Thermal Monitoring of Series and Parallel Connected Lithium-ion Battery Modules Using Fiber Optic Sensors

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Lithium-ion batteries are widely deployed in commercial and industrial applications. Continuous monitoring is necessary to prevent destructive results that can occur due to thermal runaway. Thermocouples and thermistors are traditional sensors used for thermally monitoring cells, modules, and batteries, but they only sense changes at the physical point where they are deployed. A high density of these sensors within a module or battery is desirable but also impractical. The study documented here shows that a commercial grade fiber optic sensor can be used as a practical replacement for multiple discrete thermocouples or strain gauges for a battery or module, to monitor a battery module at millimeter resolution along the fiber length. It is shown here that multiple fiber optic sensors can be series connected to allow for monitoring of a battery consisting of more than one module. In addition, it is shown that the same type of fiber can also be used to identify the onset of fault conditions by correlating the response in a fiber optic sensor suspended close to the module with an audible signature detected by a microphone at the time of failure. Early detection and identification of abnormal cell operation is demonstrated within batteries employing many cells.

Since the original lithium-ion battery was developed by J.B. Goodenough in the 1980s, 1 portable batteries have become widespread in countless consumer and industrial products. New technologies are being developed every day, and as a result there are many different battery form factors and chemistries employed commercially. Each form factor and chemistry offers its own advantages and disadvantages to the application it is intended to be used in. High energy density and power density is always desirable, but is not without costs.2 Noted failures, such as the Samsung Galaxy Note 7, demonstrate that lithium-ion batteries are susceptible to random catastrophic events and measures must be taken to prevent these occurrences.3

Batteries experience a change in temperature and strain at the time of a failure.4 Temperature measurements may be acquired using surface mounted or embedded thermocouples or thermistors. Strain measurements may be acquired using strain gauges.5 These types of sensors are “single point” measurements, intrusive, and are often electrically conductive, sometimes inhibiting high quality thermal and strain measurements from being made where they need to be. Promising results have recently been made using optical fibers to measure temperature and strain when applied to batteries and various other applications.6–11 High-density fiber optic sensors (HD-FOS) exploit Rayleigh backscatter along with the natural non-homogeneities inherent in the inception of the fiber to correlate either temperature or strain to areas within the fiber.12–14 The Luna Optical Distributed Sensor Interrogator (ODSI) system can measure temperature or strain from HD-FOSs but not both simultaneously.11 Temperature measurements are recorded by attaching the fiber to the cell(s) surface in a way such that it is thermally contacting the cell(s) but only loosely mechanically contacting the cell(s) being measured so that strain is decoupled. Encasing the fiber in a thin Teflon tube or in tape like that seen in Fig. 1a, discussed later, have provided successful results. Strain measurements are recorded by attaching the fiber to the cell(s) surface in a way such that it is mechanically contacting the cell(s) but only loosely thermally contacting the cell(s) so that it is thermally decoupled.

Advancements in this technology have allowed users to measure with a spatial resolution of less than 1 mm for fiber lengths as long as 50 m.4,12,13 When used in a battery application made up of many modules connected in series/parallel, it is not feasible to use one long fiber or to use a dedicated fiber and data sensing channel for each module. Instead, it is proposed that the optical fibers be kept at manageable lengths, installed in each individual module, and then coupled together externally to create a single, longer fiber that can be measured using a single data channel. Each optical coupler introduces some signal loss and it is critical that this be well characterized and understood to ensure that data reflected from modules further down the length of the fiber is accurate. Measurements performed here have shown that the loss is manageable for an excess of ten fiber couplers before it becomes concerning.

In addition to a change in temperature and strain, batteries also produce a pressure gradient at the time of failure due to the ventilation of gasses from the cell. When this occurs, there are usually several audible signals attributed to the destruction of the integrity of the cell. As will be shown here, this audible signal can be detected by a microphone and correlated to a change in strain detected by a closely suspended FOS occurring at the time of failure, providing further indication and prediction of potential failure by a battery monitoring system.14,15

In this study, a LUNA ODSI system coupled with an HD-FOS is used to measure the thermal change induced in multiple battery modules, each of which is instrumented with its own optical fiber, that are coupled together using optical connections. Thermocouples are also used as a comparison to the fiber optic measurements. Because it has already been shown at the cell level, and because demonstration of successful thermal measurement from multiple modules implies that strain measurement will work as well, no experiments are performed here in which strain on individual cells is measured during normal or abnormal operation. In a few of the later experiments, a microphone is placed close to the battery to detect the occurrence of an audible signal and a fiber optic sensor is also placed nearby to detect vibration or movement caused by the acoustic waves. The signals detected from the microphone and fiber optic sensor are correlated with each other to determine the sequence of events and associated strain deformation happening at the time of battery failure. The result is a new, non-intrusive technique for making high density, real-time battery temperature measurements and for quickly identifying unexpected events more reliably than traditional techniques afford.

Procedure

Previous experiments have shown the efficacy of FOSs as capable measurement devices in applications of thermal and strain sensing.11 Previous experiments studying their use in battery sensing has utilized independent fibers on individual cells or modules
consisting of six to ten cells. Expansion of previous work is performed here using arrangements of both four and ten individual modules electrically connected in series. Making a real-time thermal or strain measurement on every cell would require large numbers of thermocouples, thermistors, or strain gauges, respectively. This creates a wiring mess and requires a high data acquisition channel count for each measurement type. Instead, a single, noninvasive FOS can be installed in each module such that it thermally or mechanically contacts each individual cell and optical couplers can be used to interconnect all the modules together forming a single fiber. A single optical data acquisition channel is required to measure the expanded fiber and every cell is monitored for temperature or strain, not both simultaneously on the same fiber, in a seamless manner. In the work documented here, the methods used to install the fiber onto the modules will be discussed, the method used to locate the segments of the fiber contacting each cell will be shown, the expected loss from introducing multiple fiber optic connectors will be shown, and the fiber optic measurements recorded during a series of normal and abnormal operational conditions will be presented. Noise introduced by multiple fiber optic connections is also discussed, with estimates on the number of modules that can be interconnected before the combined loss from connectors interferes with sensor detection.

Module design and point of interest detection.—Figure 1a shows the method of implementation for FOS temperature sensing using a single 1.25 m long fiber that touches each of the respective 18650 cells that make up the 1S/6P or 6S/1P module, oriented in a sinusoidal arrangement between two polyimide adhesive strips. Previous studies have shown that a fiber arranged in a sinusoidal pattern reduces overall strain on the fiber and allows every cell within the module to be sensed by the fiber along its longitudinal

Figure 1. Photographs describing the setup of FOSs on multiple 18650 lithium-ion battery modules. In (a) a LUNA FOS attached between two pieces of polyimide tape and it is arranged in a sinusoidal pattern contacting each cell for strain reduction on the fiber as shown in (b) and (c). In (d) and (e) multiple modules that each have their own FOSs interconnected are shown.
Figure 1b shows a FOS directly attached to a module, and Fig. 1c shows the application of the taped fiber from Fig. 1a.

Measurement of each individual module's fiber requires either its own dedicated optical measurement channel or each subsequent fiber must be connected to the previous one to form one fiber that can be sensed using a single channel. The latter method is being studied here by interconnecting many of these same module types in either series or parallel. A four-module setup is shown in Fig. 1d, and a ten-module setup is shown in Fig. 1e.

The LUNA data acquisition system can acquire thermal or strain data, but not both simultaneously, from the fiber at sample rates as high as 250 Hz with spatial resolution as fine as 0.54 mm down the length of the fiber, with higher sampling frequencies possible at larger spatial resolutions. The segments of fiber in contact with the axial length of each cell are of interest and parsing that data out in real-time greatly simplifies the data collection and analysis process. Once installed on the battery, the locations where the fiber optic sensors contact each respective cell must be identified manually or by using some sort of automated process. As shown in Fig. 1a, there are many segments on the fiber that are not contacting any portion of a cell and those must be removed from the data array. Using the manual touch to identify feature would be very time consuming and impractical on larger commercially procured batteries in which the fiber is installed prior to procurement. Here, a custom NI Virtual Instrument (VI) has been written using LabVIEW to autonomously detect the segments contacting each respective cell while the battery is cycled at a low C rate. Once assembled, either individually or interconnected together, the module(s) under test is discharged and recharged at a 0.5 C rate while the custom VI is executed. While the battery is cycled, the fiber optic sensor measures the thermal rise on each cell that stems from its respective thermal losses and those appear as peaks in the data. The front-panel of the custom VI is shown in Fig. 2a for a simple scenario of a single fiber on a single cell. Figure 2b shows the data measured across the cell where the two terminals of the cell, the points where the cell gets hottest, are autonomously identified. These locations are set as the bounds of the cell and the data measured between those bounds is the valid data considered by the battery monitoring software. This same process is applied to the 4S6P multiple module system consisting of multiple cells per module. (d) Procedure applied to the 10S6P module array.
used to identify each cell in a multi-cell module or battery. Figure 2c shows the same procedure applied to the 4 S/6 P module from Fig. 1d, with 22 of the 24 cells identified, with the last two unable to be acquired due to an issue with the data file. This issue was resolved in Fig. 2d, with all 60 cells successfully identified for the 10 S/6 P module shown in Fig. 1e. This method can be utilized for a battery consisting of any arrangement of cells so long as the data loss across couplers is not significant, something better described later.

Multiple interconnected module commissioning experiments under normal operation.—It has been shown in previous work that the FOS technology discussed here can be used to measure cell temperature during normal cycling operation and that it can be used to detect abnormal operating conditions, such as short circuits and over-charge events. During these abnormal events, either high rates of temperature change, $dT/dt$, or high rates of strain change, $dS/dt$, can be measured and identified depending on how the fiber is coupled to the module. Of interest here is if that same type of detection can be made when multiple modules are connected in series and the FOSs on each of those modules are interconnected using couplers. Data loss across the couplers was of concern and something that needed to be measured and validated. To validate that this would perform under normal operation, an initial experiment was designed using four 1 S/6 P modules of 18650 cells that had 1.25 m FOS segments installed on them. The modules were connected serially as seen in Fig. 3, the fibers were interconnected using fiber optic couplers, and the single 4 S/6 P battery was cycled electrically while measuring the FOS data using a single ODiSI channel. A thermocouple was attached to the center on the side of one cell within each module which is used to verify the accuracy of the temperature data from the FOS axially attached to each cell of each module segment. The following electrical cycling procedure was performed:

1. 1 C constant current/constant voltage (CC/CV) charge to 100% state of charge (SOC).
2. 1 C constant current (CC) discharge down to 0% SOC.
3. 1 C CC/CV charge to 100% SOC.
4. 1 C CC discharge to 0% SOC.
5. 1 C CC recharge to 100% SOC.

In Fig. 3a, a plot of the optical signal recorded across the four modules is plotted. The five high spikes are the optical distortion that occurs across the couplers used to interconnect the four modules together. Notice that the amplitude of the signal linearly decreases along the fiber length. This is the expected loss that needs to be characterized to understand the limits of how many fibers can be practically connected in a higher voltage battery. In the case of these four modules, the loss is roughly 5 dB which is well within the device’s measurement tolerance. From these measurements we can estimate adding at least six additional modules before data quality degrades due to the loss from additional FOS connection points. In Fig. 3b, the thermal rise on each cell is clearly visible when cycled under the electrical conditions shown in Fig. 3c.

Expanding upon the four-module design, a 10 S/6 P battery was constructed, previously shown in Fig. 1e. A thermocouple is attached to one cell within each module, in addition to the FOS, and the temperature is recorded by the NI data acquisition system. Figure 4a shows the noise loss for the 10-module setup, with a noticeably steep trend like that in Fig. 3a. There is roughly 8 dB of loss dropped across the 10 modules, but the amplitude is still within the tolerance of the data acquisition. It is expected that at least four additional connectors can be introduced without reaching the noise

Figure 3. (a) Noise loss vs distance along the FOS. Regions are identified by a peak in noise, caused due to added reflections from fiber optic connectors. (b) Isometric view of FOS data as a function of fiber. (c) Plot of voltage and current from the outlined procedure.
floor, which would prevent the ODiSI device from properly detecting the termination of the FOS. The main cause of additional noise was due to the multiple fiber optic connectors, with the length of the fiber contributing much less to the overall noise in the system. While adding additional segments in a multi-segment fiber adds additional noise, the ease of replacement of single sections of the FOS from a single battery module is more beneficial than replacing a single fiber on a multi-module battery. Figure 4b shows raw data obtained from the ODiSI system, with noise clearly visible around the fiber optic connection points. Figure 4c shows the smoothed FOS data, with regions around fiber optic connectors set to NaN for better identification of cell temperatures on the surf plot. Figure 4d shows individual module voltages reported from the BMS, while Fig. 4e shows the total voltage and current reported by the charger/load. The following electrical cycling procedure was performed:

1. 0.5 C CC/CV charge to 100% SOC.
2. 0.5 C CC discharge down to 20% SOC.
3. 0.5 C CC/CV charge to 100% SOC.
4. 1 C CC discharge to 20% SOC.

Multiple interconnected module commissioning experiments under abnormal operation.—Temperature changes during normal operation of battery modules are typically predictable and differ greatly from abnormal events, such as an overcharge or short-circuit. A BMS can be connected so that it disconnects the battery from a charger or load if a fault condition is observed but if the density of thermal measurement is not high enough, an unexpected event can easily be missed. It is shown here that the HD-FOS can detect the rate of temperature change and act if it is higher than what is normally expected anywhere throughout the battery. Further, it is easy to identify where the unexpected measurement is occurring. In the experiment highlighted next, the 10 S/6 P battery was discharged at a 0.5 C rate. Towards the end of the discharge, a controlled short-circuit is performed on only one module while the temperature is recorded using both thermocouples and the fiber-optic sensor. Figure 5a shows the collected FOS data, with regions around fiber optic connectors set to NaN for better identification of cell temperatures on the surf plot. Figure 5b shows the voltage and short-circuit current from module 6, which was the module that was shorted during the discharge. Figure 5c shows the voltages...
reported by the BMS for all ten modules, and Fig. 5d shows the pack voltage and current reported by the BMS. Notice from the data in Fig. 5a that temperature deviations measured around the 5 m mark are very high relative to the rest of the module as this module undergoes the short-circuit. This correlates to the position of module 6.

Acoustic measurement using a FOS.—Along the way, the question arose as to whether a FOS would produce a measurable signature induced by the acoustic wave given off when a lithium-ion cell goes into thermal runaway. In this case, a fiber should be suspended close to the cell/module but not be in any contact with it. To observe this, multiple experiments were devised to detect and verify the reaction from the FOS can be correlated to an acoustic signature. For the first experiment, an 18650 cell was instrumented with a FOS in three different configurations: taped to the body of the cell, glued to the body of the cell, and suspended a distance away from the cell as shown in Figs. 6a and 6b. This was done to identify the ability of the FOS to respond to failure events, and correlate the data to recorded audio. To generate the failure event, an overcharge is subjected to the cell/module with the intent of triggering the CID, which typically has an audible “pop” sound. This first experiment did show variance in the different methods of strain measurement, but did not provide much of an indicator to the acoustic event. This was resolved in a subsequent experiment by suspending the FOS at various heights with additional slack added. Additionally, JB-Weld is injected into the cap of the cell to prevent its own internal current interrupt device (CID) from engaging during the overcharge, in addition to a silicon heating pad wrapped around the cell to force thermal runaway. For the subsequent experiments, the cell and FOS are placed in a metallic drum during destructive testing along with a microphone and a remote video capture device (USB camera). The FOS is suspended above the cell in a few different passes as seen in the experimental setup illustrated in Figs. 6c and 6d. To verify that strain changes in the suspended fiber are decoupled from the changing ambient temperature from the heated cell, a thermocouple is placed on the cell to record temperature data. LabVIEW is used to control the acquisition of the FOS data, voltage, and current measurements and Open Broadcaster Software (OBS) operating within the LabVIEW VI is used to record video from the USB camera. Video acquisition from the OBS is initiated and halted by keyboard strokes within LabVIEW to ensure the individual audio and video data are triggered at the same time. The LabVIEW VI is programmed to charge the cell at a current of 3.2 A and heat the cell with a XX W patch heater until thermal runaway failure is achieved. Destructive overcharging experimentation was also extended to study a 6 S/1 P module of 18650 cells, similar to the module design shown previously in Fig. 1c. For this experiment, the module was also heated during the overcharge process. A USB webcam was used to capture video data and a microphone was used to capture audio data during the destructive test. Experimental data and images from the video recording will be discussed in the results section.

Results and Discussion

Temperature measurement during normal operation.—An expanded presentation of the thermocouple and FOS plotted in Fig. 3 is presented in Fig. 7. The data collected from each respective module
of six cells is plotted in its own sub-plot and each discharge and recharge phase of the experiment are bounded with dashed lines. Comparison of the temperatures measured by the thermocouples and the FOS is shown. The FOS data deviates around 2 °C, with a larger deviation between thermocouple and FOS data. This is expected when considering the different thermal masses of the thermocouple versus the FOS and the different placements on the cell. The thermocouple, whose tolerance is ±2 °C, is placed on the side of the middle of the first cell of each module. The FOS results are represented as an average temperature measured along the length of each cell in the module, and is calculated with post-processing. The raw FOS data along the full length of each cell can be seen in Fig. 3c. The spread among cells is within the tolerance of the FOS and is expected with the varying air flow around the cells in an open-air environment. The temperature variation measured is a good justification for why an FOS is advantageous over single point measurements made, as average measurements along the length of the cell can help eliminate temperature variations. The FOS allows for hot spots to be identified and abnormal operation to be quickly observed anywhere in the multi-cell battery.

Expanded FOS and thermocouple data collected from the 10 S/6 P module during normal operation, shown previously in Fig. 4, is plotted in Fig. 8. As in Fig. 6, there is expected variance in data, again limited to around 5 °C. It should be noted that additional noise was observed on the thermocouples on modules 2 and 5. It is unclear why this occurs and again highlights the advantages of non-conductive FOS diagnostics that are immune to external noise. Similar to the four-module setup, thermocouples were positioned on the center of a cell within each module, and compared with a post-processed FOS temperature average along the length of the cell. Though there is some disagreement, this shows a good correlation between thermocouple data and FOS data, similar to previous experimentation.\textsuperscript{11}

Figure 6. (a) Experimental design reflecting the placement of an FOS in relation to a cell and the expected strain measurements when the fiber is taped or glued to the cell or suspended away from the cell body. (b) This cell is placed in a custom-built 3-D printed case and placed in a (c) container designed for destructive testing. (d) Test is conducted with a FOS suspended in the container along with a microphone and camera to verify and correlate vibrations detected by the fiber to an acoustic signature or visual confirmation of cell failure.
To provide a baseline for abnormal operating conditions, the change in temperature over change in time (dT/dt) was calculated using both the thermocouple and averaged FOS data on each module. Figure 9a shows the dT/dt measurement (orange) for each thermocouple (blue) on the 10 S/6 P battery, while Fig. 9b shows the dT/dt measured (orange) using the averaged FOS data (blue) from each six-cell module. For both Figs. 9a, 9b, the red plot represents a flag that can be sent to a BMS if the rate of temperature change exceeds a preset limit. For normal operation, the trigger level was set at 0.1 °C/s. This value was chosen to ensure no flags were generated.

Figure 7. (a) The temperature data acquired during cycling is plotted as a function of time, with a comparison of Thermocouple and FOS data for each module. (b) Temperature data from thermocouples and FOS data averaged along the corresponding cell.
Figure 8. Measured temperatures from both the FOS and thermocouple during normal operation of the 10 S6P module. The figure is oriented in such a way that the bottom left plot is the first module, and the bottom right plot is the tenth module, which is identical to the electrical connection shown in Fig. 1e.
Figure 9. (a) Thermocouple d\(\Delta T\)/dt during normal operation of the 10S6P module. (b) FOS d\(\Delta T\)/dt during normal operation of the 10S6P module.

Figure 10. (a) Temperature data from both thermocouples and the FOS during abnormal operation. (b) Temperature data from thermocouples and FOS data averaged along the corresponding cell.
Figure 11. (a) Thermocouple dT/dt from the 10S6P battery during abnormal operation. (b) FOS dT/dt from the 10S6P battery during abnormal operation.

Figure 12. (a) Strain data from an FOS located at two distances from the cell indicating the point at which failure occurred within the cell and the accompanying rise in strain that occurs at this moment. (b) This point of failure has three distinct regions attributed to the point when the cap vented, the first ignition sparks are observed, and the final destruction of the cell. (c) This point of destructive failure was captured by the camera included inside the test chamber.
during normal operation, while still generating flags during abnormal operation, shown in later in Fig. 11.

**FOS use during abnormal operating conditions.**—Abnormal or failure conditions within battery operation are preempted by a sudden rise in temperature, or increase in dT/dt. The 10S/6P module was subjected to a 0.5 C discharge, and similar to normal operation, a single thermocouple was attached to each module. To emulate an abnormal event, a Ross relay was connected to Module 6, so that this module could be manually shorted in a controlled manner. This short-circuit should also correspond to a large increase in temperature, which would show a rapid change in dT/dt, independent of temperatures measured from the other nine modules during the 0.5 C discharge. FOS data along each module, in addition to cell voltages and short-circuit current, was previously shown in Fig. 5. The measured temperatures for both the FOS and thermocouples are shown in Fig. 10. The measured data for the FOS data for each cell in addition to the thermocouple data and Fig. 10b shows only averaged FOS data for the cell the thermocouple is on. Exceptionally good correlation of FOS and thermocouple temperatures is observed in modules 1, 3, 5 and 6, with expected deviation shown in the remaining modules. Individual change in cell thermocouple temperatures over time, dT/dt, are shown in Fig. 11a. Figure 11b shows FOS dT/dt, also grouped by module. It should be noted that during the event, a high dT/dt was observed for both the thermocouple and FOS on Module 6. A trigger level of 0.1 °C/s was used. With this trigger level, there is a clear distinction between the other nine modules undergoing a normal discharge, and the module undergoing a short-circuit event. In Figs. 11a, 11b, there are clear dT/dt flags set when module 6 is short circuited and this allows for easy detection of the unexpected event by the host controller allowing it to isolate the battery from the source and load. Though it may not prevent catastrophic failure if the short circuit is occurring local to the module, at least it is detected and action can be taken to prevent further escalation quickly.

**FOS use during failure conditions.**—As described earlier in Fig. 6, a single 18650 cell is outfitted with a patch heater, with the FOS suspended away from the cell at multiple locations. The cell cap is injected with JB Weld to prevent the CID from engaging, wrapped with a silicone heater, and charged at 3.2 A until the cell reaches overcharge conditions and destructively fails. This experiment was set up as shown previously in Fig. 6d. Strain measurements are recorded throughout the test, shown in Fig. 12a. The sharp rise in strain in the data correlates with the time at which failure occurs. At the point of failure, there are three separate increases in strain in the FOS data, which correlate with the cell venting, the first ejection of ignition material, and the point when the cell was engulfed in flames. These three points of interest are shown in Fig. 12b along with a photograph of the thermal runaway in Fig. 12c taken during the experiment by the camera placed inside the destructive testing container.

Further analysis of the audio recordings and the strain detected by a suspended FOS is shown in Figs. 13a and 13b, where the portion of the data in yellow indicates a high strain caused by flames and hot gases passing the FOS after the cell vented. This experiment was set up as shown previously in Fig. 6c. The FOS is divided into three portions placed at different heights and, due to the height offset, the FOS shows a change in strain occurring at different times, which is shown in Fig. 13d. The offset shows that the strain measured by the
FOS is due to the time delay associated with high temperature venting fumes or flames transiting each of these separate portions of the FOS, which can then be correlated to an audible “pop” detected by a microphone inside the container. This audio recording along with the measured strain at each of the FOS locations is shown in Figs. 13b, 13d, with results showing a noticeable change in strain at the same time the audio signature is detected. This can be compared to the thermocouple temperature measurement of the cell, shown in Fig. 13c showing that the change in FOS strain is not caused by temperature changes.

The same overcharge procedure is applied to a 6 S/1 P module of 18650 cells. All six cells vented during this procedure. The module remains are shown in Fig. 14a. Figure 14b shows an image where the FOS is in frame, boxed in red. It should be noted that this image is from a different experiment, but was appended here to show the location of the FOS. Figure 14c shows the value of summed FOS data per sample, which has an upward trend. This is likely due to the increase in ambient temperature, as more energy and heat is added to make the module destructively fail. Figure 14d shows the change in strain over change in time, with the intent of filtering out the gradual change in ambient temperature, and correlating audio events with changes in FOS strain. This experiment shows the FOS data collected during this test correlated to most of the major acoustical events.

**Conclusions**

Thermocouples and thermistors are the traditional method of sensing thermal changes within materials. These devices are subject to external influences that lead to failure and are bulky in applications requiring the use of multiple temperature readings, such as battery modules. Here, an FOS is used to monitor temperature fluctuations within multiple battery modules consisting of multiple cells during normal charging/discharging cycles and abnormal operating conditions. It is shown that multiple fibers attached end-on-end using optical couplers to form a serial fiber can then be connected with a monitoring system with minimal coupler noise and data loss introduced into the thermal data. This end-on-end connection of fiber provides easier installation in larger battery fabrications and replacement of fiber sections if they become damaged compared to a single FOS wound through a battery system. Initial results of four serially connected fiber segments showed a large difference between the cumulative noise added from fiber connectors and the minimum noise requirement for the detection of the end of the fiber. This was successfully expanded to

![Figure 14. (a) Remains of module after failure. (b) Image showing placement of FOS, boxed in red. (c) Comparison of FOS data summed across the length of the fiber per sample versus recorded audio. (d) ds/dt of FOS data which was summed across the length of the fiber per sample. Most of the prominent audio events can be correlated to large ds/dt events.](image-url)
ten serially connected modules. Based off of the level of noise from each connector, we estimate that at least four additional modules, for a total of ten, can be added without interfering with the ability to determine the end of the serially connected fiber. Additionally, it is shown that fiber can detect sudden rise in temperature seen when a cell/module deviates from standard operating conditions, such as short-circuits or failure events.

It was also shown that a FOS may be suspended away from a cell or module and used to detect strain caused by vibrations due to ventilation fumes or other gasses that occur when a cell has sustained a catastrophic or destructive failure. The data collected by the FOS is compared with an audible acoustic signature collected by a microphone and video images captured by a camera. Taken together, a FOS is capable of sensing thermal changes, strain, and changes in the ambient environment when implemented through different means of attachment or suspension within the enclosure containing the batteries.

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