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Optical fiber temperature sensor design

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Abstract. The optical fiber sensing system is free from the effects of electromagnetic wave interference and radio frequency interference. The temperature difference between the incoming light source at one end of the fiber optic cable and the temperature of the sensor will cause a difference in wavelength between the incoming light source and the light reflected by a sensor or passed by a sensor. The difference in wavelength will be converted into RGB value, then the RGB value will be converted into a temperature. It becomes a strong reason why this research takes the topic of temperature sensor design using fiber optics. The method to design fiber optic sensors used in this research is experiment, such as: - heating the ends of the fiber optic core with analytic splicers so it will obtain spherical and oval shape of the optical fiber end, -peeling the jacket between two ends of the fiber optics and coating optical fiber with plates. The calibration and validation method is using RMSE (Root Mean Square Error) of the temperature which measured by Infrared thermometer and optical fiber sensor designed in this research. The test results for temperature measurements between 303oK to 543oK by using optical fiber sensor designed by researcher show that the reflected light model has error 1,596683 and forwarded light model has error 1,029278.

1. Introduction

One of the features of optical fiber is that the dielectric is free from radio frequencies, electromagnetic waves and lightning. Instead of that benefit, the power attenuation is very low. This is the advantage of optical fiber as a signal transmission media [1]. The sensing technology based on optical fiber has been receiving attention from industry and science, as a special field of research. Research and development of fiber optic sensors has been classified based on industry needs. It is also mentioned that many benefits are obtained from fiber optic sensors versus traditional electric sensors [2].

Optical fiber with polymer material is used to design temperature sensors, the method used is peeling of the cladding, then replacing with a tube that is filled with honey. The principle of working is loss power due to the change of refractive index and light reflection. The obtained result is the higher intensity of temperature changes on 20°C, while the temperature change between 10°C until 50°C shows decreased sensitivity [3].

Designing and developing optical fiber sensors is based on polymer optical fiber macro bending to detect metal expansion due to heating. The experiments gave the results of a linear response to temperature, the coefficients of expansion are 0.45; 0.35; and 0.32 for aluminum metal bars, brass bars, and copper bars at every additional 1°C. The article is not mentioned at the starting temperature of expansion and at what temperature is the saturation level of its expansion [4].

Starting with our research on the design of automatic conversion applications using optical fiber temperature sensor type OTG-M170 by Optical Spectrum Analyzer (OSA) [5]. A research found accidental changes in wavelengths of light that propagate on optical fiber media that heated, these wavelengths are measured by OSA. This phenomenon encourages us to conduct research on "Designing Temperature Sensors Using Optical Fiber", instead of that reason, the commercial price of optical fiber temperature sensors that are very expensive and I'm sure nobody has done this research yet.

2. Design principle

The material to make temperature sensors is glass optical fiber cable with multimode type. The chosen material type is based on the thought that the characteristics of the multimode type operate at 850 nm wavelength [6]. While the effectiveness of these wavelength changes is produced by temperatures between 20°C to 400°C. There are two models of temperature sensors that will be designed in this research, namely:

- Temperature sensor with the working principle of measurement from the reflected wavelength of light which obtain various heating treatments through the heat source of an electric oven.

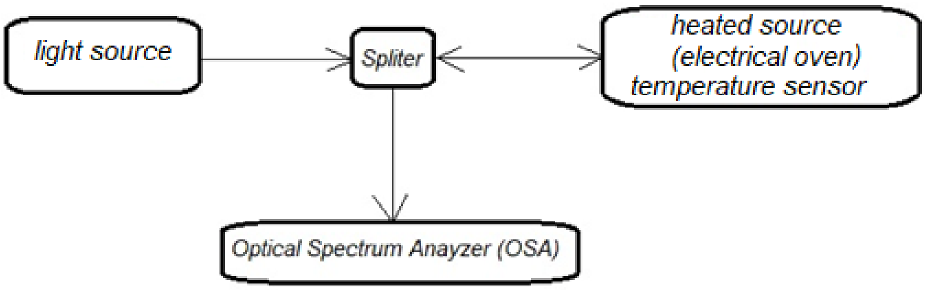


Figure 1. The model temperature sensor of reflected light.

Figure 1, hereinafter referred to the optical fiber temperature sensor reflective light model. The light source emits a laser beam with a wavelength of around 800nm propagates through a multi-mode optical fiber cable, then the light penetrates the splitter mirror propagating towards the fiber optic cable, the end of the fiber optic cable is connected to the reflected light model sensor that the researchers have designed. The temperature sensor is placed in an electric oven, the temperature in the oven is set varied, the light that comes on the sensor gets hot, so the temperature is different from the original light temperature, this temperature difference will cause changes in wavelength, light with a change in wavelength will reflect back to the splitter, as soon as the splitter is reflected towards the Optical Spectrum Analyzer (OSA), then the OSA displays the wavelength of the light that has changed.

- Temperature sensor with the working principle of measuring the wavelength of light which is transmitted to OSA after the light receive varying heating treatment through a heat source from an electric oven.

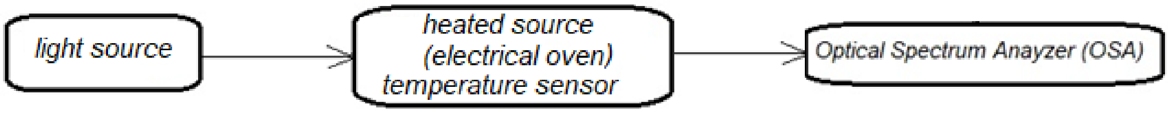


Figure 2. The Model Temperature Sensor of Light *Forwarding*

Figure 2, hereinafter referred to the fiber optic temperature sensor, the light forwarding model has a working principle: The light source emits a laser beam with a wavelength of around 800nm propagating through a multi-mode fiber optic cable media, then connected to the wave forwarding model sensor that the researchers have designed. The temperature sensor is placed in an electric oven, the temperature in the oven is varied, the light coming on the sensor gets hot, so the temperature is different from the original light temperature, this temperature difference will cause change in wavelength, light with changes in wavelength will be forwarded to OSA , then OSA displays the wavelength of light that has changed.

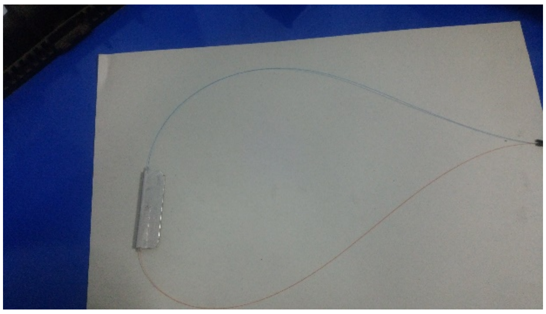
3. Experimental setup and procedure

This Experiment uses materials (a multimode optical fiber, aluminium plate), and equipments such as stripers, clever, analytical splicer, and others. The steps for making a sensor are as follows:

a) Peel the jacket from the tube
b) Peel the tube from the fiber
c) Peel the coating from fiber using a stripper
d) Flatten the surface of the fiber by cutting the fiber using clever
e) Create the optical fiber temperature sensor design using analytical splicer, the result is shown in figure 3 (i) and (ii) below,
f) Protect the core that has been designed using an aluminum plate, the result is shown in figure 3 (iii) below,

(i)

(ii)



(iii)

Figure 3. Design of sensor, (i) model oval temperature sensor of reflected light, (ii) model sphere temperature sensor of reflected light, (iii) model temperature sensor of light *forwarding* protected by aluminum.

Figure 3 (i) is the screen of analytical splicer which show result of splicing fiber as model oval temperature sensor and (ii) the screen of analytical splicer which show result of splicing fiber as model sphere temperature sensor. Figure 3 (iii) is model temperature sensor of light forwarding which is protected by alumunium.

After successfully creating a sensor design, the next step is doing the experiment, set up the sensor with other equipment to retrieve data and analysis. The equipment setup is shown in figure 4 and 5, below:

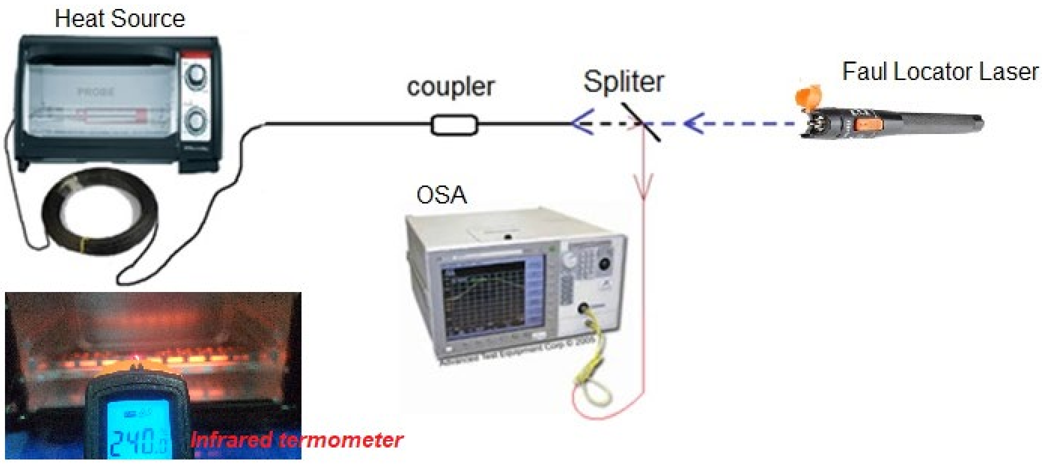


Figure 4. Setup model temperature sensor of reflected light.

Figure 5. setup model temperature sensor of light *forwarding*.

Figure 4 is the setup of reflected light model. The work system of figure 4 has been explained on sub 2(a). The experiment took 2 data, those were temperature by infrared termometer and wavelength by OSA at the same time. Figure 5 is the setup light forwarding model, the work system of figure 5 has been explained on sub 2(b), simultaneously we took 2 data, those were temperature by infrared termometer and wavelength by OSA.

4. Result and discussion

After the configuration process, the next process was taking wavelength data by adjusting the temperature changes in the oven. Measuring wavelength was done by changing the temperature, starting from room temperature which was around 30 °C with 10 °C intervals of 25 data. The temperature was measured by infrared termometer and the wavelength was meaured by OSA at the same time. The data of reflected light model is shown on Table 1 and the data of light forwarding model is shown on Table 2.

Table 1 has two data, (1) temperature in T°C which is measured by infrared termometer and (2)wavelength in nm which is measured by OSA using optical fiber temperature sensor which is designed by researcher. The next data from Table 1 will be processed and analyzed using the following conversion equation of sub (4.1 and 4.2), until the temperature results are obtained.

Table 1. Temperature and wavelength data of refelcted light model.

No	T (°C)	λ (nm)
1	30	819,4
2	40	819,81
3	50	820,22
4	60	820,6
5	70	820,8
...	...	...
22	240	826
23	250	826,3
24	260	826,6
25	270	826,9

Table 2. Temperature and wavelength data of forwarding light model.

No	T (°C)	λ (nm)
1	30	819,39
2	40	819,78
3	50	820,17
4	60	820,56
5	70	820,8
...	...	...
22	240	826,09
23	250	826,29
24	260	826,58
25	270	826,85

Table 2 is the data from experiment of figure 5. It has two data (1) temperature in T°C which is measured by infrared thermometer and (2) wavelength in nm whic is measured by OSA using optical fiber temperature sensor which is designed by researcher. The next data from Table 2 will be processed and analyzed using the following conversion equation of sub (4.1 and 4.2), until the temperature results are obtained.

4.1. Wavelength convert into temperature

Figure 6 is a sequence diagram of the conversion process from wavelength to temperature,

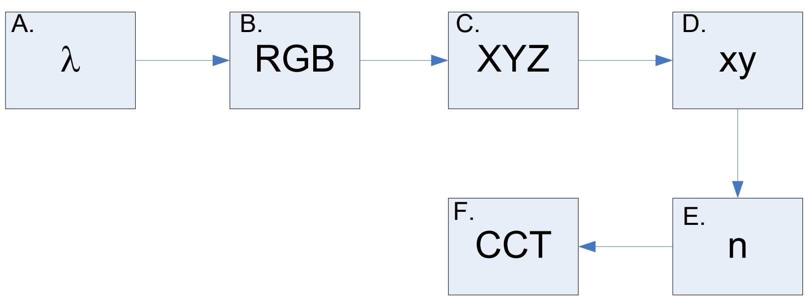


Figure 6. Diagram sequence of the conversion process wavelength to temperature.

Description of figure 6 is:

A. λ is the wavelength quantity obtained from the optical fiber analizer spectrum, the result of the measurement by the optical fiber temperature sensor.

B. RGB is the colour quantities of R (Red), G (Green), and B (Blue) that are obtained from the equation as below [7]:

$$R = e^{-\left(\frac{\lambda - \frac{520+630}{2}}{\frac{630-520}{2}}\right)^2} \quad (1)$$

$$G = e^{-\left(\frac{\lambda - \frac{500+590}{2}}{\frac{590-500}{2}}\right)^2} \quad (2)$$

$$B = e^{-\left(\frac{\lambda - \frac{410+480}{2}}{\frac{480-410}{2}}\right)^2} \quad (3)$$

by :
R = Red colour
G = Green colour
B = Blue colour
e = exponential
λ = wavelength in nm

C. XYZ is the illumination value obtained from the multiplication of the matrix with the tristimulus CIE constant in equation (4):

$$\begin{vmatrix} X \\ Y \\ Z \end{vmatrix} = \begin{vmatrix} -0.14282 & 1.54924 & -0.95641 \\ -0.32466 & 1.57837 & -0.73191 \\ -0.68202 & 0.77073 & 0.56332 \end{vmatrix} \begin{vmatrix} R \\ G \\ B \end{vmatrix} \quad (4)$$

D. "xy" is a two-dimensional chromatic value, obtained from the chromatic transformation of three-dimensional equations (5) into equations (6) and (7) as follows,

$$x = \frac{X}{X+Y+Z} \quad (5)$$

$$y = \frac{Y}{X+Y+Z} \quad (6)$$

E. "n" is a value obtained from the formulation:

$$n = (x - 0.3320) / (0.1858 - y) \quad (7)$$

F. "CCT" is the final value discovered in this study, namely the amount of temperature in the Kelvin degree unit obtained from equation (8), which can be rewritten as follow :

$$CCT = 449n^3 + 3525n^2 + 6823.3n + 5520.3 \quad (8)$$

To convert into degrees Celsius, the equation: T = CCT - 273 is used.

The formula will be used to calculate RGB, XYZ, xy, n and CCT.

4.2. Calculating of temperature

The data in table1 will be converted into RGB, XYZ, xy, n and CCT. The formulation (1) until (3) are used to calculate RGB, by using data from table 1 and sequence number 3 with temperature 50ºC and wavelength 820.2 nm, this is example of calculating RGB :

$$R = e^{-\left(\frac{820{,}2 - \frac{520+630}{2}}{\frac{630-520}{2}}\right)^2} = 73{,}918 \text{ nm}$$

$$G = e^{-\left(\frac{820{,}2 - \frac{500+590}{2}}{\frac{590-5000}{2}}\right)^2} = 24{,}721 \text{ nm}$$

$$\mathrm{B} = e^{-\left(\frac{820{,}2-\frac{410+480}{2}}{\frac{480-410}{2}}\right)^2} = 0{,}194 \text{ nm}$$

The next step is calculating XYZ by using formulation (4),

$$X = (-0.14282)(73{,}9187) + (1.54924)(24{,}72157) + (-0.95641)(0{,}19452)$$
$$= 27{,}556$$
$$Y = (-0.32466)(73{,}9187) + (1.57837)(24{,}72157) + (-0.73191)(0{,}19452)$$
$$= 14{,}878$$
$$Z = (-0.68202)(73{,}9187) + (0.77073)(24{,}72157) + (0.56332)(0{,}19452)$$
$$= -31{,}251$$

The nex step is calculating xy, n and CCT, by using formulation (5) until (8),

$$x = \frac{27{,}55654}{(27{,}55654 + 14{,}87897 + (-31{,}252))} = \frac{27{,}55654}{11{,}18401} = 2{,}463$$

$$y = \frac{14{,}87897}{(27{,}55654 + 14{,}87897 + (-31{,}252))} = \frac{14{,}87897}{11{,}18401} = 1{,}330$$

$$n = \frac{(2{,}463932 - 0{,}3320)}{(0{,}1858 - 1{,}330)} = -1{,}862$$

and the example of CCT calculation is:

$$CCT = 449(-1{,}8626)^3 + 3525(-1{,}8626)^2 + 6823{,}3(-1{,}8626) + 3707{,}33 = 326{,}118$$
°K

Furthermore, with the same calculation process and using the help of the Microsoft Excel application program, CCT values are obtained as in Table 3 below:

Table 3. Calculation result data x, y, and n to CCT value.

No	*x*	*y*	n	CCT(°K)	CCT (°C)
1	2,371187	1,288829	-1,84872	303,5721	30,4221
2	2,416532	1,309146	-1,85565	314,7543	41,6043
3	2,463932	1,330384	-1,86263	326,1188	52,9688
4	2,513531	1,352607	-1,86966	337,6679	64,5179
5	2,539203	1,364109	-1,8732	343,5123	70,3623
...	....	....	....	....	....
22	3,510629	1,799343	-1,96997	512,772	239,622
23	3,593326	1,836393	-1,97585	523,61	250,46
24	3,680427	1,875417	-1,98177	534,572	261,422
25	3,772291	1,916574	-1,98772	545,658	272,508

The calibration and validation method is using RMSE (Root Mean Square Error) of the temperature which measured by Infrared thermometer and optical fiber sensor designed by researcher, the equation of RMSE is below:

$$E = \sqrt{\frac{1}{m}\sum_{ij=1}^{m} \Delta T_{ij}{}^2} \qquad (9)$$

with E : Root Mean Square Error
m : number of samples
ΔT: difference betwen infrared temperature and calculation $(T_i - CCT_i)^2$

By using equation (9) the test results are obtained as shown in table 4 below:

Table 4. Temperature by termometer infrared and converting wavelength of refelcted light model into temperature.

No	T (°C)	CCT (°C)	ΔT^2
1	30	30,4221	0,178168
2	40	41,6043	2,573778
3	50	52,9688	8,813773
4	60	64,5179	20,41142
5	70	70,3623	0,131261
...	...	...	...
22	240	239,622	0,142884
23	250	250,46	0,2116
24	260	261,422	2,022084
25	270	272,508	6,290064
	RMS Error		**1,596683**

Table 4 is converted into the graph using the Excel application and the following results will be obtained as figure 7.

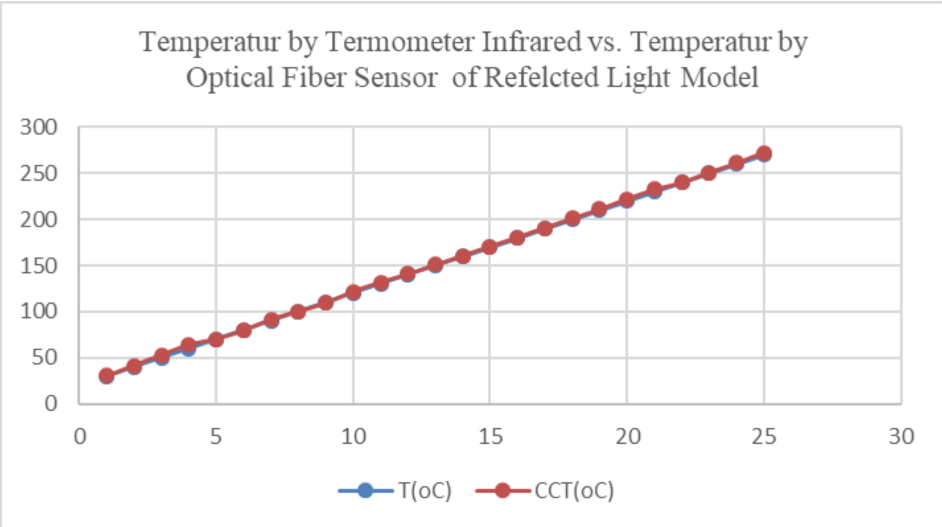


Figure 7. Comparison chart betwen temperatur by termometer infrared and temperatur by optical fiber sensor of refelcted light model.

By using the same formulation, calculation, and method from wavelength data of forwarding light model on table 2 obtain CCT and RMSE shown in table 5. Table 5 is converted into the graph using the Excel application and the following results will be obtained as figure 8.

Table 5. Temperature by termometer infrared and converting wavelength of forwarding light model into temperature.

No	**T (°C)**	**CCT (°C)**	ΔT^2
1	30	30,3221	0,103748
2	40	40,7042	0,495898
3	50	51,6686	2,784226

No	T (°C)	CCT (°C)	ΔT^2
4	60	62,7252	7,426715
5	70	70,3623	0,131261
...	...	...	...
22	240	239,989	0,000121
23	250	250,445	0,198025
24	260	261,237	1,530169
25	270	271,294	1,674436
	RMS Error		1,029278

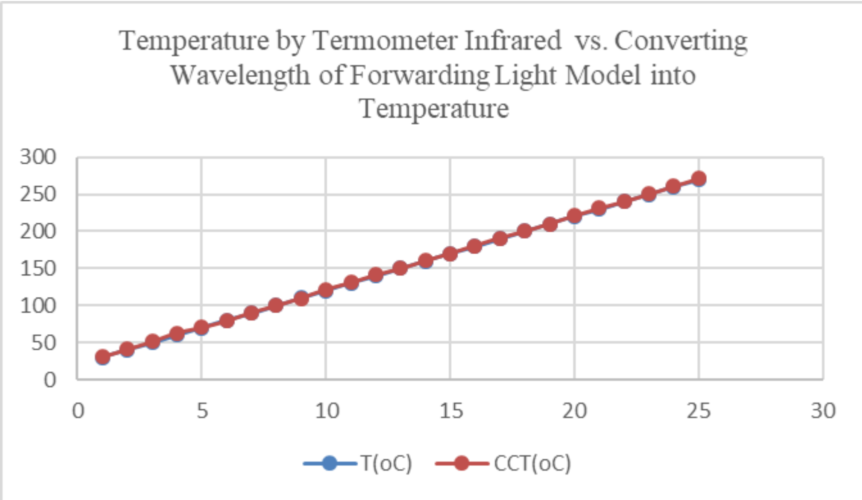


Figure 8. Comparison chart betwen temperature by termometer infrared and temperature convertion from wavelength of forwarding light model.

5. Conclusion

The method to design fiber optic sensors used in this research is experiment, such as: - heating the ends of the fiber optic core with analytic splicers so it will obtain spherical and oval shape of the optical fiber end, -peeling the jacket between two ends of the fiber optics and coating optical fiber with plates. The test results for temperature measurements between 303°K to 543°K by using optical fiber sensor designed by researcher show that the reflected light model has error 1,596683 and forwarded light model has error 1,029278.

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