Embedded Fiber-Optic Sensing for Accurate Internal Monitoring of Cell State in Advanced Battery Management Systems

Part 1: Cell Embedding Method and Performance

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Abstract

A key challenge hindering the mass adoption of Lithium-ion and other next-gen chemistries in advanced battery applications such as hybrid/electric vehicles (xEVs) has been management of their functional performance for more effective battery utilization and control over their life. Contemporary battery management systems (BMS) reliant on monitoring external parameters such as voltage and current to ensure safe battery operation with the required performance usually result in overdesign and inefficient use of capacity. More informative embedded sensors are desirable for internal cell state monitoring, which could provide accurate state-of-charge (SOC) and state-of-health (SOH) estimates and early failure indicators. Here we present a promising new embedded sensing option developed by our team for cell monitoring, fiber-optic

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sensors. High-performance large-format pouch cells with embedded fiber-optic sensors were fabricated. The first of this two-part paper focuses on the embedding method details and performance of these cells. The seal integrity, capacity retention, cycle life, compatibility with existing module designs, and mass-volume cost estimates indicate their suitability for xEV and other advanced battery applications. The second part of the paper focuses on the internal strain and temperature signals obtained from these sensors under various conditions and their utility for high-accuracy cell state estimation algorithms.

1. Introduction

Reliable, low-cost, and high-performance energy storage systems can significantly boost the adoption of clean energy technologies such as hybrid/electric vehicles (xEVs) and grid storage. Lithium-ion and other advanced battery chemistries have emerged as promising candidates in this regard. However, their broader acceptance has been challenged by factors such as high costs, battery lifetime, usable range, and the susceptibility to unexpected failure. A better understanding and real-time monitoring of internal cell state with accurate sensors is of critical need for effective control by battery management systems (BMS) [1]-[3].

Batteries are complex systems. Developing means to cost-effectively monitor, predict, and manage important performance measures such as capacity, life, and stability limits during fielded operations remains a key technological challenge [4]. The challenge of battery management stems from the complexity of battery devices and is compounded by the aggressive operational demands and severe cost constraints of practical applications [5]. Charging and discharging of a cell depend on a wide range of processes that include chemical and electrochemical reactions, phase change reactions, electronic and ionic transport through the

various cell components: liquids/gel electrolyte, porous separators, composite electrode materials, etc. All of these phenomena are coupled and influenced by the operating parameters of the device [6]. Even the best theoretical models cannot capture and predict many of the degradation and failure mechanisms resulting from the highly coupled reactions confounded by unpredictable operating and environmental stresses, defects, manufacturing imperfections, and other physical realities [7].

As a result of the high degree of complexity in cell physical and electrochemical phenomena and the lack of real-time information on degradation mechanisms, physical models have been of limited utility for fielded BMS. BMS today typically monitor parameters such as voltage, current, and temperature externally to estimate state-of-charge (SOC), state-of-health (SOH), state-of-power (SOP) and to manage/protect the batteries. None of these provides direct information on the physical and chemical state internal to the cell. Voltage provides a composite measure of changes in potentials, but does not provide critical information on the individual state of either electrode. Furthermore, the potential drop across the cell's variable internal resistance heavily muddles the cell terminal voltage at high operational currents, which can be a major challenge in advanced applications such as xEVs [3]. BMS today only can monitor cell skin temperature, not the actual internal cell temperature that drives degradation and failure. With the xEV and grid storage industry pushing towards higher-density and larger format cells [8], the difference between internal cell and external skin temperatures can be considerable and as high as 20°C, as observed in some numerical and laboratory characterization studies ([9], [10]). SOX (a generic term referring to SOC/SOH/SOP) estimation is in general considerably limited by these relatively weakly informative external parameters that BMS today are limited to monitoring.

Managing individual cells is clearly a challenge, but this is further compounded in fully integrated battery packs, where hundreds or thousands of electrochemical cells are electrically coupled to meet energy and power requirements [11]. Presently, monitoring and control of individual cells is not practical. Series and parallel cell configurations couple the states of groups of cells, and the cost of highly parallelized wiring or sensing is prohibitive. Consequently, the external parameters monitored by BMS today are typically not measured for every cell in a pack, rather they are usually monitored per group of 2 to 10 cells to keep costs low. This further exacerbates SOX estimation. BMS today needs to compensate for this considerable SOX uncertainty while still ensuring safe battery operation with the required range and available power. Consequently, batteries are often conservatively over-engineered and avoid full use of true battery capacity, leaving anywhere from 10-50% buffer capacity to meet operational requirements while minimizing the risk of premature or catastrophic failure. In spite of these conservative designs, many energy storage systems fielded today still suffer from uncertain or inadequate lifetimes. Concerns over life and safety challenge secondary applications, such as vehicle-to-grid dispatch.

More informative embedded sensors are highly desirable, particularly for cell state monitoring, which could provide accurate SOC estimates and early indications of incipient problems, enabling improved state-of-health SOH estimates for BMS [12]. Fiber optic (FO) sensors are lightweight and thin, electrically insulative, immune to electrostatic discharge, electromagnetic interference, and can measure multiple parameters with high sensitivity, such as strain, temperature, pressure, and chemical composition in multiplexed configurations. FO sensors have been demonstrated robustness to various harsh environment conditions [13]. FO sensors of certain materials have also been demonstrated to survive and function in various

acidic conditions, including exposure to hydrogen fluoride (HF), a corrosive acid known to form in leaky Li-ion cells [14]. The most common material used in FO sensors is silica, which is corrosion resistant, can withstand tensile stresses up to 1 GPa for extended periods (at least 5 years) [15], have a dielectric breakdown strength of >470 kV/mm [16], and can survive between -200°C and 800°C [17]. All of these characteristics make them very attractive candidates for embedding as sensors in Li-ion and other batteries. Our team has earlier published on the utility of FO sensors to monitor some interesting Li-ion cell electrochemistry phenomena in externally bonded configurations on the cell skin, such as fast and slow ion diffusion processes [18] and intercalation stage transition points [19].

After going through several developmental iterations, our team has recently successfully fabricated high-performance large-format Lithium-ion pouch cells with embedded FO sensors (referred to as “FO-cells” in this paper). These FO-cells were successfully assembled into commercial xEV modules. The signals from these FO-cells have shown excellent potential for high-accuracy SOX estimation under a broad range of xEV operational use cases and conditions. This paper presents the details of these interesting developments. It is organized into two parts. This first part of the paper covers the details of the method for embedding the FO sensors into pouch cells. The performance results of these FO-cells in terms of seal integrity, capacity retention under stress testing, cycle life projections, and reasonable mass-volume cost points are presented that indicate the strong potential of FO-cells to meet the high standards for xEV-grade cells. Lastly, the assembly of these FO-cells into commercial xEV modules and cost projections are discussed, showing the practicability of the approach for fielded battery packs.

2. FO Seal Method

For successful long calendar life applications using Li-ion pouch cell designs, the ability of the cell seal to maintain hermeticity under a variety of operating conditions must be addressed [20]. This is particularly critical for xEV and other advanced energy storage applications. Thus, a key initial step towards building pouch cells with embedded FO cables was the development of a suitable sealing method to ensure that the cell did not develop leaks near the FO entry point into the cell that might allow moisture ingress into the cell or electrolyte egress out of the cell. We developed a method wherein a protective heat seal film was wrapped around the FO cable between the pouch skin surfaces. This is the same heat seal film material used to seal the region around the tabs of the pouch cell. This method tended to ensure that the gap around the FO cable was filled with heat seal material after the pouch press seal step and prevented voids (Figure 1).

Figure 1: (a) SEM cross-section images of sealed pouch with optical fiber (without a layer of heat seal film) showing voids that may lead to cell leaks; (b) SEM cross-section images of sealed pouch with optical fiber surrounded by a layer of heat seal film: the pouch is well sealed in this case and does not show voids.

Studies to evaluate the ingress of moisture and egress of the electrolyte out of the cell were done by assessing HF generation in Li-ion pouches over accelerated conditions. The ingress of moisture into the Li-ion cell results in hydrolysis of LiPF_6 , the typical electrolyte salt, to generate HF, which attacks most Li-ion cell cathode materials such as LiMn_2O_4 and leads to cell degradation. The decomposition reaction leading to HF generation is [21]:

The egress of electrolyte, on the other hand, reduces the amount of electrolyte in the cell and causes deterioration of cell performance. The seal integrity tests were carried out by placing a known amount of electrolyte in a pouch sealed with the fiber-optic cable, but no electrode package. At high temperatures, the gaseous oxidation products from the electrolyte create cell internal pressures that can particularly challenge the integrity of the pouch seals. Thus, as a seal integrity qualification check, the cells are typically subject to an “accelerated” aging test at a high temperature under high humidity conditions [20]. Accordingly, the pouch was then exposed to accelerated aging at 60°C and high (95%) relative humidity for known periods of time to carry out accelerated tests.

Electrolyte-filled pouches fabricated through this method with 125- and 250- μm diameter FO cables were subject to HF titration tests to examine for seal integrity of the pouches under accelerated aging conditions. The electrolyte volume in these pouches was comparable to that in 1 Ah cells towards embedding fiber-optic cables in small-format pouch cells as an initial step. 18 such pouches were fabricated and tested: 6 each without a FO cable, 6 each sealed with a 125- μm FO cable, and 6 each sealed with a 250- μm FO cable. Soon after the start of the test, after 3 days, and at end of each week over a month, one of each of the three types of pouches were cut

Figure 2: HF titration tests done under accelerated aging conditions (to examine seal integrity of electrolyte-filled pouches with FO cables. The seal integrity of 125-micron diameter FO cables is comparable to that of pouches without FO cable.

open and the amount of HF was measured in the electrolyte. The results from these tests are shown in Figure 2.

The test results show that the moisture ingress rates (based on the amount of HF generated) for the pouches sealed with 125-micron diameter FO cable (452 ppm after 1 month) is very comparable to that for pouches sealed without FO cables (438 ppm after 1 month). This proves the effectiveness of the heat-sealing film to avoid voids for the 125-micron diameter FO cable. For the thicker FO cable (250-micron diameter), the HF amount is slightly higher initially, but is also comparable after 1 month (481 ppm). In both cases, they were lower than the maximum tolerable limit of 500 ppm/Ah/month for this test to be compatible with commercial LG Chem cell standards. Subsequently, this sealing procedure was successfully extended to large-format pouches towards integrating fiber-optic cables into large-format, xEV-grade cells, as shown in Figure 3.

(a)

(b)

Figure 3: (a) Picture of large-format pouch sealed successfully with FO cable; (b) Zoomed-in view of the pouch region near the FO cable.

(a)

(b)

Figure 4: (a) Functional configuration of FO cable with fiber Bragg grating sensors in large-format xEV pouch cells (b) Photograph of FBG sensor pair attached to the large-format cell electrode before the cell was sealed and activated.

3. FO-Cell Fabrication

Once the pouch sealing process was perfected through iterative attempts, the next step was to build functional Lithium-ion cells with embedded FO cables. After exploring various approaches for embedding the FO cable within the electrode stack, the approach shown in Figure 4 was devised. As shown there, in this particular configuration, a portion of a fiber optic cable having at least one fiber optic sensor is positioned on a layer of the bi-cell battery structure comprising multiple layers. The layers are folded into LG Chem's proprietary "stack-and-fold" bi-cell structure [22] so that an internal portion of the FO cable is folded within or on the bi-cell stack. The folded bi-cell structure is placed between cell casing layers and the cell casing layers are sealed so that an external portion of the FO cable extends from the cell casing layers. In the illustrated initial configuration, the entry point is positioned approximately halfway between the anode and cathode tabs. This was in anticipation of this being a suitably informative position for sensing centrally inside the cell.

In embedding the FO cable, it should be noted that significant bends in the FO cable in the region of the sealing edges might cause damage to the cable. This is particularly so at internal cell pressures typical in battery fabrication and activation. A significant bend in the FO cable increases the potential for it to break during the cell activation process. Damage to the FO cables may be avoided by orienting the FO cable so that bending is reduced or minimized at or near the sealing edge. Within the interior of the battery, the stress on the cable during fabrication can be less impactful such that the FO cable may even be arranged in a gentle loop within the battery cell without a high potential for breakage due to the significant bending. The distance between the level of the sealing point and the embedding level is also kept marginal to reduce the stress on the embedded FO cable.

Excessive bending of the FO cable also increases the risk of a broken fiber during the sealing process. Conversely, an unbent or slightly bent fiber is more robust and more stable during the sealing process. Since the LG Chem large-format cells used here were “double-cup” pouches, the FO cable was embedded in the middle of the electrode stack to avoid curvature when exiting the pouch. A photograph of one of the cells is shown in Figure 5.

Figure 5: Photograph of functional, high-performance large-format xEV pouch cell with FBG sensors. The FO cable exiting the cell is highlighted with a dashed oval.

As cells undergo charging and discharging, the anode experiences volume changes as Lithium ions shuttle in and out of it respectively. This manifests itself as electrode strain. In addition, the electrode temperature also changes due to thermic electrochemical reactions and

resistive heating. Accordingly, it was anticipated that bonding a FO cable to the electrode reliably could enable accurate monitoring of these two critical cell state parameters.

To achieve this, the FO cable is placed on and bonded to the anode electrode layer using styrene-butadiene-rubber, a binder suitable for the Lithium-ion cell environment. This is the same binder holding the anode particles together on the current collector and lasts over the cell life. Thus, it can allow the FO cable to reliably monitor electrode state. After the bonding, the bi-cell layers are folded and formed into a bi-cell stack. Since the tabs are much thicker than the FO cable for these particular 15 Ah nominal capacity large-format cells, to avoid sealing complications, the FO cable was embedded from the side opposite to that of the tabs, as shown in Figure 5.

4. FO Sensor Used: Fiber Bragg Grating

The FO cable within the cell shown there includes two elements of a particular class of FO sensors, fiber Bragg grating (FBG) sensors [23] that are sensitive to strain and temperature. FBG optical sensors can be formed, for example, by a periodic modulation of the refractive index along a finite length (typically a few mm) of the core of the FO cable. This pattern reflects a wavelength, called the Bragg wavelength that is determined by the periodicity of the refractive index profile of the sensor. In practice, the sensor typically reflects a narrow band of wavelengths centered at the Bragg wavelength. The Bragg wavelength at a characteristic or base value of the external stimulus is denoted λ and light having wavelength λ (and a narrow band of wavelengths near λ) are reflected when the sensor is in the base condition. When the sensor is subjected to an external stimulus, such as temperature, strain, or other such stimulus, the stimulus changes the periodicity of the grating and the index of refraction of the FBG, and thereby alters

the reflected wavelength to a wavelength, λ_s , different from the base wavelength, λ . The resulting wavelength shift, $\Delta\lambda/\lambda = (\lambda - \lambda_s)/\lambda$ is a measure of the stimulus.

Wavelength-encoded FO sensors such as FBGs allow for incorporating multiple sensing elements on a single FO cable. Through multiplexing, it is possible for one FO cable to carry the output light of multiple sensors. The sensors can be individually interrogated through time domain and/or wavelength domain multiplexing/demultiplexing. Thus, the FBG responds to both strain and temperature changes. As mentioned earlier, the strain is caused due to electrode volume change over charge-discharge cycles, as well as thermal expansion or contraction from electrode temperature changes. As the Bragg wavelength, reflected wavelength is sensitive to applied strain and temperature changes, a method similar to the reference sensor method as described in Rao et al. [23] is used to compensate for temperature impacts.

One of the two FBG sensors was enclosed in a special tubing to make it selectively sensitive to thermal strain alone. The measured wavelength shift of the “reference” FBG sensor in the tubing is then subtracted from the total wavelength shift of the adjacent FBG sensor sensitive to strain so that temperature variations are compensated. Further details on the compensation scheme and the use of the FBG signals for SOX estimation are explained in the second part of this two-part paper.

The FBG sensors can monitor strain and temperature with linearly proportional wavelength shifts until the linear elastic material limits of the silica optical fiber or its coating, especially when the FBG sensors are inscribed by a method that does not compromise fiber integrity, such as the draw tower grating approach reported in [24]. For silica optical fibers with one of the common coatings, acrylate, this strain limit is between 2.5% and 4% [25].

Lithium-ion cells have been reported to expand and contract by 3-4% in volume over full depth-of-discharge cycles [26], [27]. By considering the anode as only trigger for the volume change, and accounting for the 35% volume fraction of the anode materials in the LG Chem cell used here, anode volume expansion of up to 1.4% is expected over a full charge-discharge cycle. This should be well within the 2.5-4% linear elastic strain limit of the FBG sensors. Thus, the FBG strain sensors can be expected to accommodate the maximum anode strain at 100% SOC.

As mentioned earlier, with the right coatings, silica fibers can function between -200°C and 800°C [17]. These temperature limits are well beyond the operational and safety boundaries of Lithium-ion cells. In fact, it also opens up the possibility of using these FBG sensors to monitor safety-critical events such as thermal runaway, a process where elevated temperatures trigger heat-generating exothermic reactions, raising the temperature further and potentially triggering more deleterious side reactions. The onset temperature for thermal runaways tends to occur in the 100°C to 150°C range [10].

Thus, FBG sensors can monitor electrode strain and temperature over all operational and safety-critical scenarios of the Lithium-ion cell. After successfully fabricating FO-cells as described above, capacity retention stress tests were conducted to assess their performance. The results from those are described next.

5. FO-Cell Life

As mentioned earlier, long cell service life is a critical parameter of interest for xEVs and other advanced battery applications. To evaluate whether the method to embed FO cables into Li-ion pouch cells may cause early failure and last for a comparable number of charge-discharge cycles in comparison to regular cells without FO cables, stress tests were done with a large-format FO-cell and a comparable un-instrumented large-format cell of same construction and

chemistry. An aggressive static duty cycle (at least double the cell manufacturer LG Chem's recommended maximum C-rate) was repeatedly applied. The test was done at 25°C over 140 static cycles. The first 100 cycles were done at 2 times the standard cycle C-rates for both charge and discharge (the standard rates being 0.5C charge, 1C or 15 A discharge) while the last 40 cycles were done at 4 times the standard charge and 2 times the standard discharge to increase the stress parameters. The discharge capacity change over the cycles is shown in Figure 6.

As seen in Figure 6, the degradation curves are very similar for the FO- and un-instrumented cells. Based on the linear degradation pattern over the first 100 cycles, the Coulombic efficiency and life (for 20% capacity drop) were estimated, which are listed in Table 1. The slight disparity in cycle life between the two is well within the typical spread (200-300 cycles) observed in such stress tests using test cells from pilot production lines. Importantly, the test highlights the potential for such FO-embedded cells to last well over 1000 cycles in deep-discharge stress conditions, a key target for electric vehicle cells established by the U.S. Advanced Battery Consortium [24]. Thus, this initial test showed no major adverse effects on cell life from the embedded fiber. Having successfully built large-format FO-cells and confirmed their performance in terms of life and cell seal integrity, their assembly into xEV modules and impact of xEV battery manufacturing costs was explored, as described in the next section.

6. Module Assembly and System Cost Estimates

As shown in Figure 7, the large-format FO-cells fabricated earlier were assembled into a 4-cell module with an actively cooled thermal management system. Commercial LG Chem xEV module parts were used for this FO-cell module. Minor machining was done on the cell retaining frames to accommodate the exit of the FO cable. Apart from that, some minor additional fixturing is anticipated in the production line to support the FO cables during module assembly.

However, these points are not anticipated to drive any major module manufacturing/assembly line changes for FO-embedded cells. They will also not influence the cost of assembly for mass-volume production being relatively modest one-time setup costs.

Figure 6: Discharge capacity as a function of cycle life for large-format FO- and un-instrumented large-format pouch cells of xEV-grade chemistry.

	Cell cycle life	Coulombic efficiency
<i>Base cell without FO</i>	1373 cycles	0.999837
<i>FO-cell</i>	1149 cycles	0.999805

Table 1: Estimated life (20% capacity drop metric, listed for both the peak capacity and 15 Ah as the reference capacity measure for the 20% drop) and Coulombic efficiency for base vs. FO-cell in stress test at 2x the standard cycle parameters.

Mass-volume cost points were also estimated for the other system elements needed to achieve our vision of FO embedded sensing-enabled BMS. A key aspect studied in this regard was the cost of embedding the FO sensors in the cells. This will involve a one-time cell assembly line change prior to the folding process for LG Chem’s “stack-and-fold” design [22]. The fiber embedding on the electrode can be done using an automated fiber pick-and-place machine,

followed by the application of binder using a dispenser to bond the FO cable down. For a commercial xEV cell manufacturing plant producing millions of cells a year to meet typical xEV annual volumes in the range of hundred thousands to a few million, the effect of this one-time line change amortized over a few years will be minimal on the per cell cost. Even after accounting for the additional minor operations and maintenance cost for the added line equipment, the additional cell cost for embedding the FO sensor is expected to be within the 1-10 ¢ range.

The cost of the FBG sensors themselves can also drop considerably for such mass volumes, particularly when the sensors are inscribed on the fiber during the drawing process itself [24]. In such scenarios, the cost of the FO cable with multiplexed FBG sensors is projected to drop to <\$5 per meter for mass volume production, based on discussions with commercial vendors providing such draw tower grating fibers.

The cost, size, and weight of the optical readout to interpret the wavelength-encoded FBG sensors has traditionally been prohibitively expensive for fielded deployments of distributed FO sensing systems. In that regard, we have developed low-cost and compact wavelength detectors suitable for demodulation of optical sensors that are based on a wavelength shift, such as FBGs [29]. The combination of a detector coating with a dispersive filter and a position-sensitive photo detector (PSD) can resolve wavelength shifts as small as 50fm at 100Hz or higher ([30], [31]).

More recently, we have extended this technology to monitor a few 100s of multiplexed sensors from a single compact unit with similar resolution capability using a combination of time domain and wavelength division multiplexing [32]. As a likely module-level configuration for reading out individual FO signals from each cell using the readout, the fibers from each module

can be consolidated into a single fiber through a compact, low-cost module-level wavelength-domain multiplexer. The fibers from each module can in turn be monitored through time-domain multiplexing by a single compact central optical readout collocated with the electronic BMS controller that would run the SOX algorithms on the FO-cell signals. We will be publishing further details of this multiplexed version of the readout in the future.

Importantly, this multiplexed readout can be implemented on a photonic integrated circuit (PIC), with the chip size anticipated to be between 30-60 mm², depending on the specific battery configuration. In particular for a representative PHEV pack with 192 cells needing a 384-channel readout (to monitor strain and temperature within each cell), the chip size is estimated to be 45 mm². Based on projections by the Europic project [33], PIC costs can drop to approximately U.S. \$3.2/mm². Thus, the mass-volume cost of a PIC version of our readout can reduce to a few hundreds of U.S. dollars, thus making them attractive for fielded deployments.

The cost of the FO splicing connections can also drop to reasonable levels by adopting suitable mass volume manufacturing methods [34]. The results from other active efforts to achieve cheap automated assembly for connecting several optical connectors on a single FO bus in the communications industry can also be leveraged in this regard [35]. Overall, depending on the specifics and size of the xEV battery pack in question, the system cost for the proposed embedded FO-sensing based BMS is projected to cost in the range of U.S. \$100-500. This is comparable to and competitive with the present-day cost of the electrical sensing in BMS [36]. Importantly, a key advantage of multiplexing with FO sensors is that the cost of sensing does not scale up linearly with the number of cells in the pack, as is the case with electrical sensing today.

Figure 7: 4-cell module assembled with large-format FO-embedded cells: (a) Photograph of module details and cells in frames; (b) Schematic of cells and fins assembled in module.

7. Conclusions

In this work, we presented a promising new embedded sensing option for internal cell monitoring, fiber-optic sensors. High-performance, xEV-grade large-format Lithium-ion pouch cells with embedded fiber-optic (FO) sensors attached to the electrode were fabricated. The seal integrity, capacity retention, and projected cycle life are all comparable to contemporary xEV cells without embedded sensors. The cells can be integrated into existing xEV module designs. The mass-volume cost estimates for the FO sensing system are in the range of a few hundreds of U.S. dollars and are thus comparable with that of electrical sensing for xEV BMS today. Thus,

this work clearly establishes the possibility of embedding FO sensors into large-format cells as a low-cost, field-deployable option for direct internal cell state monitoring for BMS in xEVs and other advanced battery applications. This represents a significant advance that has the potential to resolve some of the major pain points in battery management and operational safety monitoring resulting from the present inability to understand and monitor the complex internal cell electrochemical phenomena. The second part of the paper focuses on the internal strain and temperature signals obtained from these fiber-optic sensors. The signals under various xEV operational conditions and their value for high-accuracy SOC and SOH estimation algorithms will be explored.

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References

- [1] T. Turrentine, Plug-in Hybrid Electric Vehicle Research Roadmap. UC Davis Plug-In Hybrid Electric Vehicle Research Center, June 2011.
- [2] K. A. Smith, C.-Y. Wang, Power and thermal characterization of a lithium-ion battery pack for hybrid-electric vehicles. *J. Power Sources*, 160, 662-673, 2006.
- [3] N. A. Chaturvedi, R. Klein, J. Christensen, J. Ahmed, A. Kojic, Algorithms for advanced battery-management systems. *Control Systems, IEEE*, 30(3), 49-68, 2010.
- [4] Advanced Research Projects Agency-Energy (ARPA-E) Request for Information DE-FOA-0000673 on “Advanced Technologies for Robust Control of Energy Storage,” U.S. Department of Energy, Feb. 2012
- [5] D. Linden, T. Reddy, *Handbook of Batteries*, 3rd Edition, McGraw-Hill, 2001.
- [6] J. Newman, K.E. Thomas-Alyea, *Electrochemical Systems*, 3rd Edition, Wiley-Interscience, 2004.
- [7] V. Ramadesigan, P. Northro, De Sumitava et al., “Modeling and Simulation of Lithium-Ion Batteries from a Systems Engineering Perspective,” *J. of Electrochemical Soc.*, v. 159(3), 2012
- [8] M. Anderman, “Assessing the Future of Hybrid and Electric Vehicles: The 2014 xEV Industry Insider Report,” *Advanced Automotive Batteries*, 2013.
- [9] M. Fleckenstein, O. Bohlen, M.A. Roscher, and B. Bäker, “Current density and state of charge inhomogeneities in Li-ion battery cells with LiFePO_4 as cathode material due to temperature gradients,” *Journal of Power Sources*, 196(10), 4769-4778, 2011.

- [10] T. M. Bandhauer, S. Garimella and T. F. Fuller, "A critical review of thermal issues in lithium-ion batteries," *Journal of the Electrochemical Society*, 158(3), R1-R25, 2011.
- [11] S. M. Lukic, J. Cao, et al., "Energy storage systems for automotive applications," *IEEE Transactions on Industrial Electronics*, vol. 55(6), 2008.
- [12] Reimers, Jan N., and J. R. Dahn. "Electrochemical and In Situ X- Ray Diffraction Studies of Lithium Intercalation in Li_xCoO_2 ." *Journal of The Electrochemical Society* 139, no. 8 (1992): 2091-2097.
- [13] E. Udd, W. L. Shulz, J. M. Seim, M. Morrell, T. L. Weaver, J. Bush, G. Adamovsky, "Fiber optic distributed sensing systems for harsh aerospace environments," *Proc. SPIE*(3674-136), 1999.
- [14] S. Corbellini, M. Parvis, S. Grassini, L. Benussi, S. Bianco, S. Colafranceschi, and D. Piccolo, "Modified POF sensor for gaseous hydrogen fluoride monitoring in the presence of ionizing radiations," *Instrumentation and Measurement, IEEE Transactions on*, 61(5), 1201-1208, 2012.
- [15] Nellen, P.M., Mauron, P., Frank, A., Sennhauser, U., Bohnert, K., Pequignot, P., Bodor, P. and Brändle, H., "Reliability of fiber Bragg grating based sensors for downhole applications," *Sensors and Actuators A: Physical*, 103(3), pp.364-376, 2003.
- [16] Berger, L.I., "Dielectric strength of insulating materials," *Carbon*, 1, p.2, 2006.
- [17] H. N. Li, D. S Li, G. B. Song, "Recent applications of fiber optic sensors to health monitoring in civil engineering," *Engg. Struct.* (26), 2004.
- [18] L. W. Sommer, P. Kiesel, A. Ganguli, A. Lochbaum, B. Saha, J. Schwartz, C.-J. Bae, M. Alamgir, and A. Raghavan, "Fast and slow ion diffusion processes in lithium ion pouch

- cells during cycling observed with fiber optic strain sensors,” *Journal of Power Sources*, 296, 46-52, 2015.
- [19] L.W. Sommer, A. Raghavan, P. Kiesel, B. Saha, J. Schwartz, A. Lochbaum, A. Ganguli, C.-J. Bae, and M. Alamgir, “Monitoring of Intercalation Stages in Lithium-Ion Cells over Charge-Discharge Cycles with Fiber Optic Sensors,” *Journal of The Electrochemical Society*, 162(14), A2664-A2669, 2015.
- [20] M.A. Manzo, J.C. Brewer, R.V. Bugga, E.C. Darcy, J.A. Jeevarajan, B.I. McKissock, and P.C. Schmitz, “NASA Aerospace Flight Battery Program: Generic Safety, Handling and Qualification Guidelines for Lithium-Ion (Li-Ion) Batteries; Availability of Source Materials for Lithium-Ion (Li-Ion) Batteries; Maintaining Technical Communications Related to Aerospace Batteries,” *NASA Aerospace Battery Workshop*. Vol. 2, Part 1, 2010.
- [21] A.N. Jansen, K. Amine, and G. L. Henriksen, *Low-cost flexible packaging for high-power Li-Ion HEV batteries* (No. ANL-04/09). Argonne National Lab., Argonne, IL, USA, 2004.
- [22] K. W. Kang, H. M. Lee, B. Choi, E. Goh, S.-M. Hwang, O. Y. Hyun, C. B. Ahn, H.-C. Jung, and W. Lee, “Stack and folding-typed electrode assembly and method for preparation of the same,” U.S. Patent 8,709,642, U.S. Patent and Trademark Office, Washington, DC, 2014.
- [23] Y.-J. Rao, “In-fibre Bragg grating sensors,” *Meas. Sci. Technology*, Bd. 8, pp. 355-375, 1997
- [24] M. W. Rothhardt, C. Chojetzki, and H. R. Mueller, “High-mechanical-strength single-pulse draw tower gratings,” *Photonics North* (pp. 127-135), International Society for Optics and Photonics, November 2004.

- [25] Antunes P., Domingues F., Granada M., and André P., “Mechanical properties of optical fibers,” INTECH Open Access Publisher, 2012.
- [26] N. Zhang, H. Tang, “Dissecting anode swelling in commercial lithium-ion batteries,” *Journal of Power Sources*, Bd. 218, pp. 52-55, 2012.
- [27] Siegel, J. B., Lin, X., Stefanopoulou, A. G., Hussey, D. S., Jacobson, D. L., & Gorsich, D., “Neutron imaging of lithium concentration in LFP pouch cell battery,” *Journal of the Electrochemical Society*, 158(5), A523-A529, 2011.
- [28] *Goals for Advanced Batteries for EVs - CY 2020 Commercialization*, U.S. Advanced Battery Consortium Publication, 2015.
- [29] P. Kiesel, O. Schmidt, and N. Johnson, “Wavelength monitors for optical sensing applications,” *Photonics Spectra*, v. 41(3), pp. 62-70, 2007.
- [30] K. Bellmann, P. Kiesel, and Johnson, N., “Compact and fast read-out for wavelength-encoded biosensors,” *Proceedings of the SPIE*, v. 7593-32, 2010.
- [31] A. Schuh, A. Hegyi, A. Raghavan, A. Lochbaum, and P. Kiesel, “High-resolution, high-frequency wavelength shift detection of optical signals with low-cost, compact readouts,” *SPIE Sensing Technology+ Applications*, pp. 94800B-94800B, International Society for Optics and Photonics, 2015.
- [32] A. Hegyi, P. Kiesel, A. Schuh, K. Arakaki, A. Raghavan, “A short demonstration video of PARC’s high-resolution, multiplexed fiber-optic sensing readout,” SENSOR project overview webpage: online at www.parc.com/sensor, Palo Alto Research Center, 2015.
- EUROPIC (European Manufacturing Platform For Photonic Integrated Circuits) project
- [33] final report, online at http://cordis.europa.eu/result/rcn/55864_en.html, 2013.

- [34] E. Palen, "Surface mount optical interconnects," *Integrated Optoelectronic Devices*, pp. 68990B-68990B, International Society for Optics and Photonics, 2008.
- [35] P. Bratt, "Fiber optic wavelength division multiplexing," *Empfasis*, U.S. Electronics Manufacturing Productivity Facility (EMPF), November 2010.
- [36] R. Ratz, "BMS system benchmark and standardization," *Proc. ARPA-E Advanced Management and Protection of Energy-Storage Devices (AMPED) Program Review Meeting*, Chicago, IL, March 2015.