Investigation of U-shaped microfiber temperature sensor using a combination of thermal expansion of a metal and reflectivity of a silver coated mirror

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ABSTRACT

An optical temperature sensor using a U-shaped microfiber incorporated with the thermal expansion of a metal plate and the reflection of a silver coated mirror is demonstrated. A microfiber about 5.8 μm waist diameter is fabricated using the systematic flame brushing technique, and lately, U-shaped structure is made. The proposed sensing mechanism uses the expansion of the metal plate and the reflectivity of the silver-coated circular shape mirror and measures the average output power change with respect to temperature variations. Two types of metal are investigated in this study, namely Aluminum (Al) and Copper (Cu), which have different thermal expansion coefficients. Therefore, when heated, the expansion of the metals occurs in a different degree, which affects the sensing mechanism, and therefore, a difference has been observed in terms of power loss with respect to the temperature variation. The sensitivity of the U-shape microfiber by using Al and Cu metal plates are measured as 0.0018 dB m/ ºC and 0.0007 dB m/ ºC, respectively. Moreover, the effect of a reflective mirror has also been investigated by placing the mirror on the top of the metal plates. With the inclusion of the mirror in the experimental setup, the sensitivity of the U-shape microfiber using Al and Cu metal plates are measured as 0.0019 dB m/ ºC and 0.0012 dB m/ ºC, respectively.

1. Introduction

Optical fiber sensors have attracted considerable attention in terms of their compactness and simple structure, flexibility, immunity to electromagnetic interference, suitable for remote measurement, and greater multiplexing capability compared to conventional sensors [1–3]. A diverse range of optical fiber sensors has been demonstrated to measure a vast number of physical parameters such as displacement, bend, surface, acceleration, biochemical, refractive index, temperature, current, electric and magnetic field, humidity and acoustic [4,5]. Recently, the researchers have investigated the temperature sensors made of optical fibers [6,7], where the microfiber-based sensors are of interests. Microfiber sensors in different structures and configurations have

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been proposed and utilized. Such structures are as microfiber resonator [8,9], fiber Bragg grating (FBG) [10,11], fiber coupler [12,13], Fabry-Perot interferometer [14], as well as the tapered microfiber [8,15]. Using the microfiber loop resonator, the optical temperature sensor can be realized in which the temperature variations cause the extinction ratio changes accordingly [8]. In reference [9] a polymer microfiber knot resonator has been proposed and utilized for the temperature sensor application, where the devise has respond to a high temperature of 700 °C. The monitoring system in [8,9] requires an optical spectrum analyzer, which is costly. In this paper, a sensor has been designed which doesn’t require expensive equipments for sensing observation.

Microfiber is used in this experiment because of its characteristics for example integrability, connectivity and flexibility which have directed to the development of this temperature sensor. The advantages of microfiber compared to other type of fiber sensor are its evanescent field interaction with surrounding environment. For that reason, microfiber usually coated with special compounds in order to increase sensitivity and specificity of the sensor. Bend insensitivity is another advantages of microfiber where its ability to guide the light over small bend radii [16]. The light travels outside of the core and creates an evanescent field in the waist region of the microfiber. A power loss occurs because of the evanescent field. A U shape microfiber is one of the structures of microfiber, and by bending it properly to “U” shape can create the high evanescent field. Bending loss can be used as the operating principle in many sensor applications. Up to date, the U-shaped microfiber sensors are mostly demonstrated to measure the changes in refractive index [17], displacement [18], pH values [19] and salinity [1]. In this study, a combination of a mirror and a metal plate along with U shape microfiber is used to sense the temperature variations. The metal is heated by a hot plate and the mirror is used to reflect the light back to the cavity. As an object is heated, the dimension of the object is slightly expanded by an amount proportional to its original length and the temperature changes, which is known as the thermal expansion effect. In this experiment, the metal absorbs the heat and expands. When it expands, the metal reaches close to the U shape fiber and it reflects more lights to the cavity. The mechanical displacement process occurs when the metal is heated and resulting in a temperature change in the metal [20]. This work demonstrates an implementation of U-shaped microfiber incorporating a reflection mirror and a metal plate as a sensitive temperature sensor. Two types of metals, namely aluminum (Al) and copper (Cu), with different thermal expansion coefficients are investigated to evaluate the response of the sensor due to the thermal effects. The thermal expansion coefficient of Al is $24 \times 10^{-6}/^\circ C$ at 20 °C, whereas the coefficient for Cu is $17 \times 10^{-6}/^\circ C$ at the same temperature [21,22]. Copper is a ductile metal that has very high thermal and electrical conductance. It ranks second highest among the pure metals at room temperature. On the other hand, Al also is a good thermal and electrical conductor. However, it has much lower conductivity than copper with 59% of copper conductivity.

2. Fabrication of the microfiber

A standard single mode fiber (SMF) [23] has been laterally tapered and it was created as the sensing probe. To create the tapered fiber, the flame-brushing technique has been utilized [24]. The fiber holders shown in Fig. 1 are utilized to hold the SMF fiber from its two ends, where the fiber glass has been heated up by using the translation torch. The heating creates the soften glass, where it has been pulled and stretched slowly by using the linear translation stages. The temperature of 1400 °C could be provided by the translation torch’s flame which consists of a mixture of butane and oxygen gas [25].

A tunable laser source (TLS) is inserted into one end of the fiber as input, whereas optical power meter (OPM) is connected to the output to observe the transmitted spectrum of the microfiber. The SMF is placed horizontally straight between two fiber holders on a motorized translation stage. It is a linear translation stage with two fiber holders and a sliding stage. During the tapering process, these fiber holder stages are moving in the x-axis whereas the torch is fixed at the center of the translational stage. The flame is created by burning the mixture of the Butane gas and Oxygen gas. The level of the flame and the temperature are very important parameters to fabricate quality microfiber [14]. The temperature of the flame is dependent on the pressure of the oxygen gas cylinder, and for the best performance, and the pressure is maintained as low as around 5 psi. Initially, the coating of the SMF is removed in order to taper only the cladding and the core of the fiber, and the torch is placed just below the stripped region. With a software-controlled motor, the fiber holders repeatedly move to the right and left, producing approximately 10 mm of a heated section of the fiber with the pin-point flame that is fixed underneath. The resulting microfiber has a final diameter of 5.8 μm of its waist over a length of about 40 mm.

![Fig. 1. Fabrication stage of the microfiber using flame brushing technique.](image)
3. Thermal expansion theory

Thermal expansion is the phenomena of the matter to change its volume in response to the change in temperature, overheat changes. It is a result of the change in the kinetic energy of a substance. When the heat is applied to a metal or substance, the molecules begin to move in random motion and collide with each other at larger frequency and momentum compared to that in lower temperature.

This will increase the separation between molecules. As a result, there will be a small expansion in dimension, as illustrated in Fig. 2. Over a small temperature change, the physical expansion of a material is can be described as per Eq. 1.

\[
\Delta L = \alpha L_0 \Delta T
\]

\[
L - L_0 = \alpha L_0 \Delta T
\]

\[
L = L_0 [1 + \alpha \Delta T]
\]

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

(1)

where \(\alpha\) is expansion coefficient, \(\Delta L\) is the change of the length in mm, \(L_0\) is the original length of the object in mm. The thermal expansion coefficient (\(\alpha\)) for the Aluminium and copper are \(24 \times 10^{-6}/{\degree}C\) and \(17 \times 10^{-6}/{\degree}C\), respectively. Since the thermal expansion coefficient of the Aluminium and Copper are different, it is believed that the response of the sensor will be different. Fig. 3 shows the pictorial representation of the Aluminium and Copper plate that has been used in this experiment.

4. Experimental setup

The U-shape probe has been provided and formed by bending the microfiber, and the probe has been created in such a way its waist has been positioned at the probe’s bottom. Fig. 4 has illustrated the experimental configuration of the setup, where the light has been inserted into the microfiber sensor by using a tunable laser source (TLS). The optical power meter (OPM) has been connected to the probe in order to measure the response of the microfiber in terms of average output power due to the increase of the temperature of the hot plate. A hot plate is used as the heating source to heat up the metal plate and also the ambient medium of the microfiber. The temperature of the hot plate can be controlled using a selector switch to vary between 40 \(\degree\)C and 90 \(\degree\)C. A thermocouple probe is placed on the top of the metal plate by touching the thermocouple probe on the metal plate in order to measure the temperature of the hot plate as a reference.

In this study, two metal plates such as Aluminium and Copper are investigated. The thickness of both the aluminum plate and the copper plate are measured as approximately 4 mm. The experiment is conducted in two phases - excluding and including the reflective mirror in the experimental set-up. In the first phase, the mirror is excluded in the experimental set-up. The experiment is conducted with Aluminium plate, and subsequently with the Copper plate. The schematic of the sensor set-up without the mirror is shown in Fig. 4(a). In this set-up, the Aluminium (and copper) plate is kept on the top of the hot plate. The gap between the

![Fig. 2. Thermal expansion of a metal.](image)

![Fig. 3. Metal plates that are used in this experiment: (a) Aluminum plate, (b) Copper plate.](image)
Aluminium (and Copper) plate and the U-shape microfiber is measured as 1 mm. As the temperature of the hot plate rises, the temperature of Aluminium plate increases (the temperature of the ambient medium changes too). Therefore, the Aluminium plate expands due to thermal expansion. Therefore, the distance between the microfiber and the Aluminium plate is also increased gradually which affects the propagation of the light. The changes in the output power have been measured in this study. After finishing the experiment with Aluminium plate, the experiment is repeated with the copper plate by replacing the Al plate, and the responses are recorded.

In the second phase, a mirror is included in the experimental set-up, e.g. on the top of the Aluminium plate (subsequently, on the top of the copper plate). The mirror is circular in shape, and the diameter of the mirror is measured as 2.7 cm. The back of the mirror is coated with silver, and the thickness of the mirror is measured as 2 mm. The physical specifications of the mirror are shown on the right side of Fig. 4(b). The arrangement of the hot-plate, the metal plate (Aluminium / Copper), reflective mirror and the U-shape microfiber is shown in Fig. 4(b). The gap between the mirror and the microfiber waist region is measured as 1 mm. The responses of the sensor with the combination of the Aluminium plate and the mirror have been recorded with respect to the temperature variations of the metal plate. Subsequently, the responses of the sensor using the combination of the Copper plate and the mirror have been measured. The responses of both combinations are compared.

5. Results and discussion

The responses of the U-shaped microfiber with respect to the temperature variations before the inclusion of reflective mirror (using the experimental set-up of Fig. 4(a)) are shown in Fig. 5. For the case of Aluminium plate, the output power of the sensor decreases from 3.17 dB m to 3.073 dB m for the increase of the temperature from 40 °C to 90 °C. The sensitivity of the Aluminium plate incorporated sensor is calculated as 0.0019 dB m/°C with a square regression value of 0.94. On the other hand, when the Copper plate is used in the set-up, the output power decreased from 3.197 dB m to 3.157 dB m for the increase of the temperature from 40 °C to 90 °C. The sensitivity of the Copper plate incorporated sensor is measured as 0.0007 dB m/°C with a square regression value of 0.97.

The results achieved with the Aluminium incorporated and the Copper incorporated U-shape microfiber temperature sensor are summarized in Table 1.

Subsequently, the experiment has been conducted by inserting the reflective mirror in the experimental set-up. The responses of
the U-shaped microfiber with respect to the temperature variations after the inclusion of reflective mirror (using the experimental setup of Fig. 4(b)) are shown in Fig. 6. The output power decreases from the 3.423 dB m to 3.325 dB m with respect to the increase of the temperature from 40 °C to 90 °C, when the combination of the Aluminium plate with the reflective mirror is used by placing the reflective mirror on the top of the Aluminium plate. A sensitivity of 0.0019 dB/°C is achieved with a square regression value of 0.98. On the other hand, when the combination of copper plate and the reflective mirror is used in the sensor set up, the output power drops from 3.609 dB m to 3.545 dB m responding to the increase of temperature increase from 40 °C to 90 °C. A sensitivity of 0.0012 dB/°C is achieved with a square regression value of 0.97 using the incorporation of copper plate and reflective mirror in the sensor set-up.

The results achieved by incorporating the combination of the Aluminium plate and the mirror, and the combination of the Copper plate and the mirror in the U-shaped microfiber temperature sensor set-up are summarized in Table 2.

It can be seen that in both cases (with the inclusion and the exclusion of the mirror), the Aluminium plate incorporated U-shape microfiber sensor set-up exhibits better sensitivity compared to the Copper plate incorporated one. This is due to the fact that the thermal expansion coefficient of Aluminium is higher than Copper, which causes a better performance of the Aluminium plate incorporated microfiber sensor set-up. On the other hand, when the mirror is included in the experimental set-up, the sensitivity the microfiber increases for the case of both metals due to the fact of mirror reflectivity. The sensitivity of the Aluminium plate and the mirror incorporated microfiber sensor is calculated as 0.0019 dB m/°C, whereas the sensitivity of only Aluminium plate incorporated microfiber sensor is recorded as 0.0018 dB m/°C. On the other hand, the sensitivity of the Copper plate and the mirror incorporated microfiber sensor is calculated as 0.0012 dB m/°C, whereas only Aluminium plate incorporated microfiber sensor is recorded as 0.0007 dB m/°C.

Table 3 show the comparison of different type of microfiber based on temperature sensor. As a comparison among those works (S.W. Harun et. al 2011; Y. Wu et. al 2010; Ding et. al 2012; N.Z. Muhammad et. al 2013; H. Luo et. al 2012), these work require optical spectrum analyzer (OSA) to measure the wavelength shift or power variation corresponding to temperature changes in the system. However, in this work we are using optical power meter (OPM)to measure the power changes over temperature which is low cost and significant compared to OSA in term of power measurement. The sensitivity of silica/polymer microfiber loop resonator (MLR) is 52 pm/ °C which is highest for high temperature ranged from 30 to 700 °C and lowest at 0.45 pm/ °C for bent microfiber at 20 to 80 °C. While the work by Ding et. al (2012) show nearly similar result however they observed by using OSA whereas our work by using OPM.

6. Conclusion

A non-contact U-shaped microfiber temperature sensor incorporating with a metal plate and the reflective mirror is demonstrated. A microfiber of waist diameter of 5.8 μm is fabricated using the systematic flame brushing technique and is made into a U-shaped sensor probe. A metal plate is placed on the top of a hot plate (firstly with Aluminium and secondly with Copper plate), and a distance
of 1 mm is maintained between the metal plate and the sensor problem is about 1 mm. The experiment is conducted without the inclusion and with the inclusion of the mirror in the experimental set-up. A slight improvement in terms of sensitivity has been observed, when the reflective mirror has been included in the sensor set-up. The sensitivity of Aluminium plate incorporated sensor set-up with and without the inclusion of the mirror are recorded as 0.0018 dB/°C and 0.0019 dB/°C, respectively. The sensitivity of Copper plate incorporated sensor set-up with and without the inclusion of the mirror are recorded as 0.0007 dB/°C and 0.0012 dB/°C, respectively. Interestingly, the sensitivity of Aluminium plate incorporated sensor set-up exhibits better performance compared to the Copper plate incorporated set-up, in both the cases - including and excluding the mirror in the experimental set-up. Without the inclusion of the mirror, the Aluminium plate incorporated sensor set-up demonstrates a sensitivity of 0.0018 dB/°C, whereas the Copper plate incorporated sensor set-up shows a sensitivity of 0.0007 dB/°C. On the other hand, with the inclusion of the mirror, the Aluminium plate incorporated sensor set-up demonstrates a sensitivity of 0.0019 dB/°C, whereas the Copper plate incorporated sensor set-up shows a sensitivity of 0.0012 dB/°C. The comparatively higher sensitivity of the Aluminium plate based set-up in both cases is believed to be originated from the higher thermal expansion coefficient of the Aluminium compared to the Copper metal. This work demonstrates that the microfiber is potential to be used in sensitive temperature sensing applications and particularly useful in the hot metallic environment. Further study should be conducted exploring the metal expansion behavior in designing optical microfiber based temperature sensor set-up.

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References