Carbon-steel tube surface mounted FBG sensors under high-temperature environment, part II: Gold coated and femtosecond laser written

Aayush MADAN[1,2], Ouyang LIU[2], Jun Long LIM[2], Wenyu JIANG[2], Yixin WANG[2], Perry Ping SHUM*[1], and Jianzhong HAO[2]

[1]School of Electrical and Electronic Engineering, Nanyang Technological University, Singapore 639798
[2]Institute for Infocomm Research, Agency for Science, Technology and Research, Singapore 138632
*Corresponding author: Shum@ieee.org

***Abstract*— Fiber Bragg grating (FBG) sensors must be mounted at the outer surface of a metallic test-piece or embedded into a testing surface to be able to perform continuous condition monitoring. Robust mounting and reliable operation of such sensors for parameter monitoring in high-temperature operating environment is still a key challenge. Here, in the second part of the two-part article, we focus on the mounting of gold-coated femtosecond laser written FBG sensors on a carbon-steel tube and performance monitoring of the packaged sensors for temperature up to 500°C, for three consecutive thermal cycles. The sensors experience a remarkable sensitivity to temperature, 28 pm/°C.**

***Index Terms*— Gold-coated FBG sensor; High-temperature fiber sensor; femtosecond laser written sensor; high-temperature performance monitoring; FBG sensor mounting.**

I. INTRODUCTION

Fiber-based sensing technologies have been evolved as a promising technique for various applications [1]–[5] ranging from medical, military, scientific, oil and gas, constructions, etc. Because of the ability to embed within or underneath a metallic structure and providing structural health monitoring information, and other advantages over conventional transducers, such as small-size, light-weight, corrosion resistant, fast response time, immune to electro-magnetic inductions [6] etc. the technology has become a powerful tool in various applications worldwide. An FBG structure is a periodic perturbation of refractive index (RI) within the fiber core [3] along its length. This RI modulation resonates a wavelength in the core which is reflected by the grating structure as in Fig. 1. The reflected wavelength depends on the grating spacing and the effective refractive index of the fiber core as shown in eq. (1), where λ_B is the Bragg wavelength, n_{eff} is the effective refractive index, and $\wedge_G$ is the period (or pitch) of grating. The non-resonating wavelengths are transmitted through the structure without any disturbance [7].

$$\lambda_B = 2.\eta_{eff}.\wedge_G \quad (1)$$

Zou, L. et. al. [9] reports installation of Brillouin-scattering based fiber sensor on an end-capped steel pipe for integrity monitoring and claims it to be a potential candidate for

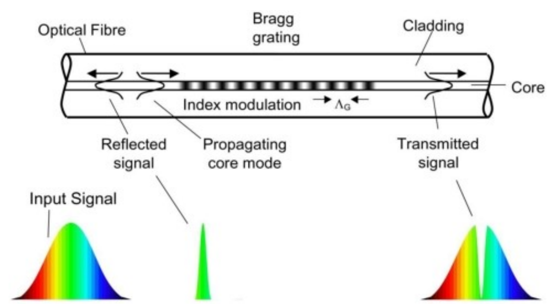


Fig. 1: Schematic of a grating structure [8]

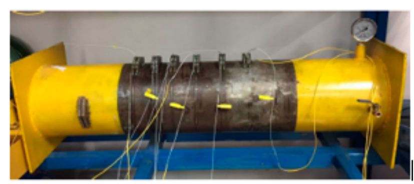


Fig. 2: Mounting of fiber on a pipeline [10]

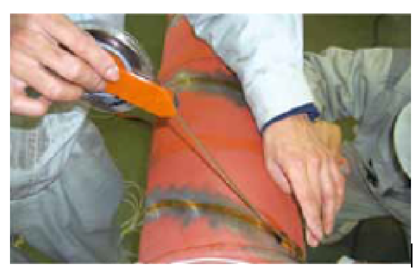


Fig. 3: Fiber installation for long-time monitoring [11]

high-performance and economical defect assessment system, while Jiang, T. et. al. [10] reports the installation of FBG sensors on polyvinyl chloride (PVC) pipes as shown in Fig. 2 to measure its health parameters. Nubrex Co. Ltd. [11] carry out long-term monitoring by installing fibers as shown below in Fig. 3 to meet the safe and reliable quality monitoring.

But what about the mounting quality and reliable sensor performance when the operating environment is harsh? Conventional FBG sensors survive till the temperature where it starts decaying, i.e. at higher temperatures the grating undergoes transformations affecting its optical response. The other reasons for decaying response include thermal expansion, dopant migration, silica devitrification, thermic-optic delay [12]. In [13], researchers from NASA Glenn Research Centre, introduces miniaturized thin-film high-temperature strain gauges to be sputtered directly onto the test piece to perform monitoring in high-temperature range. However, mounting of FBG sensors on the surface of steel tubes and reliable operations over a period of time under high-temperature environment are yet to be revealed.

As mentioned in part I of the article, the FBG sensors can be coated with any type of metallic coating, depending on the application type. Here, in second part of the two-part article, we report mounting of gold-coated femtosecond laser written FBG sensors on the outer surface of a carbon-steel tube and its performance monitoring for a temperature up to 500°C, for three consecutive thermal cycles. The article may help engineers and researchers to develop structure health monitoring techniques for the said operating environment and cover applications in the field of well and pipeline monitoring, exhaust controls and turbine, etc.

II. Sensor consideration and mounting

Femtosecond laser-based systems have become a versatile tool for fabrication of many fiber devices [14], [15] because the fiber does not need to be photo-sensitive [16]–[18], and the system is capable to inscribe structures directly within the core of the fiber [19]. High intensity ultra-short duration laser pulses result in highly localized RI change [20] to produce high-resolution structure writing [21]. The sensing structures inscribed using femtosecond lasers have long term annealing properties, therefore, provide long-term stable operation under high-temperature environment. Thus, the technique has widen the scope of fiber sensing in a new dimension of well and pipeline monitoring, turbine monitoring, exhaust control, extreme temperature sensing [22].

- Why short length fiber sensor?

The diameter of the carbon-steel tubes which we are testing is in the order of few inches (relatively smaller) because such tubes are typically used in real-world application. Therefore, we have fabricated and implemented a short length (*l*: not disclosed here) FBG sensor to avoid any misbehaviour caused by curvature. The short length FBG has smaller form-factor and multiplexing may provide best distributed sensing solutions [23], and avoid complex peak detection algorithms [24]. The FBG sensors are gold coated to make them robust enough to survive the required temperature range.

- Mounting

The gold coated FBG sensors are mounted on surface of the carbon-steel tubes with two different types of high-temperature adhesives, called adhesive-1 and adhesive-2 in this article (names not disclosed), after surface treatment. The properties of the adhesives used is shown in following Table II.

TABLE I: FBG Sensors Parameters

	FBG-1	FBG-2
Bragg Wavelength (nm)	1530.14	1540.28
FWHM (nm)	0.42	0.42
FBG length (mm)	*l*	*l*
Coating	Gold	Gold
Recoating	Nil	Nil

TABLE II: Properties of adhesives used

Name	Coefficient of thermal expansion (CTE) (x10^{-}6/°C)	Maximum temperature	Curing requirement
Adhesive 1	18	650°C	Proper curing procedure
Adhesive 2	16.2	1093°C	Proper curing procedure

TABLE III: Summary of FBG testing procedure

Channel	Tube	FBG	FBG wave-length	Adhesive	Test procedure
1	1	FBG-1	1530nm	Adhesive-1	Heat up to 500°C at 1.5°C/min; maintain at 500°C for two hours; cool down naturally; Repeat three consecutive cycles
2	2	FBG-2	1540nm	Adhesive-2	

After mounting the sensors, the tube is first placed inside an oven to carry out an appropriate adhesive curing, and afterwards placed inside a high-temperature furnace to carry out the temperature test. The furnace is set to vary from room temperature to 500°C, with a temperature heating rate of 1.5°C/min. Once the maximum temperature is achieved, the furnace is kept at the maximum temperature for two hours. The temperature is then decreased to 30°C at a rate of 0.65°C/min. The experiment is performed for three consecutive temperature cycles. The summary of FBG mounting, connection, and test procedure is shown in Table III. The temperature variation, measured using a thermocouple, inside the furnace is shown in Fig. 4.

III. High-temperature test and result

The response of the sensors is measured in terms of its peak wavelength response and spectral evolution, discussed below. The wavelength shift response of both the FBG sensors and temperature with time (day) is shown Fig. 5. Both the sensors behave similarly, in accordance with temperature variation and response during all the thermal cycles.

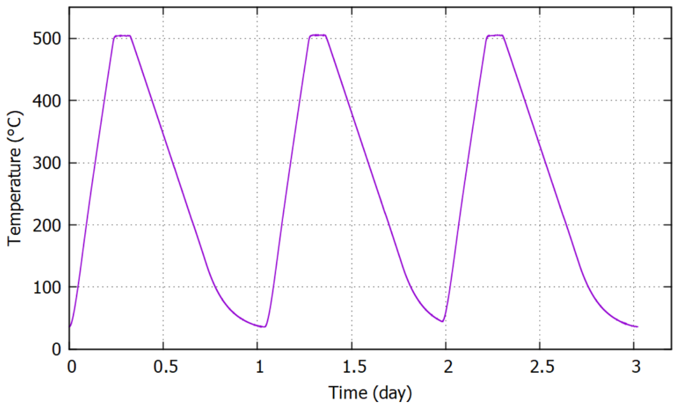


Fig. 4: Thermal cycle profile

A. *Wavelength response to temperature*

The wavelength response of both the FBG sensors with temperature is shown in Fig. 6. Table IV and Table V summarise the linear fit of heating-up and cooling-down under cycle 1 to 3 for FBG-1, and FBG-2. Both the sensors experience a remarkable sensitivity to temperature, $\approx$ 28 pm/°C with R-square over 0.99.

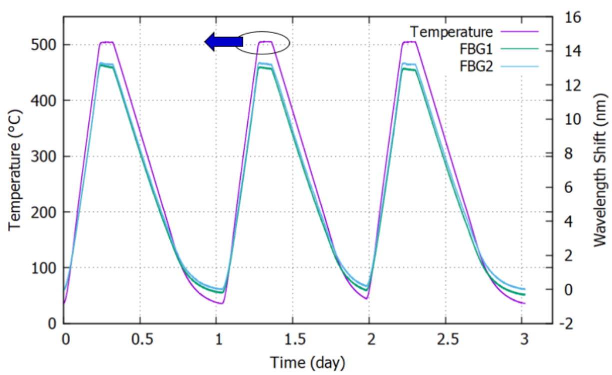


Fig. 5: Response: wavelength shift and temperature with time

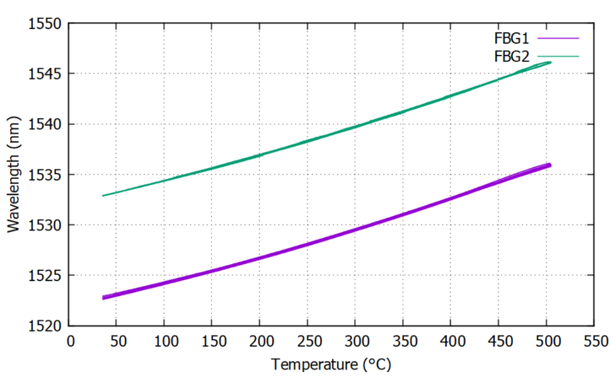


Fig. 6: Wavelength against temperature

B. *Spectrum evolution of sensors*

The spectrum evolution of both sensors during different stages is shown in Fig. 7a and 7b. There is some chirp behaviour observed which is smaller at higher temperature and greater at lower temperature causing peak splitting. One wavelength can be derived using centroid based peak selection algorithm.

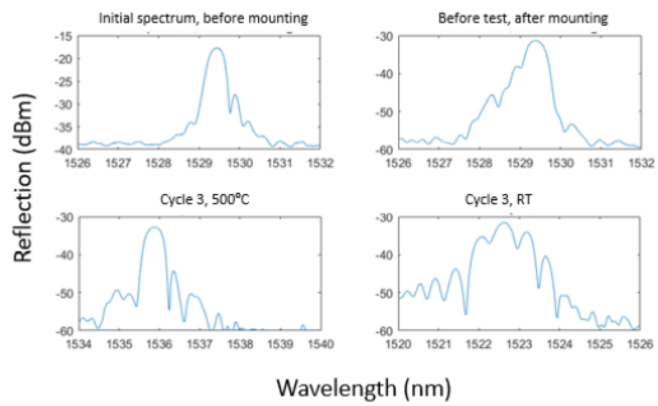
Since the CTE of steel tube increases with temperature until gets saturates at higher temperature, and both adhesives have higher CTE too. Hence, CTE mismatch is smaller at

TABLE IV: Summary: FBG-1 with adhesive-1

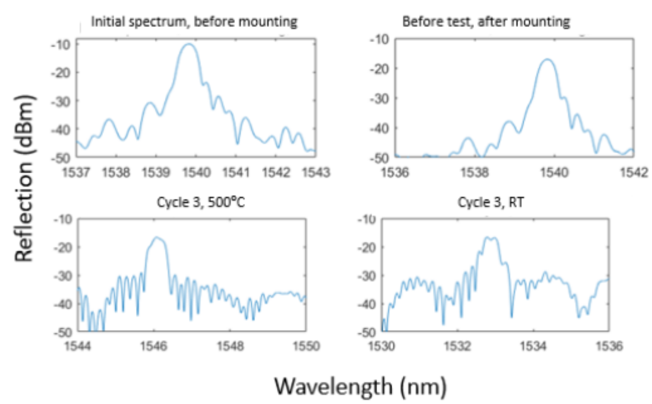
Cycle	Ramp	Slope (nm/°C)	Intercept (nm)	R^2
C1	up	0.0284	1521.409	0.99
	down	0.0277	1521.529	0.99
C2	up	0.0284	1521.237	0.99
	down	0.0280	1521.346	0.99
C3	up	0.0285	1521.145	0.99
	down	0.0277	1521.380	0.99

TABLE V: Summary: FBG-2 with adhesive-2

Cycle	Ramp	Slope (nm/°C)	Intercept (nm)	R^2
C1	up	0.0285	1531.401	0.99
	down	0.0278	1531.666	0.99
C2	up	0.0285	1531.396	0.99
	down	0.0281	1531.537	0.99
C3	up	0.0286	1531.356	0.99
	down	0.0277	1531.666	0.99



(a) FBG-1 with adhesive-1



(b) FBG-2 with adhesive-2

Fig. 7: Spectrum evolution with temperature

higher temperature causing less chirp behaviour at high-temperature, and similarly peak splitting at lower temperature range.

IV. CONCLUSIONS

The study summarises that gold-coated FBG sensors mounted with both the adhesives (adhesive-1 and 2) having higher CTE, survive up to 500°C for three consecutive thermal cycles, remain intact without any deterioration in bonding quality. Peak wavelength response to temperature is linear during later stages experiencing ≈ 28 pm/°C with R-square over 0.99. However, there is some chirp effect experienced in spectrum but it is lower in high-temperature range, and greater at lower temperature because CTE mis-match is higher at lower temperature. Overall, the sensors are highly suitable for structure health monitoring applications or surveillance systems in high-temperature operating envi-ronment. The further scoping of research include studying the relationship between chirp effect and CTE mismatch, for curved surface or structures and corresponding selected adhesive.

ACKNOWLEDGMENT

This work was supported by the National Research Foundation (NRF) Singapore, Energy Innovation Research Programme, under its Sembcorp-EMA Energy Technology Partnership (SEETP) (Singapore, LA/ Contract No: NRF2015EWT-EIRP001-010) and Ministry of Education - Singapore, Academic Research Fund Tier 1 (MOE2019-T1-001-111). The authors would like to thank Keng Boon Siah, Kheong Keng Tan, and Karan M Sabnani at Sembcorp Industries Ltd Singapore, for their domain knowledge and suggestions. The authors would also like to thank Gabriel Loh, Maryanne Toh, and Regina Low at the Institute of Chemical and Engineering Sciences Limited, under Agency for Science, Technology, and Research Singapore, for providing access to their research labs and helping to conduct the experiment.

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