External Electrode Temperature Monitoring of Lithium Iron Phosphate Batteries Based on Fiber Bragg Grating Sensors

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Abstract. Lithium-ion (Li-ion) batteries have become a promising candidate for the electrical energy storage and power delivery solutions. Thermal management is a key tool to improve performance and safety of Lithium-ion batteries. Currently, the common method is using electric sensors to monitor the thermal behaviour of batteries. In this work, an optical fiber sensor was proposed for temperature measurement of cells. The proposed sensor consists of a metal ring and a fiber Bragg grating (FBG). The FBG sensor calibration test shows a good linearity and high sensitivity. The FBG sensors were gloved on the external electrodes to monitor the temperature variation during charge/discharge cycles, and the PT100 sensors were attached on the electrodes as a comparison. Comparison test illustrates the response of proposed FBG sensors has a good agreement with PT100 sensors. It provides that the proposed FBG sensor can be used to monitor the temperature variation of cells, which provides a promising tool to improve the thermal management and safety of Li-ion batteries.

1. Introduction
Lithium-ion (li-ion) batteries have become a promising candidate for the electricity storage and power delivery solutions, due to their excellent characteristics such as high energy density, long cycle life, low self-discharge rates and environmental friendliness [1-3]. Therefore, more and more Li-ion batteries are used in energy storage power stations. The battery security is always a challenge of hindering its large-scale applications in power grid. Uneven temperature distribution would severely affect the performance, safety and cycle life of li-ion battery, so thermal stability of Li-ion batteries is one of the most important parameters [4, 5]. When the Li-ion batteries work under the abuse conditions, such as over-charge/discharge or in the presence of short circuits, the excess heat leads to quick increase of temperature and may cause irreversible damage in batteries and eventually explosion or combustion [6, 7].

Consequently, thermal management is extremely important for Li-ion batteries to guarantee good performance, long cycle life and safety. Temperature monitoring is a crucial tool for thermal management of batteries. Currently, the common-used method is utilizing electric sensors to monitor the thermal behaviour of batteries, such as thermocouples [8, 9] resistance temperature sensors[10]. However, these methods suffer from a variety of limitations, such as low-resistance to electromagnetic interference, complexity of measurement system and the high cost of highly parallelized wiring and sensing network.
Because of the excellent characteristics of small size, flexibility, immunity to electromagnetic interference and multiplexing capabilities, FBG sensors have been widely used to detect many parameters like strain and temperature [11, 12]. In recent years, many works about battery parameters monitored by FBG sensors have been reported. In ref. [13], Bae et al. embedded FBG sensors into Li-ion battery cells to detect the strain of internal electrode in the charge/discharge cycles. Peng et al. proposed a FBG sensor with high sensitivity to measure the strain on the surface of cells [14, 15]. Nascimento et al. attached FBG sensors to the smartphone Li-ion battery to monitor temperature variations at multiple points under different environmental and operating conditions [16]. Wherein, bare FBGs were used as the sensing unit in the above sensing method for temperature monitoring, which cannot work durably because bare FBGs are friable without protection and susceptible to interference.

In this study, a FBG sensor with a novel packaging structure was proposed for temperature monitoring battery external electrodes. The proposed FBG sensors were used to detect the temperature variation of Li-ion batteries during standard charge and discharge cycles.

2. Design of FBG sensor

2.1. Sensing principle

A FBG is a type of distributed Bragg reflector made in a short segment of optical fiber that reflects particular wavelengths of light and transmits all others. This is achieved by creating a periodic variation in the refractive index of the fiber core. The central wavelength of the reflected light is the so-called Bragg wavelength, which is related to the effective refractive index of the fiber core and the grating period as follows:

\[ \lambda_B = 2n_{eff} \Lambda \]  

(1)

Where \( n_{eff} \) is the effective refractive index of the fiber core and \( \Lambda \) is the grating period.

The Bragg wavelength shift \( \Delta \lambda_B \) is related to temperature changes (\( \Delta T \)), which can be calculated by the formula as follows:

\[ \Delta \lambda_B = \lambda_B \left( \frac{1}{\Lambda} \frac{\partial \Lambda}{\partial T} + \frac{1}{n_{eff}} \frac{\partial n_{eff}}{\partial T} \right) \Delta T = \lambda_B (\alpha + \xi) \Delta T = K_T \Delta T \]  

(2)

Where \( \alpha \), \( \xi \) and \( K_T \) are the thermal expansion coefficient, thermo-optic coefficient of the optical fiber material and the temperature sensitivity of the FBG, respectively. It is obvious that the Bragg wavelength shift \( \Delta \lambda_B \) is linear with the temperature variation \( \Delta T \). Therefore, the \( \Delta T \) can be obtained by measuring the \( \Delta \lambda_B \).

2.2. Structure design

For temperature monitoring on the external electrode of lithium iron phosphate cells, a FBG sensor with matching packaging structure was proposed, as shown in Figure 1. The proposed FBG sensor consists of a fiber with FBG, a metal ring and two protecting covers. There are a circular hole and a hexagonal hole in the metal ring, which is easy to install on the electrodes. At the circle direction of the metal ring, there are two rectangular grooves with different depths. The deeper one is designed for injecting adhesive and thermal paste to fix the FBG. The other is for assembling the protecting covers. The protecting cover is a semi-circular ring with half round holes at the end of both sides, which protects the FBG from the external interference, and the holes are easy to pass through the optical fiber. A fiber with a FBG is attached on the deeper groove loosely, and thermal paste was coated on the grating area. The sensor can be easily installed on the external electrodes of cell in the battery pack.
Figure 1. Schematic graph of the proposed FBG sensor for external electrodes of cells: (a) assembly diagram; (b) exploded diagram.

3. Sensor fabrication and calibration
The aluminum alloy was selected as the material of ring body. A 10 mm long FBG was chose as sensing element, with specifications of reflectivity of 90%. Epoxy glue was used to fix the fiber on the metal ring body, and the thermal paste has a high thermal conductivity of 73 W/mK. The FBG sensor prototype was fabricated as shown in Figure 2a.

A calibration experiments were conducted to acquire the temperature sensitivity before installing the sensor on the electrodes. The sensitivity was calibrated by a thermostatic bath (resolution: 0.005 °C, accuracy: 0.01 °C) in the range from 5 to 85 °C. A FBG interrogator (resolution: 1 pm) was used to demodulate the FBG wavelength shifts.

In the calibration test, the temperature sensitivities of two proposed FBG sensors were acquired. The average responses of sensors are demonstrated in Figure 2b. It shows that the FBG sensor has a good linearity. The sensors can resolute 0.1 °C on the condition that the resolution of FBG interrogator is 1 pm. The temperature sensitivities of two FBG sensors are shown in Table 1.

![Prototype of proposed FBG sensor and the calibration result of FBG sensors I.](image)

Table 1. Sensitivities of FBG sensors.

| FBG sensors | λB / nm | KT / pm/°C |
|-------------|---------|------------|
| Sensor I    | 1545.652| 10.39      |
| Sensor II   | 1553.702| 12.50      |
4. Experiment Setup

To validate the effectiveness of the proposed FBG sensor, an application experiment on temperature monitoring of the battery was conducted. A commercial lithium iron phosphate battery with nominal capacity of 60 Ah and voltage of 3.2 V (V0D5N0, ATL, China) was used in the experiment. The proposed FBG sensors were used to monitor the temperature variation under different charge/discharge cycles. Two proposed FBG sensors (Sensor I and Sensor II) were mounted on positive and negative electrodes. To verify the accuracy of the proposed FBG sensors, two resistance detectors (PT100, ±0.15 °C) were used to monitor the temperature on two electrodes of the cell, respectively.

The Bragg wavelength shifts were detected by a FBG interrogator (resolution: 1 pm). The signal of the PT100 was recorded by the data acquisition system (TRION-2402, DEWETRON GmbH, Austria). A battery testing system (BTS-4000-5V40A, Neware Technology Limited, China) was used to run defined charge and discharge cycles. The experiment devices are shown in Figure 3. This experiment was carried out in a room temperature. The experimental steps are as follows:

A standard cycle was repeated three times, which consisted of charging at a constant current (CC) of 18 A to a cut-off voltage of 3.65 V, then charging at a constant voltage (CV) of 3.65 to a cut-off current of 3.2 A, and discharging at a CC of 18 A to a cut-off voltage of 2.8 V. The rest time between charge and discharge was set to 2 hours.

![Figure 3](image)

Figure 3. Schematic diagram of the experimental setup for temperature monitoring of the battery

5. Results and discussion

Figure 4a shows the response of the FBG sensors and PT100 sensors under a standard charge/discharge cycle with 0.3 C-rate. It can be seen that the signals of FBG sensors have a same change trend with that of PT100 sensors, which proves the feasibility of the proposed FBG sensors for temperature monitoring of batteries.

According to the sensitivity calibration test, the sensitivity of FBG sensors were defined. The temperature variation can be calculated through dividing the wavelength shift by sensitivity coefficient, as shown in Figure 4b. It can be observed that the temperature variation extracted from FBG sensors has a good agreement with that detected by PT100 sensors.

The temperature variation curves of the external positive electrode for three standard charge-discharge cycles are shown in Figure 5. It illustrates temperature variation of cell measured by FBG sensors during three standard charge-discharge cycles. The temperature variation curves have
similar changing trend. The curves exhibit the same features such as peaks and valleys, which indicates that the temperature variation of the external electrode has good repeatability. Overall, the results demonstrates that the proposed FBG sensor is available for monitoring the temperature variation of cell.

![Figure 4](image.png)

**Figure 4.** Comparison of the response of the FBG sensor and the PT100 sensor; (a) signals of FBG sensor and the PT100 sensor, (b) temperature variation monitored by FBG sensors and PT100 sensors

![Figure 5](image.png)

**Figure 5.** The temperature variation of two electrode monitored by FBG sensors during three charge-discharge cycles.

6. Conclusions

In this study, a FBG sensor with special packaging structure matching with the external electrodes of the battery, was developed and successfully applied to monitor the external electrode temperature variation of the lithium iron phosphate Li-ion battery. The sensitivity calibration shows the proposed FBG sensor has a good linear response and high sensitivity.

Comparison test demonstrates the response of proposed sensors has a good agreement with PT100 sensors, which validates the feasibility of the proposed FBG sensors for temperature monitoring of batteries. The developed FBG sensor is easy-to-install, non-invasive, precise and immune to external
interference, which can provide a promising tool to improve the thermal management and safety of Li-ion batteries.

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References
[1] Wang Y, Gao Q, Wang G, Lu P, Zhao M, Bao W 2018 A review on research status and key technologies of battery thermal management and its enhanced safety Int. J. Energ. Res. 42(13) 4008-4033.
[2] Scrosati B, Garche J 2010 Lithium batteries: Status, prospects and future J. Power Sources 195(9) 2419-2430.
[3] Amietszajew T, McTurk E, Fleming J, Bhagat R 2018 Understanding the limits of rapid charging using instrumented commercial 18650 high-energy Li-ion cells Electrochim. Acta 263 346-352.
[4] Lu Z, Yu X L, Wei L C, Cao F, Zhang L Y, Meng X Z, Jin L W 2019 A comprehensive experimental study on temperature-dependent performance of lithium-ion battery Appl. Therm. Eng. 158.
[5] Jouhara H, Khordehgah N, Serey N, Almahmoud S, Lester S P, Machen D, Wrobel L 2019 Applications and thermal management of rechargeable batteries for industrial applications Energy 170 849-861.
[6] Wang Q, Ping P, Zhao X, Chu G, Sun J, Chen C 2012 Thermal runaway caused fire and explosion of lithium ion battery J. Power Sources 208 210-224.
[7] Bandhauer T M, Garimella S, Fuller T F 2011 A Critical Review of Thermal Issues in Lithium-Ion Batteries J. Electrochem. Soc. 158(3) R1-R25.
[8] Panchal S, Dincer I, Agelin-Chaab M, Fraser R, Fowler M 2016 Experimental temperature distributions in a prismatic lithium-ion battery at varying conditions Int. Commun. Heat Mass Transf. 71 35-43.
[9] Mutyala M S K, Zhao J, Li J, Pan H, Yuan C, Li X 2014 In-situ temperature measurement in lithium ion battery by transferable flexible thin film thermocouples J. Power Sources 260 43-49.
[10] Wang P, Zhang X, Yang L, Zhang X, Yang M, Chen H, Fang D 2016 Real-time monitoring of internal temperature evolution of the lithium-ion coin cell battery during the charge and discharge process Extreme Mechanics Letters 9 459-466.
[11] Rao Y 1997 In-fibre Bragg grating sensors Meas. Sci. Technol. 8(4) 355-375.
[12] Lee B 2003 Review of the present status of optical fiber sensors Opt. Fiber. Technol. 9(2) 57-79.
[13] Bae C, Manandhar A, Kiesel P, Raghavan A 2016 Monitoring the strain evolution of lithium-ion battery electrodes using an optical fiber Bragg grating sensor Energy Technol. 4(7) 851-855.
[14] Peng J, Jia S, Jin Y, Xu S, Xu Z 2019 Design and investigation of a sensitivity-enhanced fiber Bragg grating sensor for micro-strain measurement Sens. Actuators A: Phys. 285 437-447.
[15] Peng J, Zhou X, Jia S, Jin Y, Xu S, Chen J 2019 High precision strain monitoring for lithium ion batteries based on fiber Bragg grating sensors J. Power Sources 433 226692.
[16] Nascimento M, Ferreira M S, Pinto J L 2019 Temperature fiber sensing of Li-ion batteries under different environmental and operating conditions Appl. Therm. Eng. 149 1236-1243.