB) dye solution was measured by using Mach-Zehnder interferometer (MZI) sensor with concatenating tapered multimode fiber (MMF) between two sections of single-mode fiber (SMF). The interaction between the operating parameters, diameter of MMF and concentration of RBB dye solution was studied. Central composite design (CCD) coupled with Response surface method (RSM) was applied to obtain optimum operating parameters for achieving well-responding operating variables, wavelength shift in quadratic model. The proposed sensor was tested experimentally at optimum conditions for this model (MMF with diameter of 19.5 μm; dye solution with concentration of 200ppm and corresponding wavelength of 1550nm). Quadratic model for wavelength shift demonstrated 0.54±0.04 nm/ppm or uncertainty 8.0%. The difference between the experimental and modeled data was only less than 10% which showed good agreement between them. This can be said that high linearity of the devices during sensing was achieved that it makes the device properly attractive for chemical sensing in practical applications.

Keywords: remazol black B; mach-zehnder interferometer; central composite design; response surface method; multimode fiber; environmental sensing

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1. Introduction

Fiber optic sensors with minute size, high sensitivity, and fast response are in the trend now for such sensing systems [1, 2]. It is growing attention in optimization and validation of fiber optics sensor by focusing on the parameters that are most suited to practical problem. Based on the Central composite design (CCD) model coupled with Response Surface Methodology (RSM), experiments were conducted to visualize the interactions of independent factors. This approach can evaluate the interaction between the effects of operating parameters each other and compared to traditional method which only employs single parameter at a time. Besides, it able offers assessments of error in statistic form.

In this study, the authors proposed a Mach-Zehner interferometer (MZI) sensor consisting of sensing portion by simply concatenating a short section (~10 mm) of multimode fiber (MMF) in the middle of a single-mode fiber (SMF), SMF_1-MMF-SMF_2. The sensitivity was enhanced by adopting a thinner MMF to achieve larger evanescent field [3] which can be influenced by external perturbation [4, 5]. The MMF was tapered and core section exposed to different concentrations of Remazol Black B dye solution (RBB). Reduces diameter of MMF and increase in RBB concentration can induce variation in the interference signal [6] and wavelength shift were investigated in this study.

2. Experiments

In this experiment, SMF (SMF28) and MMF (FSC105/125) were employed. Both fibers were cleaved and spliced with a fusion splicer machine (Sumitomo, model Type-36). Next, the MMF fiber section was tapered by flame-brushing technique and tapering process was being monitored in real time by using a 1550 nm light source. The tapering process was stopped at the moment the interference spectrum was achieved as shown in Figure 1. MMF with diameter of 27.7 µm, 23.2 µm and 19.5 µm at the uniform region of ~10 mm long were fabricated. Remazol Black B, with chemical formula of $C_{26}H_{21}N_5Na_4O_{19}S_6$ was used as a sensing medium in this study. Stock solution of 500 ppm was prepared by dissolving 0.5 g of RBB in one liter of distilled water. The analyte was obtained by diluting the stock solution to the desired concentrations. CCD coupled with RSM was chosen from

Design of Experiment software Version 10.0 and used to design, optimize and validate the parameters. The process parameters were optical fiber with diameter MMF between 19.5 µm to 27.7 µm and RBB solution with concentration between 80 ppm to 240 ppm. In the meantime, face-centered central composite design was generate by setting the alpha value at 1 while the actual and code values were designated as low (-1), medium (0) and high (+1). This is required because a three-level design can ensure that accurate model can be provided [7]. Table 1 presents the coded levels of the process parameters.

Figure 1. Transmission spectral of the fabricated MZI device based SMF_1-MMF-SMF_2 configuration.

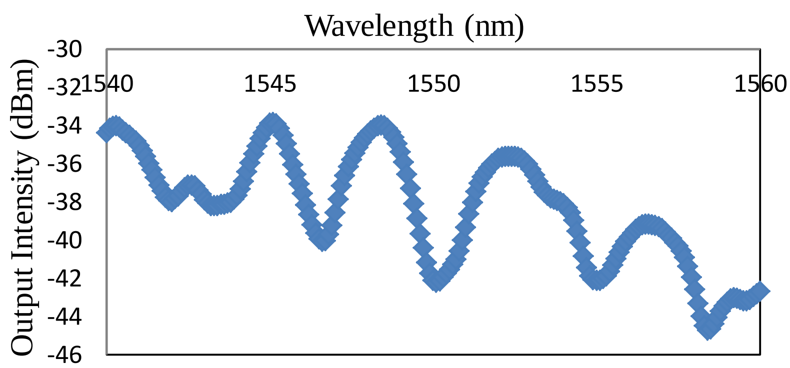


Table 1. Process parameters level in actual and coded forms.

Parameters	**Code**	**Unit**	**Low level**	**Medium level**	**High level**
Diameter of fiber	A	µm	19.5 (-1)	23.2 (0)	27.7 (+1)
Concentration of RBB solution	B	ppm	80 (-1)	160 (0)	240 (+1)

3. Results and Discussion

The results were accessed by investigation of variance, ANOVA. The results of the ANOVA for the models are given in Table 2. The statistical significance of the acceptable model was tested by the F-test which was based on a probability value with 95% confidence level. The F-value of wavelength shift model was 32.07 which implied that the models were significant. It was found that the value probability error of F-value (Prob.> F) for model was equal to 0.0001 represent there was a low probability that the model would be affected by noise [8]. Furthermore, the adequacy of the model generated was tested through lack-of-fit [9]. The lack-of-fit value of model was 0.2326, implying that the model was not significant relative to the pure error since the probability values were more than 0.05. Desirable of the both F-value and lack-of-fit showed that the model was applicable with the predicted response variables within the range.

Table 2. ANOVA for the wavelength shift Response Surface Models (RSM).

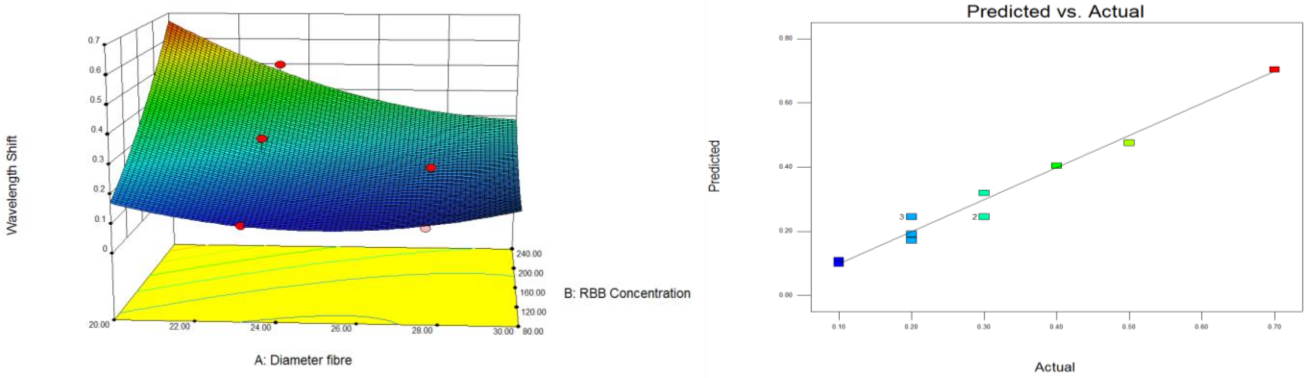
Parameter	F-value	Prob>F	Remarks	LOF	LOF p	Remarks
Model	32.07	0.0001	Significant	0.2326	0.8696	Not Significant
A	9.80	0.0166	Significant			
B	59.27	0.0001	Significant			
AB	11.38	0.0119	Significant			
A^2	4.06	0.0839	Not Significant			
B^2	2.54	0.1544	Not Significant			

A: diameter of fiber; B: concentration of RBB solution; Prob>F: probability error of F-value; LOF: lack of fit; AP: adequate precision.

3.1 Effect of parameters on the wavelength shift

The ANOVA Table 2 reveals that diameter of fiber (A), concentration of RBB dye solution (B) and interactions between the diameters of fiber-concentration of dye solution (AB) were statistically significant during the sensing process of wavelength shift. The significance of the parameters is confirmed by their p-values which were all below 0.05. Figure 2 (a) illustrates surface response in 3-dimension plots of the wavelength shift in the sensing module. Figure 2 (b) shows the comparison between the predicted and the actual values. These figures also reveal that decrease of fiber diameter increased the sensitivity of the sensor in terms of wavelength shift while the dye concentration increased. Wavelength shift in spectrum transmission is related to the effective refractive index within the fiber and sensing medium. Thinner fiber is more sensitive for sensing in dye solution. Based on the result, it showed that fiber with diameter of ~20 µm obtained the highest sensitivity among the others.

Figure 2. (a) Response surface plot for wavelength shift over different concentration of RBB solution with different fiber diameter. (b) Predicted vs. actual values plot for wavelength shift using different fiber diameter in various concentration of RBB solution.



(a) (b)

4. Validation of the model

Finally, an additional experiment was conducted according to the optimum conditions suggested by RSM to verify the proposed model. Optical fiber with diameter equal to 19.5 µm and RBB with concentration equal to 200 ppm were used. The value of wavelength shift predicted by the model was 0.53 nm which could also be calculated from the modeling equation in Table 3, Equation (1) and Equation (2). At these optimum conditions, the value of wavelength shift model was 0.50 nm percentage error between the experimental and predicted results was 8.00 %. Good agreement between the experimental and predicted results verified the validity of the models and existence of the optimum conditions.

Table 3. Equations of developed model in code, Y_{cod} and actual, Y_{act} forms.

Model	**Models in terms of coded (Y_{cod}) and actual (Y_{act})**	
Wavelength shift	$Y_{\text{cod}} = (8.181E-2)A^2 + (4.310E-2)B^2 - (9.216E-2)AB - (9.646E-2)A + 0.1551B + 0.1995$	(1)
	$Y_{\text{act}} = (3.272E-3)A^2 + (6.735E-6)B^2 - (2.304E-4)AB - (0.1461)A + (5.543E-3)B + 1.6677$	(2)

5. Conclusions

A MMF-based MZI sensor was developed for measuring wavelength shift in order to measure concentration values (in unit ppm) of color samples. The authors proved that higher sensing performance could be achieved using optical fiber with thinner MMF, 19.5 µm if compared with thicker MMF, 27.7 µm and 23.5 µm. Optimization study in proposed sensor had demonstrated by using CCD coupled with RSM method. Quadratic models for wavelength shift had been established. Furthermore, validation the models were ask to predict wavelength shift in 200 ppm by using 19.5 um MMF. There were only less than 10% differences between the experimental and theoretically data. Therefore, it can be concluded that proposed sensor is reliable and highly reproducible to measure color in ppm values. The optimization parameters may offer useful information pertaining to the development of efficient sensing application using multimode fiber optics.

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Conflicts of Interest

The authors declare no conflict of interest.

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