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′Highly sensitive micro-structured Fiber Bragg Grating-based temperature sensor enhanced by Electroplated Cu-Ni layer

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KeyWords: Femtosecond laser, Fiber Bragg grating, Fiber optics sensor, Temperature sensor, Ni-Cu.

Abstract

The temperature FBG probe head inscribed with eight micro-structured at 30 mW laser pulse power and embedded with bi-mettalic temperature sensitive films (nickel and copper) are proposed. The copper rod (anode) is connected to the positive terminal of the supply, and the conductive fiber (cathode) is connected to the negative terminal. Both electrodes are immersed in the copper sulfate ($CuSO_4$) plating solution. During the electroplating process, copper is oxidized at the anode to Cu^{2+} by losing two electrons. The Cu^{2+} associates with the anion $SO4^{2-}$ in the solution to form copper sulfate. At the cathode, the Cu^{2+} is reduced to metallic copper by gaining two electrons. Thermal expansion between silica and metallic elements is integrated with micro-laser grooves and temperature trasducer(Cu-Ni) layer. Thus, sensitivity of bi-metal coated FBGs improved significantly due difference of Young's modulus. Temperature and strain showed a very good agreement during characterization, with temperature sensitivity being 18.8 pm/^{o}C between 20-300 ^{o}C temperature range. This is a 86% more sensitive compared with a reported bare FBG sensor (10.1 pm/^{o}C).

1.0 Introduction

Temperature is one of the most importance parameters to be measured in industrial process control, in scientific activities and in daily life[1,2]. A wide range of existing instruments is available for temperature measurement either in industries or in laboratories[3,4]. Due FBG unique advantages, such as miniaturized size, multiplexing capabilities and non-electromagnetic radiation interference, they pose an active research and seek to become an alternative means of temperature sensing[5,6]. However, bare FBG have relatively low temperature sensitivity. In an attempt to improve sensitivity, integration of bimetallic thin films and micro-structured optical FBG will be conducted. This is based on the fact that copper and nickel have higher thermal expansion coefficient than silica [7].

Recently, several configurations temperature sensors such as standard fiber Bragg gratings (FBGs), long period fiber gratings (LPFGs) and fiber interferometers have been reported[7.8]. Despite FBG-based temperature sensors being widely used in industrial areas, their sensitivity is relatively low, ~10 pm/°C owing to its small thermo-optic coefficient of silica and its small thermal expansion coefficient [9]. LPFG-based temperature sensors have relatively high sensitivity suffer from cross sensitivity to fiber bending and surrounding materials. Optical fiber interferometers including Fabry-Perot (F-P) interferometers [10], Mach- Zenhder interferometers (MZIs)[11], Sagnac fiber loops[12] and Michelson interferometers [13] are good candidates for highly sensitive temperature sensors but difficult to stabilize the system and extend temperature range[14].

Sandlin et al., [15] developed a low temperature sensor by combining conductive Ag layer to a Ni layer and embedding them on an optical fiber. Firstly, conductive Ag layer was coated by using reducing silver ammonium complex with glucose in a Tollen's silver mirror test. Ni layer was coating method with electroplating process.In another research, Sandlin et al [66], developed a groove and covered it with metal Inconel using a vacuum brazing method at 1050°C in FBGs sensor. The metallic coating FBG in Inconel was tested at high temperature and can be stable for a long time. However, if vacuum brazing coated the bare fiber directly with the brazing alloy, then the brazing alloy would not contact with the fiber tight enough and the surface of the fiber would be etched resulting in a joint with Inconel. Iadicicco et al [17] using an evaporation technique, coated optical fiber sensors with a gold layer at nano-scale by. In none of these studies is the sensitivity of the embedded sensor reported. By magnetron sputtering, Li et al., developed bi-metal low temperature FBG sensor. Later, they sputtered about ~1 μm thick of titanium film first and on top was a ~2 μ m thick Ni film. Using electroplating method, they coated 0.5–1 mm of protective Ni layer to ensure FBG sensors could be embedded into metals with a high temperature process such as laser fusion or a casting process[3]. Thermal sensitivity of the FBG sensor arising from this experiment is twice higher with the respect to the original bare FBG. However, residual stress is a major misgiving associated with this method since it affect the strain. Copper and nickel FBG temperature sensor, coated by electroless and electroplating processes respectively has been reported. It was discovered that FBGs coated with Cu–Ni, Cu, Ni–Cu and Ni showed different thermal sensitivities, with the Cu–Ni coating giving optimum performance. They suggested that the optimum coating material in their application was Ni–Cu[18]. Feng et al.,[19] concluded that duplex metal coating to enhanced both FBG's temperature sensitivity and repeatability. They reported temperature sensitivity for Ni–Cu to be 0.01886 nm.C^{-1}. FBG sensitivity at cryogenic temperature was enhanced by electroplating technology involving various metals such as tin, lead, zinc and aluminum. Nevertheless, lead-coated FBG showed the highest sensitivity[20].

2.0 Methods

The samples were prior coated with 5 nm nickel thin film that promoted adhesiveness between fiber and copper layer. Besides, it acts as a thermal conductive layer. In this experiment, straight micro-grooves were machined on the fiber by conducting laser spot double pass. Multiple passes of the sample under the focused laser spot can be used to produce deeper grooves because in each pass, large amount of debris is ejected from the trench. Additionally, back-and-forth pass under the same focal spot, may lead to a wider trench, since laser spot translate different directions as shown in Fig.1. Eight and six straight micro-grooves were ablated at 20, 25 and 30 laser pulse power as shown in Fig.5.2. The machining translation power was maintained at 5 mm/min. In order to identify various samples developed, d-p-n code (d-double pass, p-laser power and n-number of micro-grooves) was used. Finally, the micro-machined samples were wet etched using HF solution as post processing technique recommended for debris removal after femtosecond micro-machining.

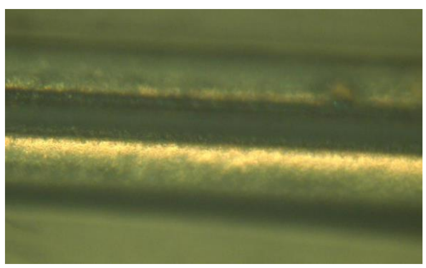

Fig.1: A straight micro-groove structure ablated by laser double pass and coated with 5 µm of nickel thin film.

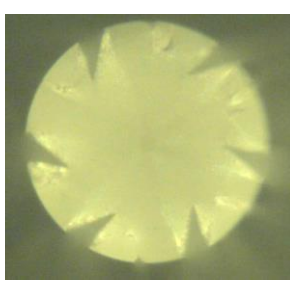

Fig.2: A pictorial diagram of a six microgrooves FBG sample manufactured at 33.4 µm/s feedrate

3.0 Results and Discussions

3.1 The micro-structured FBG (without coating)

These sensor sample heads were machined eight micro-grooves on the bare FBG cladding at varying laser pulse power of 20, 25 and 30 mW. The temperature sensitivity of h-30-5-8, h-25-5-8, h-20-5-8 and standard FBG is 11.79, 10.73, 9.74 and 8.21 pm/^{o}C respectively as shown in Fig.5.8. The graph is nearly linear between 20-300^{o}C. The effect of machining eight micro-grooves on the fiber cladding at varying laser power increases temperature sensitivity. The results indicate that the 30 mW energy fabricated FBG is nearly 30.36% more sensitive compared to non-micro-structured standard FBG sample. The reason could be explained from the fact that laser machining reduces the effective diameter of the fiber. This increases its tensile strength thus enhancing fiber stretchability. The greater the pulse power (30 mW) subjected to the fiber during the micro machining process, the deeper the micro-trenches (21.5 µm). As a result, the micro-structured FBG becomes mechanically elastic at higher temperature.

3.2 Bare FBG with embedded layer(s)

The three FBG samples were first mechanically peeled off about 12 mm length of polyimide protective layer around the FBG section using fiber stripper. The first fiber (std) is a conventional FBG with 125 um diameter. The second (std +Ni) is sputtered with 5 um nickel (135 um) and third FBG (std+Ni+Cu) is sputtered with nickel (5 um) followed by copper layer (30 um). All the sensors shows a linear variation in wavelength shift with changing temperature from 20-300^{o}C. Temperature sensitivity is 8.2, 10.1 and 12.5 pm/^{o}C for standard FBG, std+Ni and std+Ni+Cu respectively as shown in Fig.3. The bi-metallic coated temperature standard FBG sensor head is 52.4% as sensitive as conventional FBG sensor.

When the temperature increased, std+Ni sample expands more than silica which results in an increased pitch length than that of the silica fiber without metallic coating (std). Bimetallic embedded sensor (std+Ni+Cu) fiber's thermal sensitivity was highest. The nickel coating improved fiber-metal adhesiveness besides protecting FBG against high temperature. Copper layer with large thermal expansive coefficient improved the temperature sensitivity of FBG sensors. The sensitivity of bi-metal coated FBGs improved significantly due difference of Young's modulus and thermal expansion between silica and metallic elements.

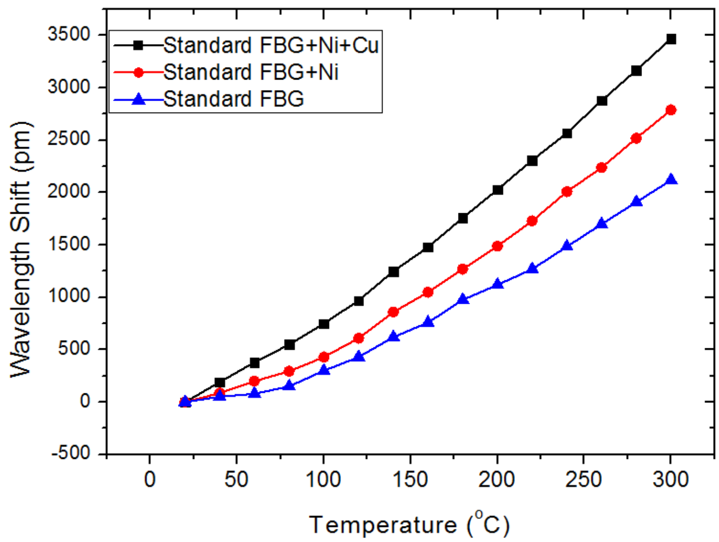

Fig.3: A graph of wavelength shift against temperature for the standard FBG sensor head coated with different metals.

3.3 Effect of micro-grooves on embedded bi-metallic temperature sensor

In order to further improve the temperature sensitivity of the probe head, we integrated the concept of fiber laser machining and metallic film embedding. Comparatively, the three samples shows a linear variation between wavelength shift and temperature as shown in Fig.4. The sample, std FBG, is a standard and unprocessed FBG while d-30-6 is a six micro-grooves FBG machined at 30 mW laser power and coated with bi-metallic layers (nickel-5 um and copper-30 um). Lastly, d-30-8, is an eight micro-grooves FBG machined at 30 mW laser power, coated with nickel (5 um) and copper (30 um) thin films. The temperature sensitivity is 8.2, 13.5 and 18.8 pm/°C for the temperature sensor probe standard FBG, d-30-6 and d-30-8 respectively as shown in Fig.4. The d-30-8 sensor head is about 135.4% as sensitive as standard FBG. The d-30-6 is 64.6% as sensitive as the conventional FBG temperature sensor (conventional FBG). Thus, effect of increasing number of micro-grooves leads to an immense increase in thermal sensitivity. It can also be clearly shown that the FBG sensor temperature sensitivity can be enhanced by integration of engraving micro-grooves on the fiber cladding and deposition of temperature sensitive films. Since fiber laser machining increases the surface area of the fiber, the total surface area of the bimetallic coating on the fiber is enhanced. On the other hand, eight-micro-grooved sensor will undergo greater deformation as compared to six-micro-grooved sensor when subjected to tension forces as revealed by ANSYS. Thus, the thermal strain acting on the FBG results to longer wavelength shift. This central wavelength shift can be correlated to the temperature sensitivity response.

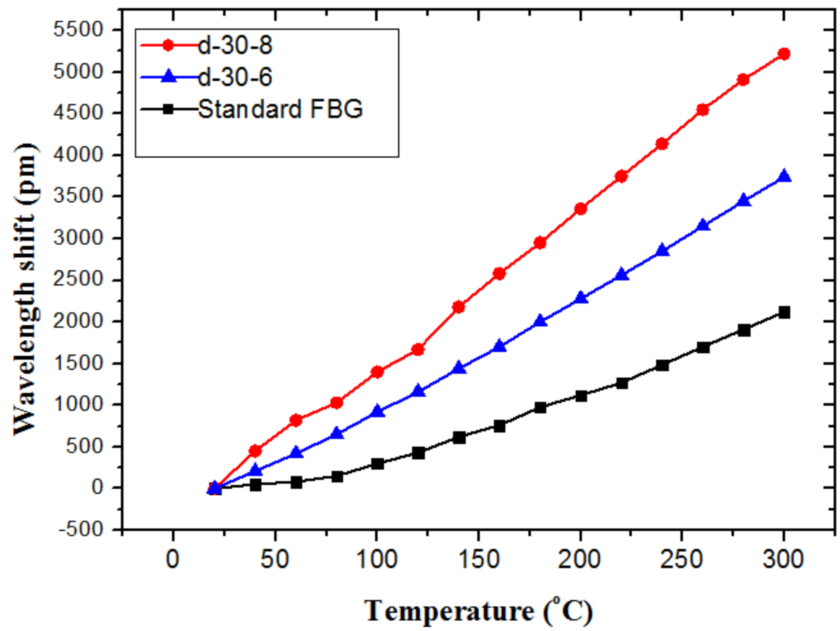

Fig.4: A comparison graph of micro-structured FBG temperature sensor coated with nickel-copper and conventional FBG sensor.

The micro-trenches increases the surface area of the fiber in contact with the temperature sensitive films. Since copper has higher thermal expansion and conductivity as compared to silica material, thus when the sensor is subjected to high temperature, the copper films creates a greater strain on the fiber. Ultimately, the FBG pitch length experiences expansion leads to a wavelength shift. From the Fig.5, there exist a good linearity between wavelength shift and temperature. The dotted line on the graph represents a linear fit to the experimental data whereas the solid line represents a linear fit. The increasing temperature response of the Bragg wavelength using a linear fit to data can be expressed as $\lambda_B = 0.01884T + 1552.81$. According to the manufacturer, the FBG parameters are: α=0.55x10^{-6} $/^o C$ and $\xi = 6.3\text{x}10^{-6}$ $/^o C$. Theoretically, the temperature sensitivity coefficient of the naked FBG is $S_T = \alpha + \xi = 6.85\text{x}10^{-6}$ $/^o C$. The fitting results reveal that the slope of the sensor head is 18.84 pm/°C for increasing temperature. Thus, the temperature sensitivity coefficients of increasing denoted by S_{T1} can be determined as follows,

$S_{T1} = 18.84 / 1553.22 = 12.13 \text{x} 10^{-6} / ^{o}C$.

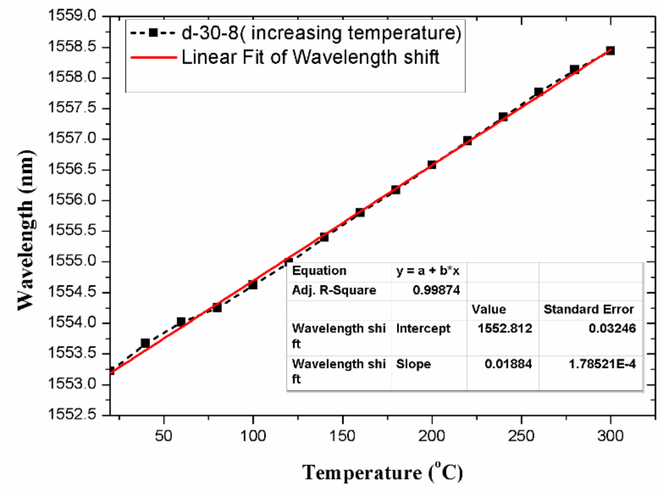

Fig.5: An experimental and a fitted graph for the micro-structured temperature sensor head coated with bimetallic thin films (Ni-Cu) during heating.

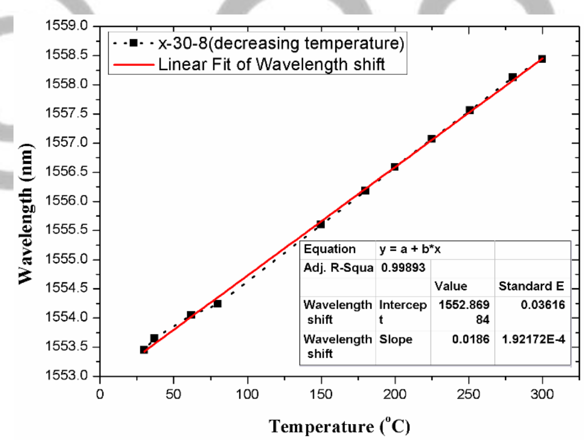

Fig.6: An experimental and a fitted graph for the micro-structured temperature sensor head coated with bimetallic thin films (Ni-Cu) during cooling.

The experimental and fitting results of Fig.6, reveals that the slope of the sensor head is 18.6 pm/°C for decreasing temperature. The decreasing temperature response of the Bragg wavelength using a linear fit to data can be expressed as $\lambda_B = 0.0186T + 1552.87$. Thus, the temperature sensitivity coefficients of decreasing denoted by S_{T2} can be determined as follows, $S_{T2} = 18.6 / 1553.22 = 11.98 \text{x} 10^{-6} / ^{o}C$. Since $ST_1 \approx ST_2$, we can conclude that the Ni-Cu metal coating provides a relative stable thermal FBG sensor with improved temperature change detection. The larger thermal expansion coefficient and thermal conductivity coefficient of copper coating may be responsible for this phenomenon.

Conclusion

The temperature FBG probe heads inscribed with eight micro-structured at 30 mW laser pulse power and embedded with bi-mettalic temperature sensitive films (nickel and copper) showed a temperature sensitivity of 18.8 pm/^{o}C between 20-300 ^{o}C temperature range. This is a 86% more sensitive compared with a reported bare FBG sensor (10.1 pm/^{o}C). On the other hand, effect of laser machining only raised sensitivity by 16.7%. Thus, sensitivity of bi-metal coated FBGs improved significantly due difference of Young's modulus and thermal expansion between silica and metallic elements when integrated with straight micro-grooves machining. Temperature and strain showed a very good agreement during characterization.

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