

Embedded Fiber Optic Sensors for Battery Performance Monitoring in Lithium Ion Battery Cells

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ABSTRACT

Rechargeable Lithium Ion Batteries (LIB) are the key components of the energy storage systems in electric and hybrid electric vehicles. In order to provide a reliable and safe source of energy for driving electric vehicles, the battery packs are controlled by a centralized Battery Management System (BMS). BMS relies on the direct measurement of electric current and voltage to estimate the battery charge conditions in order to ensure the optimum operation of individual cells and to protect them from operation outside their safe conditions. Measurement errors and uncertainties in the estimation algorithms have resulted in applying large safety factors in the design of battery cells. In this paper, an embedded optical sensor technology for direct sensing of the electrochemistry of the battery cell is demonstrated. The sensor consists of an optical fiber, encapsulated inside a battery cell, with direct interaction with the cell electrochemical environment. The development of an optical signal interrogation system is also demonstrated in this research work. The optical fiber sensor operates on the basis of the changes in the optical properties of the LIB cell electrodes, i.e., changes in optical absorption and reflection at different charge levels. The optical sensor not only shows the state of charge in battery cells but also provides information about battery aging and stabilization following charge and discharge cycles. The performance of this sensor has been tested in several conditions including partial and full charge and discharge cycles.

Keywords: Lithium ion batteries, embedded fiber optic sensors, charge monitoring

1 INTRODUCTION

Lithium Ion Batteries (LIB) are the most common type of energy storage devices used in electric and hybrid electric vehicles. Compared with other types of rechargeable batteries, the advantages of LIB cells are high energy density, short priming time, low maintenance, and the capability for supplying high current. The growth of the LIB industry is mainly driven by the promotion of the electric mobility and the global initiatives for clean and zero-emission transportation. According to the International Energy Agency (IEA), the global sales of electric vehicles is

projected to reach \$6M by the year 2020 with market dominance in the USA, China, and Japan [1]. The BCC Research market study speculates the LIB global market to reach \$13.4B in 2018 from \$6.5B in 2008 [2].

Battery packs, which are the combination of multiple cells, are among the most critical components in electric vehicles. The individual cells in each battery pack are continuously controlled and balanced by a central Battery Management System (BMS) to ensure optimum performance and to protect them from operation outside their safe conditions, e.g., over-temperature, over-current, etc. BMS relies on measurement data such as voltage, current, and temperature to estimate the State of Charge (SOC), based on Open Circuit Voltage (OCV), and the State of Health (SOH). The charge estimation, which may be performed by methods such as Kalman filtering, is susceptible to measurement error accumulation and numerical uncertainties [3][4][5][6]. As a result, a safety factor is applied to the design of battery cells to compensate for these uncertainties. This safety factor can make the battery packs larger and heavier which also results in the increase of the negative environmental impacts when battery cells are disposed and recycled at the end of their effective life cycle.

Given the complex electrochemical environment of a battery cell, an in-situ sensor embedded inside the cells has the advantage of direct monitoring of the changes in electrochemistry compared to the indirect voltage and current measurements. The battery cell is a corrosive environment that is not friendly for many electronic sensors. Even hermetically sealed sensors cannot be reliably used in battery cells due to their susceptibility to Electromagnetic Interference (EMI). As a result, an optical based sensor device made of non-conductive materials (e.g., glass) can be a feasible solution for this application. In this paper, we demonstrate the world's first optical fiber sensor embedded inside LIB cells. The optical fiber has the unique advantages of immunity to EMI, robustness to corrosive environments, and small form factor. The sensor design and integration, sensors testing, and the analysis of the behavior of the optical signal will be discussed in this paper.

2 OPTO-CHEMISTRY OF LIB

An LIB cell is composed of cathode and anode electrodes and a separator soaked in electrolyte. Graphite is the most

common type of material for LIB anodes due to its relatively high capacity (372 mAh/g), high reversible lithium ion intercalation, good electrical conductivity, simple production process, and low cost [7]. The cathode material may be composed of different lithium compounds such as lithium iron phosphate (LiFePO_4), lithium manganese oxide (LiMn_2O_4) or lithium cobalt oxide (LiCoO_2). The operation of the LIB cell is based on the reversible intercalation of lithium ions in the layers of graphite; i.e., the graphite cathode is lithiated/de-lithiated during the battery charging/discharging cycle (Figure 1). Graphite anodes in LIB cells have ordered structures by the periodic arrangement of intercalated lithium ion layers within graphite sheets. The level of intercalation is classified by the number of graphite layers between adjacent layers of Li-ions: Stage I (LiC_6), stage II (LiC_{12}), stage III (LiC_{18}), and stage IV (LiC_{24}).

The optical properties of lithiated graphite can be explained by the Drude model. The optical reflectivity of lithiated graphite exhibits characteristic Drude edge at the plasma frequency ω_p . As the frequency of the photons decreases below ω_p , the reflectivity increases, which is typical of metallic free carrier absorption [8]. The process of lithium intercalation increases the carrier density, which shifts ω_p to higher frequencies or smaller wavelengths (Figure 1). As a result the optical properties of the graphite anode are charge-dependent variables. According to the Drude model, the optical absorption and reflection at certain frequencies are modified at different stages of charge. These charge-dependent properties can be leveraged toward the development of an optical based transducer system inside an LIB cell.

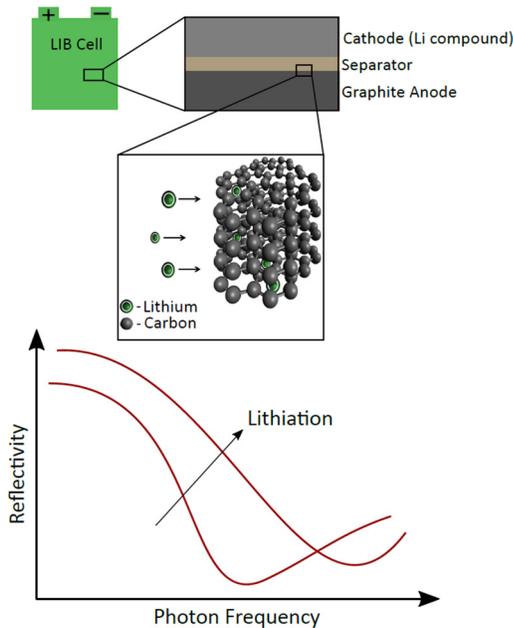


Figure 1: Lithium ion intercalation in LIB cells and the effect of lithiation on optical properties of graphite anode

In order to characterize the optical properties of anode, we conducted reflectance spectroscopy of a graphite anode at different charge levels (i.e., different SOC levels). The results, as shown in Figure 2, indicate that the state of lithiation or SOC can be correlated to the optical reflectance of graphite. These results can be used as the basis for the design of an optical sensor for monitoring the level of charge in LIB cells. As seen in this figure, the reflectance of graphite increases at higher wavelengths. According to this graph, an operating wavelength above 800 nm maximizes the transducer sensitivity to changes in the battery charge. Higher wavelengths above 850 nm may exhibit larger sensitivities; however, they have not been studied in this research work.

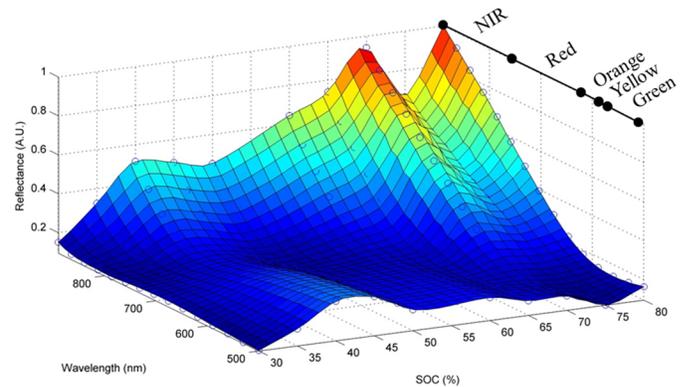


Figure 2: Reflectance spectroscopy measurement of graphite anode in LIB cells at different charge levels

3 OPTICAL FIBER SENSING

Given the charge-dependent optical properties of the graphite cathode in LIB cells, an embedded optical fiber that interacts directly with the graphite layer can be used as the transducer mechanism. Fiber optic has unique features which make it a viable solution for battery sensing applications. These features are immunity to EMI, robustness to corrosive environments, and small form factor. The light passing through the optical fiber interacts with the electro-chemistry of the cell where the intensity of the light is modulated due to the charge-dependent changes in the optical properties of anode. Two design configurations are realized for the sensor – reflection and transmission based optical power monitoring (Figure 3). In these configurations, the modulated optical signal is either transmitted to the other end of the fiber or is reflected back where it is monitored by a photo-sensitive device such as a photo-detector.

We have developed an in-house battery assembly and fiber optic sensor integration process. Our manufacturing platform has the capability of assembling LIB cells with a footprint of $4'' \times 4''$. We design and fabricate sensors from standard telecom glass fibers prior to encapsulation inside battery cells. The fiber integration and cell assembly process is shown in Figure 4.

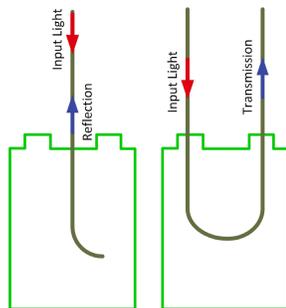


Figure 3: Optical fiber sensor configurations – reflection and transmission mode sensing

Our in-house setup for monitoring the battery using optical fiber sensors is shown in Figure 5. The system consists of an LED light source at 850 nm, LED current driver, photo detector, Transimpedance Amplifier (TIA), A/D converter, and a communication module. We have miniaturized the system into an Optical Signal Interrogation (OSI) unit, as shown in Figure 5. The optical signal measurement data are processed in a data analytics software developed in-house.

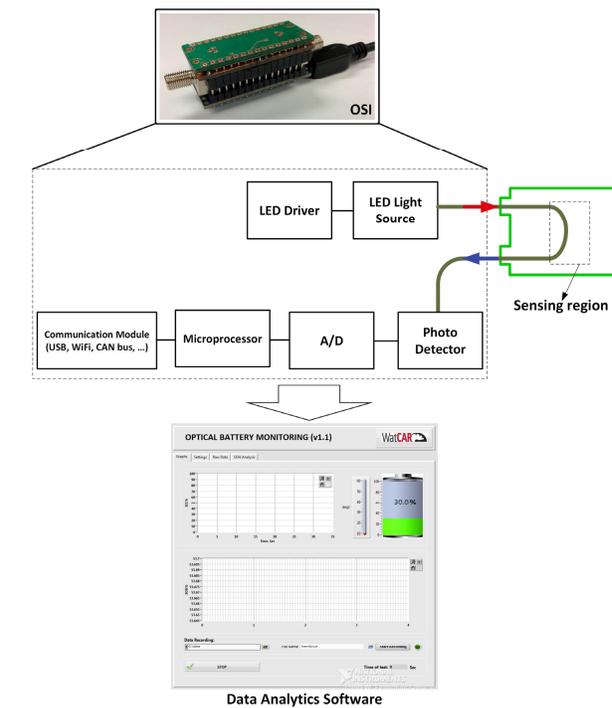


Figure 5: Optical signal interrogation system

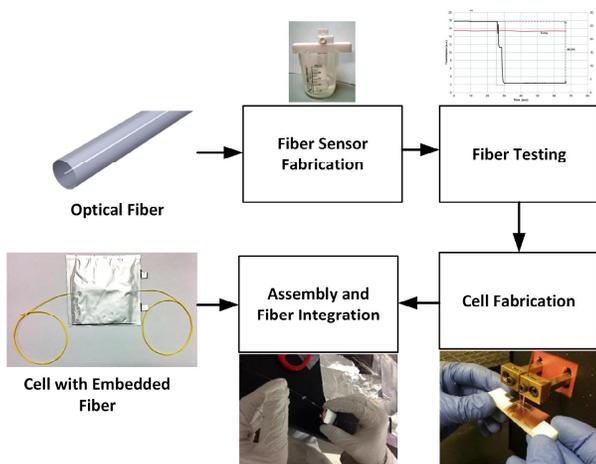


Figure 4: Cell assembly and fiber integration process

4 TESTING AND DATA ANALYSIS

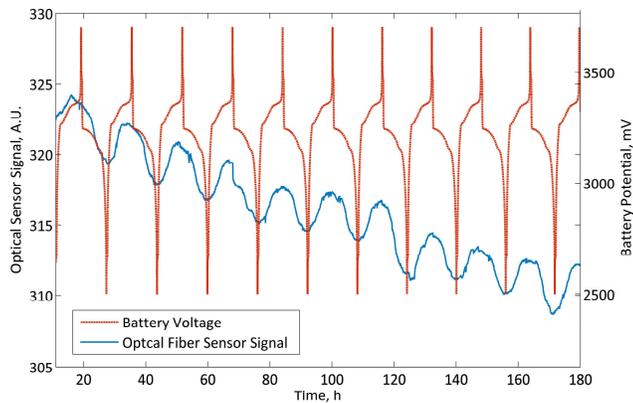
To characterize and calibrate the embedded sensors, the cells were cycled by controlling the input current using a battery cycler. The measurement data for a battery cell during full charge and discharge cycles at 0.6 mA are demonstrated in Figure 6. The optical signal, measured in transmission mode, shows a cycling behavior at the same frequency as the cell charge and discharge cycles. As observed in the figure, the optical sensor signal follows the battery charge level. This behavior can be explained by the Drude model and the reflectance spectroscopy measurement data in Figure 2. Battery discharging, which involves delithiation, results in higher absorption in the graphite anode at a given frequency. This leads to the attenuation of the transmitted optical power. However, cell charging and

lithiation increases the reflection which results in an increase in the transmitted power.

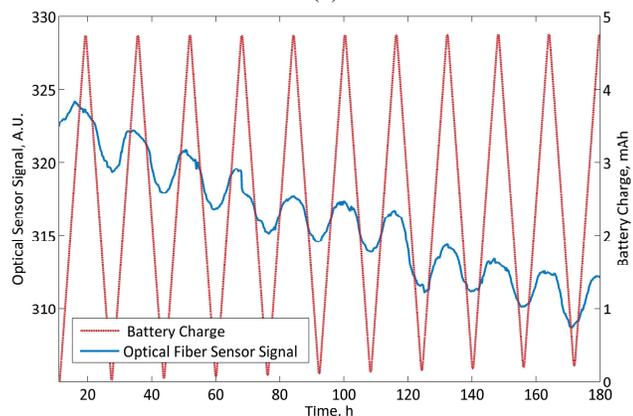
In addition to the cycling trend, the optical sensor signal shows a slow decaying trend. This trend is believed to be associated to battery aging. Each charge and discharge cycle results in the reduction of the capacity of the cell which is a typical characteristic of LIBs. However, this trend is accelerated in this cell as it has not been fabricated in a commercial battery manufacturing facility.

In another set of experiments, we conducted partial cell charging and discharging with test data shown in Figure 7. Similar to the full charge cycles, the optical signal follows the battery charge level. The partial charge cycles contain a relatively long resting period where the current is 0 A. Although the battery is not drawing or draining any current, the optical sensor signal shows variations. This change in the optical signal is an indication of battery stabilization which is not observable by only the measurement of current and voltage. However, this behavior might be observable by estimating the Open Circuit Voltage (OCV). Since the optical fiber has direct interaction with the electrochemical environment inside the cell, this phenomenon can be well detected by the optical fiber sensor.

The information obtained from the embedded optical fiber sensor is complementary to the electric current and voltage measurement data in order to gain deeper insight into the internal dynamics of the battery. We are working on the development of an estimation algorithm to incorporate the optical signal and other measurement data such as current for the estimation of the battery charge and battery health.



(a)



(b)

Figure 6: Optical sensor signal during full charging and discharging cycles at 0.6 mA (a) battery voltage, (b) battery charge

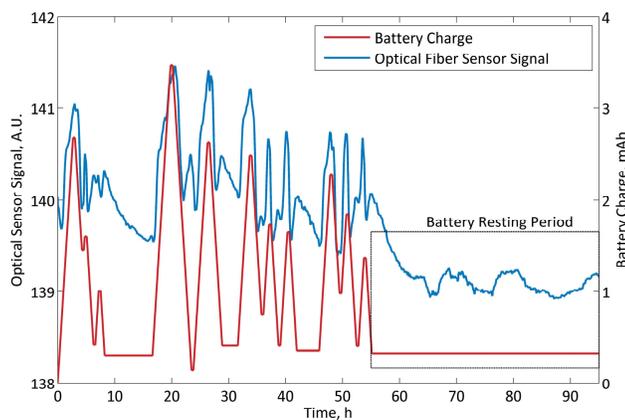


Figure 7: Optical sensor signal during partial charging and discharging cycles at 0.6 mA

5 CONCLUSION

An embedded optical fiber sensor technology for the monitoring of charge in LIB cells was demonstrated in this paper. The battery charge and aging can be monitored at the same time by using the embedded fiber optic sensor. The

experimental results show that the optical fiber sensor signal follows the level of charge in the battery cell. Additionally, the sensor data show dynamic changes inside the battery cell during battery resting which is not observable by the current and voltage measurements. The information obtained from the optical sensors can facilitate the design of charge estimation and balancing algorithms with higher accuracy and reduced uncertainties. This is of significant advantage from a commercialization point-of-view.

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