Er-Doped LiNi$_{0.5}$Mn$_{1.5}$O$_4$ Cathode Material with Enhanced Cycling Stability for Lithium-Ion Batteries

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Abstract: The Er-doped LiNi$_{0.5}$Mn$_{1.5}$O$_4$ (LiNi$_{0.495}$Mn$_{1.495}$Er$_{0.01}$O$_4$) sample was successfully prepared by citric acid-assisted sol-gel method with erbium oxide as an erbium source for the first time. Compared with the undoped sample, the Er-doped LiNi$_{0.5}$Mn$_{1.5}$O$_4$ sample maintained the basic spinel structure, suggesting that the substitution of Er$^{3+}$ ions for partial nickel and manganese ions did not change the intrinsic structure of LiNi$_{0.5}$Mn$_{1.5}$O$_4$. Moreover, the Er-doped LiNi$_{0.5}$Mn$_{1.5}$O$_4$ sample showed better size distribution and regular octahedral morphology. Electrochemical measurements indicated that the Er-doping could have a positive impact on the electrochemical properties. When cycled at 0.5 C, the Er-doped LiNi$_{0.5}$Mn$_{1.5}$O$_4$ sample exhibited an initial discharge capacity of 120.6 mAh·g$^{-1}$, and the capacity retention of this sample reached up to 92.9% after 100 cycles. As the charge/discharge rate restored from 2.0 C to 0.2 C, the discharge capacity of this sample still exhibited 123.7 mAh·g$^{-1}$ with excellent recovery rate. Since the bonding energy of Er-O (615 kJ·mol$^{-1}$) was higher than that of Mn-O (402 kJ·mol$^{-1}$) and Ni-O (392 kJ·mol$^{-1}$), these outstanding performance could be attributed to the increased structure stability as well as the reduced aggregation behavior and small charge transfer resistance of the Er-doped LiNi$_{0.5}$Mn$_{1.5}$O$_4$.

Keywords: Lithium-ion battery; LiNi$_{0.5}$Mn$_{1.5}$O$_4$; Er-doping; citric acid-assisted sol-gel method; cycling stability

1. Introduction

Lithium-ion batteries are widely believed to be the most promising power sources for next-generation electrical equipment. As an important component, cathode materials have a large impact on the electrochemical properties of lithium-ion batteries [1,2]. Up to now, researchers have developed several cathode materials, such as LiCoO$_2$, LiFePO$_4$, LiMn$_2$O$_4$, and LiNi$_x$Co$_y$M$_z$O$_2$ (M = Mn, Al), etc.

Among these commercial materials, LiMn$_2$O$_4$ has broad development prospects because of the abundant manganese resource and environmental protection performance. However, this material presents poor cycling stability, especially at high temperature. For the derivatives of LiMn$_2$O$_4$, transition metal doped LiM$_x$Mn$_{2-x}$O$_4$ (M = Cu [3], Ni [4], Fe [5], Co [6], Cr [7], etc.) cathode materials can exhibit a high voltage plateau at around 5.0 V, which creates a good condition for increasing the energy density and power density. Among them, LiNi$_{0.5}$Mn$_{1.5}$O$_4$ has been recognized as the ideal high-voltage material due to the abundant nickel and manganese resources, eco-friendliness, low-cost, etc. [8–10]. As a result, LiNi$_{0.5}$Mn$_{1.5}$O$_4$ has attracted much attention from academics and enterprises.
According to the existing literatures [11,12], the LiNi$_{0.5}$Mn$_{1.5}$O$_4$ structure (disordered or ordered structure) depends on the ordering of nickel and manganese ions. Compared with the ordered sample, the disordered sample can show better electrochemical performance because of excellent electronic conductivity and low activation energy [13,14]. And the actual discharge capacity of this material can achieve about 130 mAh g$^{-1}$. Therefore, LiNi$_{0.5}$Mn$_{1.5}$O$_4$ has great prospect in cathode materials for high-performance lithium-ion batteries. However, the commercial application of LiNi$_{0.5}$Mn$_{1.5}$O$_4$ is restricted by some factors, such as the chemical dissolution of Mn, existence of Li$_x$Ni$_{1−x}$O impurities, oxidative decomposition of electrolyte working at high voltage and so on [15−17]. According to research results [18,19], doping technique can play an active role in modifying the LiNi$_{0.5}$Mn$_{1.5}$O$_4$. Liu et al. [20] have prepared the Er-doped LiMn$_2$O$_4$ sample by the rheological phase reaction method. The Er-doped LiMn$_2$O$_4$ can display good cycling stability, indicating that small amounts of Er$^{3+}$ ions can promote the improvement of electrochemical properties. Moreover, the Er-doping also demonstrates a positive role in improving the cycling stability of other cathode materials such as LiFePO$_4$ and LiV$_3$O$_8$ [21,22]. Therefore, it is interesting to speculate that the substitution of Er$^{3+}$ ions for partial nickel and manganese ions may show a positive effect on the electrochemical performance of LiNi$_{0.5}$Mn$_{1.5}$O$_4$.

In this work, the Er-doped LiNi$_{0.5}$Mn$_{1.5}$O$_4$ was successfully prepared by the citric acid-assisted sol-gel method with erbium oxide as the erbium source for the first time. The substitution of Er$^{3+}$ ions for partial nickel and manganese ions did not change the intrinsic structure of LiNi$_{0.5}$Mn$_{1.5}$O$_4$. Moreover, the Er-doped LiNi$_{0.5}$Mn$_{1.5}$O$_4$ showed better size distribution and regular octahedral morphology. The effect of doping with Er$^{3+}$ ions on the electrochemical performance of LiNi$_{0.5}$Mn$_{1.5}$O$_4$ was studied in detail.

2. Experimental

The Er-doped LiNi$_{0.5}$Mn$_{1.5}$O$_4$ (LiNi$_{0.495}$Mn$_{1.495}$Er$_{0.01}$O$_4$) sample was successfully prepared by citric acid-assisted sol-gel method. Firstly, a certain amount of erbium oxide was suspended in concentrated nitric acid and continuously stirred for 30 mins. And then, the erbium oxide turbid liquid was refluxed at 80 °C until a clear solution was obtained. The pink solution was shifted in a small beaker and evaporated to remove excess nitric acid. Subsequently, stoichiometric amounts of manganese acetate, nickel acetate, and erbium nitrate were dissolved in deionized water. The molar ratio of Li:Ni:Mn:Er:O was 1:0.495:1.495:0.01:4. The mixed solution of citric acid and lithium hydroxide was prepared and added to the former solution under stirring. Next, adding ammonia water manipulated the pH of the obtained solution to about 7.5. The achieved solution was evaporated at 80 °C to get a wet greenish gel. After being dried at 110 °C for 24 h in oven, the greenish gel was sintered at 450 °C for 4 h in air. Subsequently, the decomposed gel precursor was ground in mortar and sintered at 800 °C for 18 h in air to get the darkish product. The undoped LiNi$_{0.5}$Mn$_{1.5}$O$_4$ sample was prepared by the same citric acid-assisted sol-gel technology.

In order to confirm the crystal structure, X-ray diffraction (XRD, Bruker DX-1000, Cu Kα radiation, Bruker Corporation, Karlsruhe, Germany) was carried out. The surface morphology of the LiNi$_{0.5}$Mn$_{1.5}$O$_4$ and Er-doped LiNi$_{0.5}$Mn$_{1.5}$O$_4$ samples was identified by scanning electron microscopy (SEM, Japanese Electronics Co., Ltd., Tokyo, Japan). For electrochemical evaluation, the working electrode was tested by using CR2025 coin-type cells. The electrode mixture was pasted on the aluminum foil and dried at 100 °C for 30 min, and then compressed to obtain round positive plates. Lithium foil and polypropylene membrane were used as anode material and diaphragm, respectively. 1 M LiPF$_6$ in a mixture (EMC:DMC:EC = 1:1:1) was used as the electrolyte. Electrochemical measurements were carried out by using LAND CT2001A (Wuhan LAND Electronics Co., Ltd., Wuhan, China). Electrochemical impedance spectra (EIS) and cyclic voltammogram (CV) were studied by CS-350 electrochemical workstation (Wuhan Corrtest Instruments Corp., Ltd., Wuhan, China).
3. Results and Discussion

Figure 1 shows the XRD patterns of the LiNi$_{0.5}$Mn$_{1.5}$O$_4$ and Er-doped LiNi$_{0.5}$Mn$_{1.5}$O$_4$ samples. The characteristic diffraction peaks of the Er-doped LiNi$_{0.5}$Mn$_{1.5}$O$_4$ sample are indexed to LiNi$_{0.5}$Mn$_{1.5}$O$_4$ (JCPDS No. 80-2162) [23]. This indicates that the substitution of Er$^{3+}$ ions for partial nickel and manganese ions has very little effect on the intrinsic structure [24–27]. Notably, these results can be associated with the fact that the radius of Er$^{3+}$ ions (1.04 Å) [20] is bigger than that of Mn$^{4+}$ ions (0.53 Å) [25,26] and Ni ions (0.69 Å) [9]. According to the research results [18,27], if the dopant ions are located on the tetrahedral (8a) sites, the intensity of (220) peak, which arises only from the diffraction of the tetrahedral sites, must increase, even if the doping concentration is very low. From the Figure 1, it can be noted that the (220) peak does not appear in the XRD pattern of Er-doped LiNi$_{0.5}$Mn$_{1.5}$O$_4$ sample. This indicates that the tetrahedral sites (8a) are occupied by Li$^+$ ions, the Er$^{3+}$ ions only occupy the octahedral (16d) sites to substitute nickel and manganese ions. Furthermore, the diffraction intensities of the Er-doped LiNi$_{0.5}$Mn$_{1.5}$O$_4$ are stronger, which suggests that the substitution of Er$^{3+}$ ions for partial nickel and manganese ions can enhance the crystallinity of LiNi$_{0.5}$Mn$_{1.5}$O$_4$.

![XRD patterns of the LiNi$_{0.5}$Mn$_{1.5}$O$_4$ and Er-doped LiNi$_{0.5}$Mn$_{1.5}$O$_4$](image.png)

Figure 1. XRD patterns of the LiNi$_{0.5}$Mn$_{1.5}$O$_4$ (a) and Er-doped LiNi$_{0.5}$Mn$_{1.5}$O$_4$ (b).

Figure 2 shows the SEM images of the LiNi$_{0.5}$Mn$_{1.5}$O$_4$ and Er-doped LiNi$_{0.5}$Mn$_{1.5}$O$_4$ samples. As shown in Figure 2a, we can see that the undoped LiNi$_{0.5}$Mn$_{1.5}$O$_4$ sample presents very undesirable grain size distribution with average particle size distribution of about 2.0 μm. The smallest particle size is only 0.8 μm, while the biggest particle size can reach up to about 5.0 μm. By contrast, the Er-doped LiNi$_{0.5}$Mn$_{1.5}$O$_4$ sample shown in Figure 2b exhibits better size distribution. Although the average particle size distribution is very close to that of the undoped LiNi$_{0.5}$Mn$_{1.5}$O$_4$ sample, the biggest particle size has reduced to about 3.0 μm. These results indicate that the substitution of Er$^{3+}$ ions for partial nickel and manganese ions efficiently optimize the particle size distribution and reduces the aggregation behavior to some extent, which agrees with the research results [21,22]. According to the existing literature [21], the particle size of the Er-doped LiFePO$_4$ powders is less than that of undoped LiFePO$_4$ and the agglomerisation of powders is decreased via Er doping in the lattice. Moreover, Xie et al. [22] has also confirmed the Er-doping can play an active role in optimizing the morphology of the Er-doped LiV$_3$O$_8$ sample. Figure 3a,b show the energy dispersive spectrometry (EDS) pattern of the undoped LiNi$_{0.5}$Mn$_{1.5}$O$_4$ and Er-doped LiNi$_{0.5}$Mn$_{1.5}$O$_4$ sample (the inset in
Figure 3a,b is corresponding EDS data. According to Figure 3a,b, we can clearly observe the presence of the erbium element in the Er-doped LiNi$_{0.5}$Mn$_{1.5}$O$_4$ sample. It should be noted that the signal strength of Er element is very small compared with Mn element, which can be attributed to the very low content of Er element. According to the ICP-OES result, the real compositions of the Er-doped LiNi$_{0.5}$Mn$_{1.5}$O$_4$ sample is Li$_{0.997}$Ni$_{0.494}$Mn$_{1.497}$Er$_{0.009}$O$_{4.000}$. Such low content can help explain why the signal strength of Er element is very small. The corresponding EDS data of these two samples in Figure 3a,b also illuminates the low content of Er element. Moreover, the elemental mapping images of Ni, Mn, Er, and O elements of this material are shown in Figure 3c–f. It can be seen that the erbium element is evenly distributed in the Er-doped LiNi$_{0.5}$Mn$_{1.5}$O$_4$ sample. The above results indicate that the Er-doping can play a significant role in the optimization of product size distribution. The obtained Er-doped LiNi$_{0.5}$Mn$_{1.5}$O$_4$ sample may show excellent electrochemical properties.

![Figure 2. SEM images of the LiNi$_{0.5}$Mn$_{1.5}$O$_4$ (a) and Er-doped LiNi$_{0.5}$Mn$_{1.5}$O$_4$ (b).](image1)

![Figure 3. Cont.](image2)
which is slightly lower than that of the undoped LiNi0.5Mn1.5O4. These results indicate that the Er-doping effectively promotes the improvement of cycling stability.

Interphase (SEI) on the spinel after the initial cycle, which can hinder the further side reactions [29]. Such improved cycling efficiency can be ascribed to the stable solid electrolyte interphase (SEI) on the spinel after the initial cycle, which can hinder the further side reactions [29].

To compare the effect of doping with Er3+ ions on the cycling stability, the LiNi0.5Mn1.5O4 and Er-doped LiNi0.5Mn1.5O4 samples were cycled at 0.5 C between 3.6 and 4.9 V. Figure 4a,b shows the representative charge/discharge curves of these two materials. As shown here, the charge/discharge curves of these two samples have a high similarity in the shape of these curves, suggesting that the substitution of Er3+ ions for partial nickel and manganese ions does not produce a fundamental impact on the insertion/deinsertion process of lithium ions. The Er-doped LiNi0.5Mn1.5O4 sample presents two obvious platforms at around 4.7 V and 4.0 V, which agrees well with that of disordered LiNi0.5Mn1.5O4 in the literatures [26,27]. These two plateaus can be ascribed to the redox reaction of Ni2+/4+ and Mn3+/4+, respectively. Figure 4c,d shows the cycling performances of these two materials. According to Figure 4d, the initial discharge capacity of the Er-doped LiNi0.5Mn1.5O4 sample is 120.6 mAh·g−1, which is slightly lower than that of the undoped LiNi0.5Mn1.5O4 sample (124.5 mAh·g−1). However, it is important to note that the initial discharge capacity of the undoped LiNi0.5Mn1.5O4 sample begins to fade greatly with the cycling going on. After 30 cycles, the Er-doped LiNi0.5Mn1.5O4 sample presents excellent capacity retention of 93.2%. By contrast, the undoped sample shows very low capacity retention (64.5%).

In order to investigate the cycling stability, the long cycling performance of the Er-doped LiNi0.5Mn1.5O4 sample was carried out at 0.5 C, as shown in Figure 5a. The Er-doped LiNi0.5Mn1.5O4 sample still achieves more than 112.0 mAh·g−1 and the capacity retention of this sample reach up to 92.9% after 100 cycles. By contrast, the cycling stability of the undoped LiNi0.5Mn1.5O4 sample is much worse. It delivers the bad capacity retention of 70.9% after only 30 cycles. The excellent cycling stability of the Er-doped LiNi0.5Mn1.5O4 sample is linked most strongly with the substitution of Er3+ ions for partial nickel and manganese ions in the spinel structure. For the Er-doped sample, the bonding energy of Er-O (615 kJ·mol−1) is higher than that of Mn-O (402 kJ·mol−1) and Ni-O (392 kJ·mol−1), which can make the spinel structure of the Er-doped LiNi0.5Mn1.5O4 sample become more stable [9,20,26]. Figure 5b shows the coulombic efficiency of the Er-doped LiNi0.5Mn1.5O4 sample after 100 cycles. As shown here, the coulombic efficiency of the initial cycle is about 93.6%, which can be explained by the side reactions of electrolyte and electrode working at high voltage [28]. As the increase of the charge/discharge cycle, the coulombic efficiency is increased to 95.4% after 3 cycles and 98.6% after 30 cycles. Such improved cycling efficiency can be ascribed to the stable solid electrolyte interphase (SEI) on the spinel after the initial cycle, which can hinder the further side reactions [29].

Figure 3. Energy dispersive spectrometry (EDS) patterns of the undoped LiNi0.5Mn1.5O4 (a) and Er-doped LiNi0.5Mn1.5O4 (b) sample (The inset in Figure 3a,b is corresponding EDS data); (c-f) Elemental mapping images of Ni, Mn, Er, and O elements in the Er-doped LiNi0.5Mn1.5O4 sample.
presents a discharge capacity loss from 130.2 mAh·g⁻¹. However, the higher rate can spur the increase in the polarization of cathode material, which will decrease the discharge voltage plateaus. By contrast, the Er-doping significantly enhances the rate performance of the Er-doped LiNi₀.₅Mn₁.₅O₄. As shown in Figure 6b, the increased charge/discharge rate does not noticeably alter the representative discharge curve of the Er-doped LiNi₀.₅Mn₁.₅O₄. However, the discharge voltage plateaus of the spinel gradually decrease as the charge/discharge rate increases, which may be explained by the following two reasons. On the one hand, the higher rate can spur the increase in the polarization of cathode material, which will decrease the discharge voltage plateaus [18]. On the other hand, the increased essential resistance can cause an obvious voltage drop when lithium-ion battery is cycled at higher rate [30].
As the charge/discharge rate increases to 2.0 C, the discharge capacity of this material can still prove that the electrochemical performance of spinel LiNi$_{0.5}$Mn$_{1.5}$O$_4$ samples at 0.5 C. When cycled at 0.2 C, the Er-doped LiNi$_{0.5}$Mn$_{1.5}$O$_4$ sample delivers 123.7 mAh·g$^{-1}$ with excellent recovery rate. Figure 6c shows the cycling stability of the Er-doped LiNi$_{0.5}$Mn$_{1.5}$O$_4$ sample at 2.0 C. It can be seen that the Er-doped LiNi$_{0.5}$Mn$_{1.5}$O$_4$ sample exhibits an initial discharge capacity of 100.4 mAh·g$^{-1}$, and the capacity retention of this sample reached up to 97.6% after 30 cycles. The analysis results once again prove that the electrochemical performance of spinel LiNi$_{0.5}$Mn$_{1.5}$O$_4$ can be greatly enhanced by the addition of Er$^{3+}$ ions.

![Figure 6](image_url)

**Figure 6.** Representative discharge curves of the LiNi$_{0.5}$Mn$_{1.5}$O$_4$ (a) and Er-doped LiNi$_{0.5}$Mn$_{1.5}$O$_4$ (b) at different rates; (c) rate capability of the LiNi$_{0.5}$Mn$_{1.5}$O$_4$ and Er-doped LiNi$_{0.5}$Mn$_{1.5}$O$_4$; (d) cycling stability of the Er-doped LiNi$_{0.5}$Mn$_{1.5}$O$_4$ at 2.0 C.

Figure 7 shows the cycling performance of the LiNi$_{0.5}$Mn$_{1.5}$O$_4$ and Er-doped LiNi$_{0.5}$Mn$_{1.5}$O$_4$ samples at 55 °C. When cycled at 0.5 C, the Er-doped LiNi$_{0.5}$Mn$_{1.5}$O$_4$ sample exhibits an initial discharge capacity of 120.3 mAh·g$^{-1}$, which is slightly lower than that of the undoped LiNi$_{0.5}$Mn$_{1.5}$O$_4$ sample (124.3 mAh·g$^{-1}$). However, after 30 cycles, the Er-doped LiNi$_{0.5}$Mn$_{1.5}$O$_4$ sample still delivers 113.7 mAh·g$^{-1}$, retaining 94.5% of its initial discharge capacity. Contemporaneously, the undoped LiNi$_{0.5}$Mn$_{1.5}$O$_4$ sample retains just 58.1%. Figure 8a,b shows the representative discharge curves of the LiNi$_{0.5}$Mn$_{1.5}$O$_4$ and Er-doped LiNi$_{0.5}$Mn$_{1.5}$O$_4$ at 55 °C. The initial discharge curves of these two
samples have a high similarity in the shape of these curves, but the corresponding 30th discharge curves present obvious difference. For the Er-doped LiNi_{0.5}Mn_{1.5}O_{4} sample, there is no discharge voltage drop after 30 cycles, while the discharge voltage drop of the undoped LiNi_{0.5}Mn_{1.5}O_{4} sample is quite obvious. The above result shows that the addition of Er^{3+} can enhance the cycling stability of LiNi_{0.5}Mn_{1.5}O_{4} at elevated-temperature.

![Figure 7. Cycling performance of the LiNi_{0.5}Mn_{1.5}O_{4} and Er-doped LiNi_{0.5}Mn_{1.5}O_{4} at 55 °C.](image)

Figure 7. Cycling performance of the LiNi_{0.5}Mn_{1.5}O_{4} and Er-doped LiNi_{0.5}Mn_{1.5}O_{4} at 55 °C.

![Figure 8. Representative discharge curves of the LiNi_{0.5}Mn_{1.5}O_{4} (a) and Er-doped LiNi_{0.5}Mn_{1.5}O_{4} (b) at 55 °C.](image)

Figure 8. Representative discharge curves of the LiNi_{0.5}Mn_{1.5}O_{4} (a) and Er-doped LiNi_{0.5}Mn_{1.5}O_{4} (b) at 55 °C.

Figure 9 shows the cyclic voltammograms of the LiNi_{0.5}Mn_{1.5}O_{4} and Er-doped LiNi_{0.5}Mn_{1.5}O_{4} samples. The scan rate is 0.1 mV·s^{-1} and the scanning voltage is from 3.5 to 4.9 V. It can be clearly observed that these two samples present three pairs of reduction and oxidation peaks. Among them, the small reduction and oxidation peaks at around 4.0 V suggests the redox reaction of Mn^{3+/4+} couples [32]. And the main two pairs of redox peaks at around 4.7 V are ascribed to redox reactions of Ni^{2+/3+} and Ni^{3+/4+}, respectively [33]. From the redox peaks of Ni^{2+/3+} of the two samples, we can find that the Er-doped LiNi_{0.5}Mn_{1.5}O_{4} sample presents a little smaller anodic peak and a much higher cathodic peak than the undoped LiNi_{0.5}Mn_{1.5}O_{4} sample. Such much smaller difference suggests a higher reversibility of electrode reaction [34].
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Figure 9. Cyclic voltammograms of the LiNi0.5Mn1.5O4 and Er-doped LiNi0.5Mn1.5O4 in the range of 3.5–4.9 V.

Figure 10 shows the Nyquist plots of the the LiNi0.5Mn1.5O4 and Er-doped LiNi0.5Mn1.5O4 samples. The possible equivalent circuit model is embedded in Figure 10, where $R_e$ and $R_{ct}$ represent the ohmic resistance and charge transfer resistance, respectively [35,36]. And the fitting results of impedance parameters are listed in Table 1. Between the two kinds of resistances, the charge transfer resistance is much related to electrochemical property of electrode material [37]. The undoped LiNi0.5Mn1.5O4 sample displays a high charge transfer resistance of 377.1 Ω. However, after the addition of Er3+, the charge transfer resistance is decreased to 210.8 Ω, which makes it much easier for lithium-ion diffusion during the process of charge/discharge. Therefore, it should make sense why the Er-doped LiNi0.5Mn1.5O4 spinel presents better electrochemical property.

Figure 10. Nyquist plots of the LiNi0.5Mn1.5O4 and Er-doped LiNi0.5Mn1.5O4 before cycles (the insert is the equivalent circuit model of EIS).
Table 1. Impedance fitted data from EIS spectra for the LiNi$_{0.5}$Mn$_{1.5}$O$_4$ and Er-doped LiNi$_{0.5}$Mn$_{1.5}$O$_4$.

| Sample                | $R_\varepsilon$ ($\Omega$) | $R_{ct}$ ($\Omega$) |
|-----------------------|-----------------------------|---------------------|
| LiNi$_{0.5}$Mn$_{1.5}$O$_4$ | 4.01                        | 377.13              |
| Er-doped LiNi$_{0.5}$Mn$_{1.5}$O$_4$ | 3.04                        | 210.81              |

4. Conclusions

The Er-doped LiNi$_{0.5}$Mn$_{1.5}$O$_4$ sample was successfully prepared by the citric acid-assisted sol-gel method with erbium oxide as erbium source for the first time. XRD and SEM characterization indicated that the substitution of Er$^{3+}$ ions for partial nickel and manganese ions did not change the intrinsic structure of LiNi$_{0.5}$Mn$_{1.5}$O$_4$ and the Er-doped LiNi$_{0.5}$Mn$_{1.5}$O$_4$ sample showed better size distribution and regular octahedral morphology. When cycled at 0.5 C, the Er-doped LiNi$_{0.5}$Mn$_{1.5}$O$_4$ sample exhibited an initial discharge capacity of 120.6 mAh·g$^{-1}$, and the capacity retention of this sample reached up to 92.9% after 100 cycles. Furthermore, it could show excellent recovery rate, superior rate capability, and good high-temperature performance. The above results indicate that the substitution of Er$^{3+}$ ions for partial nickel and manganese ions can play an active role in modifying LiNi$_{0.5}$Mn$_{1.5}$O$_4$.

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