A Gold-Coated FBG Sensor for Heat-Flux Measurement in Harsh Environment

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***Abstract*—We report the development of a fiber-optic heat-flux sensor based on gold-coated fiber Bragg gratings and the tests of its operation in a high-temperature (>500 °C) environment. The work offers a feasible solution to the demand for heat-flux sensing under extreme conditions.**

Keywords—fiber-optic sensing, heat flux, fiber Bragg grating, temperature sensing, harsh environment

I. Introduction

Heat flux is an important metric for a lot of scientific and industrial applications, including planetary exploration, oil and gas drilling, jet engine development, etc. Unfortunately, in many practical cases, heat-flux measurement must be performed under extreme conditions. For example, measuring the heat flux on the surface of Venus is a critical task for NASA's future Venus landing missions. However, such endeavors will likely face the steep challenges posed by the harsh atmospheric conditions on Venus, including high temperature (~500 °C), high pressure (~90 atm), and highly acidic gases in the Venus atmosphere [1]. Conventional heat-flux sensors based on thermocouples and thermistors have poor long-term survivability in such environments [2,3]. Meanwhile, advances in fiber-optic technologies in recent years have opened up a new avenue toward environment-tolerant heat-flux sensors.

In the work reported here, we developed and tested a heat-flux sensor using fiber Bragg gratings (FBG) and showed that it is able to operate at temperatures above 500 °C for extended periods. Moreover, the construction of the sensor also allows it to withstand corrosive environments and high pressure.

II. Sensor Design

Fig. 1 shows the structure of the sensor head. The sensor consists of two stainless-steel plates sandwiching a macor spacer of 16 mm thickness. The plates and the spacer are assembled together by four zirconia screws at the corners, as illustrated in Fig. 1(a). A groove is machined along the middle line of each plate, and a gold-coated FBG (Technica T160) is embedded in the groove, as shown in Fig. 1(b). Each FBG is 10 mm long and is inscribed on the fiber by means of femtosecond lasers (Type II fs-FBG) [4]. Such FBGs have demonstrated thermal stability up to ~1000 °C [5]. The two FBGs used in the sensor share similar specifications, with a Bragg wavelength at about 1552 nm at the room temperature. Fig. 1(c) shows a picture of the sensor head.

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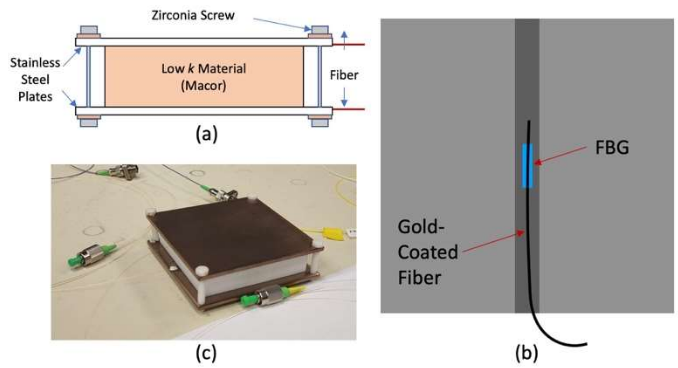

Fig. 1. Design of the FBG heat-flux sensor: (a) sensor configuration, (b) FBG-embedded stainless-steel plate, and (c) a picture of the actual sensor head.

Such a design ensures that the sensor can withstand harsh ambient conditions without compromising its performance. The use of Type II fs-FBG and gold-coated optical fibers allows the sensor to reliably operate at temperatures as high as 1000 °C. The gold coating, stainless-steel plates, and ceramic spacer and fasteners also resist corrosions caused by acidic environments. Finally, the solid build of the sensor makes it pressure-proof.

III. Sensor Testing

Fig. 2 outlines the experimental setup for testing the sensor. A superluminescent diode (Thorlabs SLD1550S-A40) serves as a broadband light source. A 50:50 fiber coupler splits the diode output evenly into two arms, where the optical power is directed toward the FBGs via two identical circulators. The circulators also route the reflected signals from the FBGs into an optical spectrum analyzer. The FBGs are placed in a high-temperature oven (Carbolite Gero LHT6030) to simulate the harsh ambient condition. The oven can reach temperatures up to 600 °C.

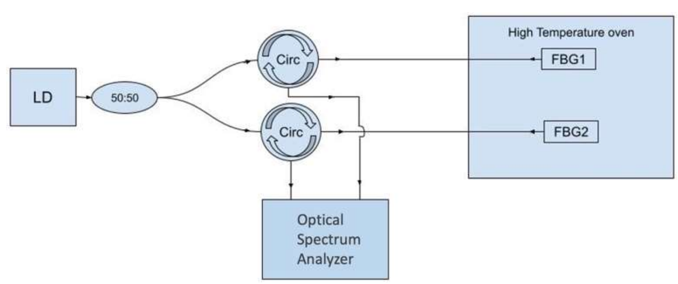

Fig. 2. Schematic of the heat-flux sensor testing system. Circ: circulator; LD: superluminescent diode.

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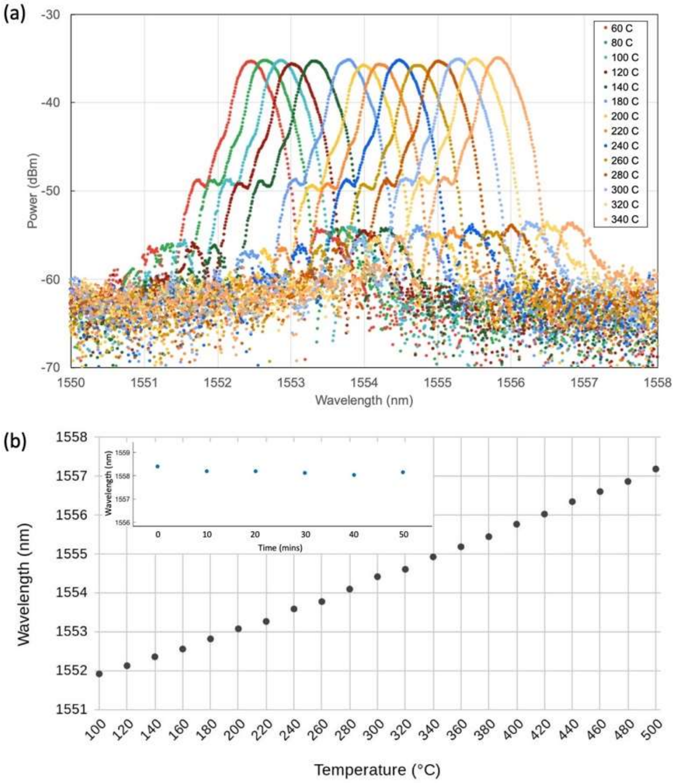

Fig. 3. (a) The measured FBG response as temperature increases. (b) A typical wavelength-to-temperature calibration trace up to 500 °C. Inset: Stability of the FBG response at 600 °C over an extended period of time (50 minutes).

IV. Experimental Results

To demonstrate the operation of the fiber-optic heat-flux sensor, the first step is to test the response of the FBG to ambient temperature changes and make sure the FBGs remain properly functional at high temperatures for extended periods of time. This can be done by adjusting the set temperature of the oven while monitoring the Bragg wavelength of the FBG under test. Fig. 3(a) shows the measured spectra of the FBG reflection as the temperature gradually increases. It is evident that the Bragg wavelength experiences a constant red shift, which is caused by the expansion of the FBG grating pitch. By measuring the Bragg wavelengths under different temperatures, we are able to obtain a wavelength-to-temperature calibration relation, which exhibits a high degree of linearity, as shown in Fig. 3(b). The FBG sensor also shows excellent tolerance to high temperatures, maintaining good stability at 600 °C for tens of minutes, as demonstrated in Fig. 3(b) inset.

To measure heat flux, it is necessary to create a temperature difference between the top and the bottom plates of the sensor head. This has been done in the room temperature by placing the sensor head on a hotplate, with the bottom plate in direct contact with the heating surface. Two thermocouples are attached to the sensor head, one on the top plate and one on the bottom plate. They provide an additional means of temperature measurement for verification purposes. Once the temperature difference between the two plates is determined, heat flux can be computed via the relation:

$$\Phi = -\kappa \Delta T / L, \quad (1)$$

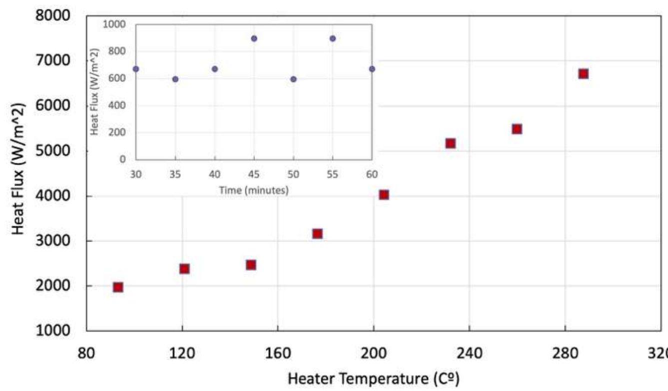

Fig. 4. Measured heat flux at different set temperatures of the hotplate. Inset: Heat-flux measurement in a 500 °C environment over a 30 minute span.

where Φ is the heat flux flowing through the sensor head, κ is the thermal conductivity of the spacer, ΔT is the temperature difference between the top and the bottom plates, and L is the thickness of the spacer. For the macor spacer used here, $\kappa = 1.46$ W/(m·K) and $L = 16$ mm. Fig. 4 shows the measured heat flux at different set temperatures of the hotplate.

Heat-flux measurement is also demonstrated in the high temperature environment. This is done by inserting an airflow barrier in the oven to create a temperature gradient inside the oven. As such, when the heat-flux sensor is placed at certain locations in the oven, a relatively stable temperature difference can be generated between its two plates. For example, when the oven temperature is set at 500 °C, the temperature difference across the sensor can be maintained between 6–10 °C upon a sufficient settling time. Fig. 4 inset shows such a measurement after the oven reaches 500 °C for half an hour.

Currently, the heat flux resolution of the FBG sensor is limited by the 0.1-nm resolution of the spectrum analyzer. With a state-of-the-art FBG interrogator, e.g., Ibsen I-MON 512 USB, the spectral resolution can potentially improve to 0.1 pm. The corresponding heat-flux resolution can reach about 0.7 W/m^2.

V. Conclusion

In conclusion, we have developed a fiber-optic heat-flux sensor based on gold-coated Type II fs-FBGs and demonstrated its operation in a high-temperature (>500 °C) environment. Such sensors enable heat-flux measurement under harsh conditions.

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