Optical fiber sensor based on a polymer optical fiber macro-bend to study thermal expansion of metals

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Abstract. Thermal expansion is an important parameter for characterization of metals. As metal is heated, the molecules vibrate more violently and expand in all direction. Investigators have focused to study the thermal strain. However, the amount of expansion is difficult to measure. An attempt has been made to develop an apparatus using optical technique. The principle of this system is the transformation of length changes into changes of light intensity. The purpose of this work is to design and develop an optical fiber sensor based on a macro-bend of a polymer optical fiber. In this system, thermal expansion of metal was converted into the rolling of a needle in which placed beneath a flat bar of metal. Optical fiber sensor was attached to the ended section of a needle. As the crimp tube of the fiber sensor was moved due to thermal expansion of metal, the bend radii of optical fiber sensor was changed. As a sequence, the loss induced by the bending effect was depended on the expansion of metal that changed with temperature. In this study, we utilized optical fiber sensor to monitor and compare the thermal expansion of copper, brass and aluminum. According to our experimental results, the linear response with temperature was reported. The measured values of coefficient of thermal expansion was analyzed to be 0.45, 0.35 and 0.32 a.u./˚C for aluminum bar, brass bar and copper bar, respectively. In addition, the effect of the size of the diameter of a needle on the response of bending loss was investigated.

1. Introduction
Thermal expansion is a fundamental property of material. It relates to the dimensional changes of material when temperature is changed. Fundamentally, for small change in temperature (ΔT), the length change (ΔL) is proportional to the temperature change. A convenient measure of thermal expansion is the linear coefficient of thermal expansion (α). The linear coefficient of thermal expansion is defined as [1]

\[ \alpha = \frac{\Delta L}{L_0 [\Delta T]} \]  

where \( L_0 \) is the original length of the object. In other word, α measures the amount of strain which accompany a material with a change in temperature. Accurate measurement of α is very important...
because it reflects the binding force in solid. Previously, S. Kanagaraj and S. Pattanayak [2] reviewed comprehensively of the various techniques to explore the thermal expansion of metals. Interestingly, there were various research groups made effort to conduct optical technique for investigation of thermal expansion in solid. We found that interferometric principle was widely developed. Wolff and Eselun [3] modified Michelson interferometer to study thermal expansion of fused silica and quartz tube. However, all mentioned techniques required the complex set-up equipment and the systems were gigantic. Therefore, we decided to explore for the optical fiber system to cope with this task.

In the last decade, sensors based on fiber optics have demonstrated very good performance to deal with various monitoring. Also, it is simplicity, low cost and immune to electromagnetic interference. Due to those advantages, we had a strong focus on the creation of optical fiber sensor to provide an effective measurement which could compete with the conventional method. A number of useful reviews of fiber optic sensor technology had been discussed in detail by K.T.V. Grattan and B.T. Meggitt [4].

Basically, a light ray absolutely reflected at core-cladding interface if the incidence angle ($\theta$) is greater than the critical angle ($\theta_c$) as described in Figure 1(a). When its angle of incidence is inferior to the critical angle ($\theta < \theta_c$), at these corners the light will not satisfy the condition for total internal reflection and hence the refracted wave escapes out from the fiber as described in Figure 1(b). Therefore, an optical fiber that one bending beyond a critical radius causes optical power guided mode experiences loss as it goes through a bent section and it escapes the core. This is called as macroscopic bending loss [5].

![Figure 1](image_url)

**Figure 1.** Geometrical illustration of macroscopic bending losses in optical fiber: (a) $\theta > \theta_c$ and (b) $\theta < \theta_c$.

In short, we proposed an invention of fiber optic sensor which based on fiber bending loss. In recent years, applications of bending loss to innovate sensor have been reported by the following research groups. Liu et al [6] innovated displacement sensor based on the macro-bend coupling effect which caused power transmission between two twisted bending plastic optical fibers. Gattass et al [7] demonstrated the bending loss for multimode chalcogenide fiber over a wide range of infrared wavelength. They concluded that the bending loss was not dependent on the wavelength used. Obviously, their measured results indicated that there was increasing loss significantly due to tight bends. The design and development of a polymer optical fiber (POF) was reported to be used for temperature sensing[8]. It based on the concept that macrobending loss caused by the different thermo-optic coefficient of the cladding and core of POF. At this point it was challenged us to design and develop a simple sensor which required only a relative low-cost component, compact size and
easy to build. Crucially, our innovated sensor had an intuitive capability of detecting at quite small change of thermal expansion.

2. Experimental setup and procedure

The design system is presented in Figure 2. First, the metal bar was grabbed to fix by one side. By direct contact to the hot plate, heat transferred by conduction caused metal to expand on the free side. Since the expansion was quite small, it needed a trick to amplified. At the free side of metal, a needle was placed beneath a bar of metal. Basically, thermal expansion of metal was converted into the rolling of a needle. Thus, rolling of needle was a key monitoring. As mentioned before, we intended to propose optical fiber sensor. In this situation, we planned to convert the amount of this rolling to relate with light intensity of optical fiber sensor. In order to approach the required intention, the optical fiber sensor was attached to one end of a needle.

![Figure 2](image2.png)

**Figure 2.** Schematic diagram of the system to convert the thermal expansion into the rolling of a needle.

The whole optical fiber sensor unit was illustrated in Figure 3. The setup system was composed of He-Ne Laser, the macrobending loss sensor and photodetector.

![Figure 3](image3.png)

**Figure 3.** Schematic diagram of the optical fiber sensor unit.

Figure 4 was attempted to explain the mechanism of this sensor. As the crimp tube of the fiber sensor was moved (via the rolling of needle) due to thermal expansion of metal, the bend radius of optical fiber sensor was changed as compared in Figure 4(a) and 4(b). Then, the loss induced by the bending effect was depended on the expansion of metal that changed with temperature.
Figure 4. Comparison of bend radius of sensor (a) without the effect of rolling of needle and (b) with the effect of rolling of needle.

Figure 5. Photographs of the experimental setup: (a) shown a bar of metal placed on hot plate, (b) shown exploits of the laser and photodetector and (c) shown installation of the macrobending loss sensor.
Photograph of the experimental setup was shown in Figure 5. Hot plate provided heat to increase temperature from 30 to 300 degree Celsius. Metal conducted heat and lead to the expansion. When the optical fiber sensor experienced to bending effect due to the expansion of metal, the changes in output light intensity (△I) were recorded. In our demonstration, aluminum, brass and copper bars with the dimensions of 12.80 mm x 3.26 mm x1000 mm were utilized as the sample of metal. The measured coefficient of thermal expansion of those metals would be compared.

In addition, we were very keen to study the influence of the size of the diameter of a needle on the sensitivity of the optical fiber sensor. All experimental results will be displayed in the next section.

3. Results and Discussion

Each figure should have a brief caption describing it and, if necessary, a key to interpret the various lines and symbols on the figure.

3.1 Investigation the coefficient of thermal expansion for the selected metals

In the first experiment, we proposed to compare the thermal expansion of aluminum, brass and copper bars. Here, the needle which composed of stainless steel with fixed diameter of 1.74 millimeter was used for the whole experiment. As the temperature of metal bar increased, the optical loss induced by the bending effect was monitored. For temperature in the range of 150-300 °C, the data points were approximated by a linear curve. For all kind of metal bars, the relationship between the change in optical intensity (△I) and temperature (T) trended to be linear as displayed in Figure 6.

As can be seen, the larger the slope of graph, the more rapid increase of expansion. Here, it should be noted that the slope of graph was described as the coefficient of thermal expansion. According to the measured results and comparing among three metals, aluminum had the highest coefficient of thermal expansion. We obtained values of the coefficient of thermal expansion to be 0.45, 0.35 and 0.32 a.u./°C for aluminum bar, brass bar and copper bar, respectively. It seem to us that brass and copper bars have very similar value of coefficient of thermal expansion. We compared our measured results with the values that published in physics textbook [1]. The value of coefficients of expansion was listed as 25x10^-6, 19x10^-6 and 12x10^-6 (°C)^1 for aluminum, brass and copper, respectively. Due to the differently measured method, we could just consider arranging the value of the coefficient of thermal expansion of those metals. Thus, our results were in accordance with the results obtained by other method. For now, we were satisfy with the performance of this design system because at least it could resolve the characteristic for each kind of metal.
Figure 6. The change in optical intensity (ΔI) as a function of temperature for monitoring thermal expansion of various metals: (a) aluminium, (b) brass and (c) copper.

For the future work, it needs to convert the light output reading to the corresponding expanding distance. Also we may further do the calibration between our results with the standard values. We may modify some part of our design sensor to serve as a macrobend displacement sensor which had been presented by Efendioglu et al [9]. Similar work was also adapted by Li et al [10] to monitor
corrosion of metal. With that smart system, it is enable us to measure the coefficient of thermal expansion in the unit of length per temperature such as millimeter /°C. In addition, the tapered plastic optical fiber may introduce in the sensing system in order to achieve enhanced performance. Combination of tapering and macrobending ideas are optimized and then it motivates the fiber sensor to reduce the number of modes [11]. Without doubt, it will affect the sensing performance.

3.2 The influence of the size of the diameter of a needle on the sensitivity of sensor
In the second part, only aluminum bar was selected to use and we employed needles with different size. Figure 7 shows the response of sensor to the varying size of the diameter of a needle. Obviously, the sensor shows more sensitive to the larger needle. This means that larger size of needle could contribute to speed up the bending loss of the optical fiber. Attention should be paid to the case of larger size of needle. However, the results which obtained from using needle with diameter of 1.74 mm and 3.90 mm were given quite similar sensitivity. One can predict that once the needle become large enough, the sensitivity of sensor may saturate and limit. For further scope of investigation, a considerable amount of friction between needle and crimp tube must be concerned.

![Figure 7](image)

**Figure 7.** Comparison the change in optical intensity (□I) as a function of temperature for monitoring thermal expansion of aluminium bar when using various sizes of diameter of needle with the following marks to represent the diameter of needle: □ 1.24 mm, O 1.74 mm and △ 3.90 mm.

4. Conclusion
An innovation of optical fiber sensor for measuring thermal expansion of metal was proposed. The compact and sensitive sensor used the concept of light loss by elaborating the macrobending loss. The coefficient of thermal expansion of aluminum, brass and copper bars were revealed. Finally, experimental results indicated that the sensitivity of the sensor could be enhanced by increasing the size of the diameter of a needle.

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