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Polymer-based Fiber Fabry-Perot Interferometer for Temperature Monitoring of *Operando* Lithium-Ion Batteries

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Summary:
A microscopic Fabry-Perot interferometer made of a thermo-sensitive polymer deposited on the facet of a single-mode fiber is proposed for highly sensitive temperature sensing. The miniature interferometer was used for monitoring thermal effects in a rechargeable (lithium-ion) battery. The temperature changes in the battery due to electrochemical events that occur internally during the charge/discharge stages were successfully tracked, non-invasively, with the proposed sensor. Our sensors may be used for real-time diagnostics, safety assurance, and lifetime estimation of lithium-ion batteries.

Keywords: Optical fiber interferometer, temperature sensors, lithium-ion batteries.

Introduction

The use of lithium-ion batteries (LIBs) is being promoted globally due to their positive impact on achieving a carbon-neutral world. LIBs can be charged and discharged multiple times but is has associated risks such as fires and even explosions. Furthermore, maintaining the temperature controlled during the battery operation is crucial as overheating can affect stability, efficiency, capacity degradation, and hence the lifespan of such batteries. Thus, temperature in LIBs is a parameter that must be monitored continuously and ideally non-invasively.

Optical fiber sensors for rechargeable batteries have attracted considerable attention in the last few years [1]. These sensors provide electromagnetic immunity, are low weight, safe, and can provide precise temperature measurements in real-time. For example, it has been demonstrated that temperature sensors based on Bragg gratings are as accurate as electronic ones. Thus, fiber sensors have been used for temperature monitoring and control during battery charging/discharging processes.

Herein, we demonstrate that a polymer-capped fiber Fabry-Perot interferometer can be an alternative to monitor non-invasively temperature during the charging/discharging process of LIBs. We have selected a polymer as a temperature sensitive material because the temperature sensitivity of our interferometers is approximately one order of magnitude higher than that of sensors based on Bragg gratings.

Results

The structure of the interferometer is shown in Fig. 1. The fabrication steps are reported in [2]. Basically, a drop of commercial polymer (PMDS) is deposited on the flat facet of a conventional single mode fiber (SMF). Then, the polymer is cured at 60 ºC for 4 hours. The resulting dome had a height of 72 µm approximately. This polymer-capped fiber tip was calibrated as temperature sensor from 20°C to 60°C. To do so, we correlated the phase of the interference pattern with temperature. The phase observed at different temperatures and the calibration curve are shown in Fig. 1. The sensor exhibited a temperature sensitivity of 0.129 rad/°C. This is equivalent to 346.5 pm/°C, which is 34 times more sensitive than temperature sensors based on Bragg gratings (~10 pm/°C). Moreover, it is well known that polymers, PDMS in particular, respond faster than glass to temperature changes.

After the calibration of the sensor, it was used to monitor temperature changes in a commercial LIB (model INR18650-30Q) during the charge and discharge processes. The fiber interferometer was protected with a capillary tube to prevent its response from being influenced by other parameters such as humidity or dust particles. The protected sensor was positioned externally at the center of the battery.

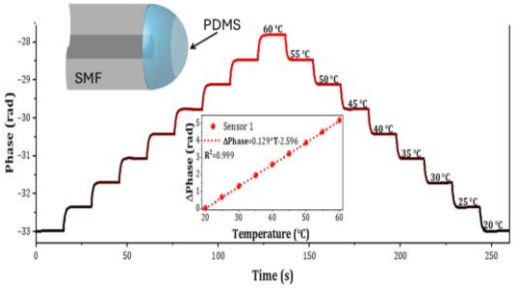

Fig. 1. Schematic of the polymer-based interferometer. SMF is single mode fiber. The graph shows the phase of the interference pattern at different temperatures. The calibration curve is shown in the inset graph.

A potentiostat was used for cycling the battery at different charge rates (C). The potentiostat was programmed to apply three charge/discharge stages with constant current densities at C-rates of C/5, C/3, and 1C. This cycling protocol was executed in conjunction with the acquisition of the optical signal from the interferometer. In this manner, the thermal changes in the LIB could be correlated with the voltage.

The voltage profiles obtained with the potentiostat over time and corresponding phase in the interference pattern and temperature changes are shown in Figure 2. It can be noted from the figure that during the discharge stages variations of approximately 1.5 ºC, 4°C and 14 °C for C-rates of C/5, C/3 and 1C, respectively, were measured with our device. As expected, more prominent phase or temperature changes were observed at faster charge rates.

The phase changes suffered by the interferometer are caused by the modification of the thermal properties of the PDMS cavity when the temperature in the battery increases. There is a greater temperature change during the charge/discharge stages at 1C rate in contrast with C/5. It can be principally associated to exothermic events that occur by electrochemical and resistive reactions of the battery.

The results shown in Fig. 2 demonstrate that minute temperature variations can be detected in the battery by means of the polymer-capped fiber tip. By tracking the phase of the interference pattern, the sensor response can also be more sensitive and accurate. Thus, monitoring temperature in a non-invasive manner can be reached without compromising the battery structure.

It is important to point out that currently, voltage differential analysis and temperature monitoring are used as quality parameters and lifespan of LIBs. The thermal evolution is usually associated with the degradation mechanisms in LIBs. In

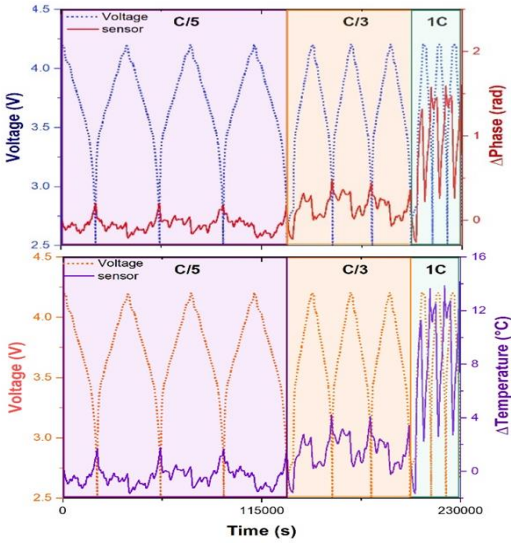

Fig. 2. Changes in phase (temperature) observed in the polymer-based interferometer during the charge and discharge stages of a rechargeable battery. The C-rates are indicated with the voltage profiles maintained.

some cases, the monitoring of temperature requires internal measurements due to the low sensitivity of the sensor used. In this work, we have shown how an easily manufactured, ultra-compact Fabry-Perot interferometer can be used to monitor non-invasively temperature changes of a LIB. More experiments are being carried out to investigate the feasibility of the sensor reported in the diagnosis for *operando* assessment of thermal behavior, safety conditions, and degradation pathway of LIBs. The results of these investigations will be presented at the conference.

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