Rare-earth doped YPO₄ has been studied extensively, both for potential technological applications and in more fundamental investigations of electron transport and trapping processes. Nakazawa reported on the vacuum ultraviolet (VUV) spectroscopy of Ln³⁺ doped microcrystalline YPO₄₆ and assigned excitations due to host, 4f – 5d, and charge transfer transitions for all of the lanthanides (except Pr and Lu). Additional studies of YPO₄ included one by Lai et al. that described a precipitation route to ∼20 nm YPO₄:Eu³⁺, but only the UV optical properties are discussed. Di et al. have compared the VUV optical properties of YPO₄:Ta³⁺ prepared via solid state reaction and co-precipitation. However, unlike in the work presented here, the high calcination temperatures applied to the co-precipitated samples led to materials that were similar in size to solid state samples but with improved morphology. Van Pieterson et al. obtained high-resolution excitation spectra of YPO₄ doped with both light and heavy lanthanides at 6 K. They assigned spectral features and compared the experimentally observed spectra with energy level calculations for the 4fⁿ15d¹ states. Mahkov et al. investigated the optical properties of YPO₄:Nd³⁺ under VUV synchrotron radiation over a temperature range of 9–300 K. Their work included the assignment of various host-sensitized excitation mechanisms that will be discussed more later. The optical properties of nanocrystalline YPO₄:Ln³⁺ are compared to larger crystallites of YPO₄:Ln³⁺ prepared via traditional solid state reaction. In larger crystals (∼330 nm) a distinct peak is observed at 150 nm in the excitation spectra, the intensity of which decreases markedly in smaller crystals (∼20 nm). Using excitation and reflectance spectroscopy, host-to-activator energy transfer efficiencies were calculated for Y₁₋ₓPO₄₉Lnₓ³⁺ (0.01 ≤ x ≤ 0.10). From the transfer efficiency data, we estimate that trapping by Eu³⁺ and Sm³⁺ is at least five times more efficient than trapping by Tb³⁺ for excitation at the band edge. The fraction of energy lost to the surface or grain boundaries for excitation at 150 nm and 138 nm is also estimated. We propose that in the samples prepared via co-precipitation, an amorphous phase forms at grain boundaries that is responsible for the loss of efficiency under 150 nm excitation.

The optical properties of nanocrystalline YPO₄:Ln³⁺ (Ln = Eu, Sm, Tb) prepared via co-precipitation are compared to larger crystallites of YPO₄:Ln³⁺ prepared via traditional solid state reaction. In larger crystals (∼330 nm) a distinct peak is observed at 150 nm in the excitation spectra, the intensity of which decreases markedly in smaller crystals (∼20 nm). Using excitation and reflectance spectroscopy, host-to-activator energy transfer efficiencies were calculated for Y₁₋ₓPO₄₉Lnₓ³⁺ (0.01 ≤ x ≤ 0.10). From the transfer efficiency data, we estimate that trapping by Eu³⁺ and Sm³⁺ is at least five times more efficient than trapping by Tb³⁺ for excitation at the band edge. The fraction of energy lost to the surface or grain boundaries for excitation at 150 nm and 138 nm is also estimated. We propose that in the samples prepared via co-precipitation, an amorphous phase forms at grain boundaries that is responsible for the loss of efficiency under 150 nm excitation.

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filter in order to subtract sample emission out of the raw reflectance data.

**Results and Discussion**

All samples were found to be phase pure by X-ray diffraction. Representative powder XRD data are shown in Figure 1. These exhibit the expected line broadening at smaller particle sizes. The particle diameters estimated using the Williamson-Hall method are found to be approximately 20 nm for the samples prepared via co-precipitation and approximately 330 nm for samples prepared via grind and firing. Scanning electron microscope images are shown in Figure 2. Both preparations result in polycrystalline agglomerates. The images allow an estimate of the particle size of the samples prepared by grind and firing (250–300 nm), whereas individual crystallites cannot be distinguished for the samples prepared by co-precipitation.

Before discussing the optical properties of the various doped samples, it is useful to present the absorption spectra of the undoped compounds. These spectra (as 1-R) are shown in Figure 3 for YPO₄ prepared by both methods. Two important features are worth noting. First, the sample prepared by solid state methods exhibits a distinct onset of band edge absorption at about 148 nm. In the co-precipitation sample, this absorption is less distinct, instead appearing as a broad feature with absorption to longer wavelengths. We believe that the most reasonable interpretation for the difference in absorption is the presence of an amorphous phase at the grain boundaries of the particles prepared via co-precipitation. Those samples also exhibit considerably higher background, presumably due to a difference in the light scattering properties of the smaller grains. We associate the small peak at 207 nm with impurities. We note also that we collected IR spectra of both samples, but we saw essentially no difference between them.

Emission spectra of YPO₄:Eu prepared both ways are shown in Figure 4. Excitation is via the host at 150 nm. The spectra exhibit characteristic \( ^5D_0 \rightarrow ^7F_1 \) and \( ^5D_0 \rightarrow ^7F_2 \) transitions at 593 nm and 615 nm, respectively, and are comparable to what has been reported previously for this material. The relatively high intensity of the \( ^5D_0 \rightarrow ^7F_1 \) transition is indicative of Eu³⁺ occupying a site with inversion symmetry, consistent with the Y site symmetry in YPO₄. We observe no systematic change in the ratio of these two peaks with Eu concentration. However, we do observe a slight increase in the red/orange ratio in the smaller crystallites. An increase in the relative amount of \( ^5D_0 \rightarrow ^7F_2 \) emission implies that the inversion symmetry is being relaxed, which is likely the result of lower crystallinity in the 20 nm material. Spectra were collected up to 10 mol% Eu, and it appears that quenching may begin to set in around 10 mol%.

Representative excitation spectra are shown in Figure 5 for YPO₄:Eu prepared both ways. Features at wavelengths shorter than 150 nm are associated with excitation via the YPO₄ host, while features at longer wavelengths are due to Eu charge transfer (CT) excitation. There are several curious features that appear in the excitation spectra. Most notable is a sharp peak at ~150 nm that decreases dramatically at small crystallite sizes. This is observed regardless of Eu concentration. Secondly, the CT band appears to exhibit two broad peaks, rather than one.
The unusual shape of the CT band is not apparent in reports that discuss only UV excitation of YPO₄:Eu⁺⁺ because typical UV instruments do not provide significant excitation intensity below ∼250 nm. It is our opinion that the position of the CT is not correctly determined in that case. In the reports of VUV excitation, the spectra more closely resemble what we report here (a broad, asymmetric feature at ∼225 nm). However, the asymmetric nature of the CT excitation is not commented on. The shape of the excitation suggests the possibility of two distinct Eu³⁺ sites. However, there is only a single Y site in YPO₄ and we see no differences in the line ratios of emission spectra as we vary the excitation across this band, which suggests that there is only one type of Eu³⁺. We also note that there is little change in the shape (although not the intensity) of the CT band with concentration. We might speculate that the two peaks represent charge transfer from different O atoms in the lattice, given that in YPO₄ there are two sets of four O atoms around the Y site at 2.39 and 2.57 Å. However, we have not seen this type of argument presented in the literature, and excitation spectra of the other dopants studied suggest only one type of activator site. Thus at this point we can propose no definitive explanation for the shape of the Eu³⁺ CT band, and in what follows we make the assumption that there is only a single Eu³⁺ site. Finally, we observe a change in the shape of the CT band in the co-precipitated samples, in which there is a decrease in intensity on the short wavelength side of the band (170–200 nm). An explanation for this may be provided by the absorption data.

Absorption, as 1-R, for YPO₄:Eu is shown in Figure 6 for both preparations. Absorption spectra are generally much noisier than emission and excitation spectra. This is due to the fact that there is lower signal than in the other two measurements, compounded by the fact that the final spectra are a combination of three measurements, generated as (with filter) – (without filter) then divided by the reflectance of MgF₂. In the solid state samples, the band edge is distinguishable at ∼150 nm, with CT absorption taking place between 170 and 230 nm. The CT absorption mimics the double peak seen in excitation spectra. In the co-precipitation samples, the distinct absorption at the band edge is somewhat washed out by the broad absorption feature that is seen in the undoped samples. In both cases, we observe that CT absorption increases with Eu concentration. We believe that the change in the shape of the CT band in the co-precipitation samples is due to interference from the phase that is causing the long absorption tail after the band edge. This phase blocks excitation of Eu in the 170–200 nm window and thus reduces the observed excitation intensity.

Similar optical data sets were obtained for YPO₄:Sm³⁺ prepared both ways. Representative emission data are shown in Figure 7, excitation in Figure 8, and absorption as 1-R in Figure 9. Unlike with Eu³⁺, we observe that Sm³⁺ exhibits significant concentration quenching.
after 1 mol%. In the excitation spectra, a distinct peak appears at 150 nm in the solid state samples that again decreases substantially in the co-precipitation samples. Two additional peaks at 175 nm and 180 nm have been assigned to 4f – 5d and CT transitions, respectively. In the absorption data we again observe that the band edge can be distinguished in the solid state samples, but this feature is washed out by a broad absorption in the co-precipitation samples.

Optical data sets were also obtained for YPO₄: Tb³⁺ prepared both ways. Representative emission data are shown in Figure 10, excitation in Figure 11, and absorption as 1-R in Figure 12. Tb³⁺ does not exhibit significant concentration quenching up to 10 mol%. In the excitation spectra, the distinct peak at 150 nm in the solid state samples is still present, though to a lesser degree than is observed with Eu and Sm. This peak again decreases substantially in the co-precipitation samples. Additional peaks at wavelengths longer than 160 nm have been assigned to 4f – 5d transitions. In the absorption data we again observe that the band edge feature is washed out by the broad absorption in the co-precipitation samples, although the difference is less obvious than with Eu and Sm. Although the absorption data are very noisy and it can be difficult to distinguish some features in the spectra, we believe it is still instructive to consider the results, particularly when it comes to estimating host-to-activator transfer efficiencies as is discussed later.

Figure 8. Excitation spectra of Y₀.₉₉PO₄:Sm₀.₀₁ prepared by traditional solid-state methods (solid line) and via co-precipitation (dashed line). λₑₘ = 601 nm.

Figure 9. Absorption spectra (as 1-R) of Y₀.₉₉PO₄:Sm₀.₀₁ prepared by traditional solid-state methods (solid line) and via co-precipitation (dashed line).

Figure 10. Emission spectra of Y₀.₉₅PO₄:Tb₀.₀₅ prepared via solid state methods (solid line) and via co-precipitation (dashed line). λₑₙ = 150 nm.

Figure 11. Excitation spectra of Y₀.₉₅PO₄:Tb₀.₀₁ prepared by traditional solid-state methods (solid line) and via co-precipitation (dashed line). λₑₘ = 543 nm.

Figure 12. Absorption spectra (as 1-R) of Y₀.₉₉PO₄:Tb₀.₀₁ prepared by traditional solid-state methods (solid line) and via co-precipitation (dashed line).
In the excitation spectra, the sharp peak at 150 nm can reasonably be assigned to excitation at the band edge of the YPO₄ host. It corresponds almost exactly with the observed band edge absorption and is in the same place for all dopants. Nakazawa and Shiga assigned this feature to phosphor absorption. We note, however, that density of states calculations indicate that the top of the valence band is comprised primarily of O 2p states, while the bottom of the conduction band is primarily Y 4d, suggesting that band edge excitation would involve these states rather than PO₄³⁻ states. In the low temperature work of Makarov et al., they proposed a bandgap of 9.4 eV (≈132 nm) based on lifetime measurements of YPO₄:Nd³⁺ emission under host versus direct excitation. They also observed self-trapped exciton (STE) emission at 430 nm, with the excitation spectrum of this emission indicating STE formation at about 8.4 eV (~147 nm). In YPO₄:Eu³⁺, van Pieterson et al. assigned the peak at ~150 nm to 4f → 5d transitions. This suggests the possibility that the STE energy and the Eu²⁺ 4f → 5d energy match very closely. Interestingly, we find that the intensity of this peak is somewhat activator dependent, as was observed previously (although not commented on) by Nakazawa. Bos et al. published the energy level scheme for lanthanides in YPO₄ which was arrived at using a semi-empirical method. Thermoluminescence experiments confirm that the scheme provides a reasonable estimate of the location of Ln³⁺ and Ln³⁺ ground states relative to host states. Using this scheme we note that the sharp feature at 150 nm appears most pronounced for cases in which the Ln³⁺ ground state energy is lower than (or very close to) the valence band energy (i.e. Eu³⁺, Sm³⁺, Tm³⁺), while this feature is less prominent or not observed when the Ln³⁺ ground state energy is notably greater than the valence band edge (i.e. Tb³⁺, Dy³⁺). Thus it is possible that the enhanced excitation efficiency is due to more efficient capture of the electron-hole pair when activator ground states are in the valence band, perhaps via resonant capture of a self-trapped exciton formed from excitation at the band edge. Certainly more systematic work needs to be done to clarify this phenomenon, and we only mention it here as a general observation. It may also point to the additional utility of developing energy level schemes using Dorenbos’ method. Based on our excitation spectra, we obtain values of η₁/Φ₁ for each dopant (220 nm for Eu³⁺ and 222 nm for Tb³⁺). For the host term (Φ₉host and Φ₈host) we used efficiencies at 150 nm as well as 138 nm. That is, the transfer efficiency was calculated for excitation at each of these wavelengths separately. This allows us to compare energy transfer from the unusual excitation at 150 nm to energy transfer from higher energies that appear to be less affected by the preparation method. In addition, excitation at 138 nm versus 150 nm is expected to result in different types of processes within the host. 138 nm is sufficient energy to produce mobile e-h pairs, whereas excitation at 150 nm creates STE’s. Dorenbos previously referred to this as the “mobility gap”, and suggested that mobile e-h pairs are created when the excitation energy is at least 8% greater than the absorption edge.

By way of an example calculation of transfer efficiency, consider the excitation and absorption data for YPO₄:Eu³⁺ prepared by solid state methods, presented in Figures 5 and 6. From the excitation spectra we obtain values of Φ₉host = 0.42 at 150 nm and Φ₈act = 0.41 at 220 nm. From the absorption spectra we obtain values of Φ₈abs = 0.85 at 150 nm and Φ₈em = 0.50 at 220 nm. Plugging these into Equation 3 results in η₁ = 0.59. That is, 59% of absorbed energy is trapped by Eu³⁺ at a concentration of 1 mol%. Complete data sets and flux values are available on request. Here, we report the final results. Transfer efficiencies plotted versus activator concentration, as well as reciprocal plots (1/η₁ vs 1/[Ln³⁺]), are provided in Figures 13–15 for both preparation methods. Concentrations have been converted to Ln³⁺/cm³ using the mole% and the structure of YPO₄. The η₁ calculation was performed for host excitation at both 138 and 150 nm. As expected, η₁ increases with Ln³⁺ concentration as trapping of an e-h pair becomes more likely. Under 138 nm excitation, the transfer efficiency is relatively insensitive to the preparation method. Under 150 nm excitation e-h trapping is much more efficient for the large particles, consistent with the excitation spectra discussed above.

These data can be modeled using first-order competition kinetics where, for excitation energies just greater than the bandgap, the transfer efficiency is given by:

\[ \eta_t = \frac{\alpha N}{\alpha N + \beta} \times S_{host} \]  

The term \( \alpha \) is the rate constant for trapping by activators, \( N \) is the activator concentration, and \( \beta \) is the overall rate of transfer to killers. Therefore, \( \alpha N \) is the rate of transfer to activators (rate constant \( \times \) concentration) and the transfer efficiency is the ratio of the rate of transfer to activators to the total trapping rate (the sum of rates to activators plus killers). Killer concentration is assumed to be a feature of the host and not affected by the activator concentration. The term \( S_{host} \) represents energy lost to the particle surface, where \( S_{host} = 1 \) corresponds to no surface losses. Values of \( S_{host} \) less than 1 represent the fraction of the e-h pairs that are available for transport and trapping by a dopant (i.e. if \( S_{host} = 0.8, \) then 80% of excitation energy is available for trapping). In this treatment, \( S_{host} \) is assumed to be a constant. This approach was used previously to quantify surface loss effects in nanocrystalline YBO₃:Eu³⁺ and Y₂O₃:Eu³⁺. It is
Figure 13. Transfer efficiency versus Eu$^{3+}$ concentration in YPO$_4$:Eu for excitation at (a) 138 nm and (b) 150 nm. Reciprocal plots of these data are in (c) and (d). Solid circles are for samples prepared by solid state reaction, while open diamonds were prepared via co-precipitation.

Figure 14. Transfer efficiency versus Sm$^{3+}$ concentration in YPO$_4$:Sm for excitation at (a) 138 nm and (b) 150 nm. Reciprocal plots of these data are in (c) and (d). Solid circles are for samples prepared by solid state reaction, while open diamonds were prepared via co-precipitation.
Figure 15. Transfer efficiency versus Tb$^{3+}$ concentration in YPO$_4$:Tb for excitation at (a) 138 nm and (b) 150 nm. Reciprocal plots of these data are in (c) and (d). Solid circles are for samples prepared by solid state reaction, while open diamonds were prepared via co-precipitation.

important to point out that this analysis does not allow us to distinguish loss to surface defect states from loss to an amorphous phase at the grain boundaries.

The surface or interface loss imposes a limit on the maximum value observed for $\eta_t$. This can clearly be seen when comparing 20 nm particles to 330 nm particles under 150 nm excitation in Figure 13b. The maximum transfer efficiency approaches 0.90 for 330 nm particles, but reaches a limit of about 0.30 in the 20 nm particles.

Equation 4 can be rearranged to slope-intercept form as:

$$\frac{1}{\eta_t} = \frac{1}{S_{loss}} + \frac{\beta}{\alpha N} \left( \frac{1}{S_{loss}} \right)$$  \[5\]

where a plot of $1/\eta_t$ versus $1/N$ will have a slope of $\beta/(\alpha \cdot S_{loss})$ and a y–intercept of $1/S_{loss}$.

Such plots are shown in Figures 13–15, and the parameters calculated from linear regression are given in Tables I and II. The values of $\alpha$ and $\beta$ cannot be extracted independently from these plots, however, the term $\alpha/\beta$ gives a relative assessment of the e-h pair mobility and capture efficiency for a given system, and allows us to quantify and compare some of our qualitative observations. As noted above, $S_{loss}$ should have values between 0 and 1, which is generally observed in our data. However, the solid state Tb data yield unrealistic values. Here, we find $S_{loss} = 5.1$ and $S_{loss} = -9.1$ at 138 nm and 150 nm, respectively. We attribute this at least partly to the absorption data. Samples doped with Tb consistently produced noisier, lower quality reflectance spectra. In addition, measured host absorption values decrease slightly with Tb concentration, a phenomenon that was also observed in our prior study of YBO$_3$:Tb. This results in an anomalously low value of $1/\eta_t$ and an unreasonable intercept. Because of this, we have also reported the $\alpha/\beta$ ratios obtained if $S_{loss}$ isn’t taken into account.

Higher $\alpha/\beta$ ratios imply more efficient trapping of the e-h pair by the dopant. From the data in the tables, it is clear that for Eu and Sm energy transfer is more efficient for excitation right at the band edge (150 nm) for both particle sizes, when compared with excitation at 138 nm. Excitation at 150 nm in the large particles is unusually

| Ln$^{3+}$ | Synthesis | $\alpha/\beta$ (cm$^3$)$/(x10^{21})$ | $S_{loss}$ |
|----------|-----------|-------------------------------|-----------|
| Sm       | SS        | 1.84 ± .11                    | 0.76 ± .10|
|          | CP        | 4.39 ± .46                    | 0.66 ± .06|
| Eu       | SS        | 2.09 ± .04                    | 0.65 ± .03|
|          | CP        | 1.79 ± .11                    | 0.61 ± .09|
| Tb       | SS        | 0.065 ± .002 (0.33 ± .01)     | 5.1 ± 8.1 |
|          | CP        | 1.42 ± .15                    | 0.71 ± .21|
Table II. Kinetic parameters obtained from reciprocal plots for excitation at 150 nm. SS = solid state preparation; CP = co-precipitation. The number in parentheses for Tb is the α/β ratio calculated if S_loss is ignored, given the physically unrealistic values calculated from the intercept.

| Ln³⁺ | Synthesis | α/β (cm³)(×10¹¹) | S_loss |
|------|-----------|------------------|--------|
| Sm   | SS        | 14.1 ± 4.3       | 0.73 ± 0.06 |
|      | CP        | 4.03 ± 0.65      | 0.31 ± 0.05 |
| Eu   | SS        | 11.5 ± 1.3       | 0.94 ± 0.03 |
|      | CP        | 1.81 ± 0.26      | 0.42 ± 0.14 |
| Tb   | SS        | 0.060 ± 0.006 (0.55 ± 0.05) | -9.1 ± 58.6 |
|      | CP        | 2.98 ± 0.67      | 0.39 ± 0.12 |

Conclusions

We have evaluated the optical properties of YPO₄:Ln³⁺ (Ln = Eu, Sm, or Tb) prepared by co-precipitation and by solid state grinding and firing. Co-precipitation yields crystallite sizes of about 20 nm, while crystallites prepared by grinding and firing are about 350 nm. Excitation spectra of samples prepared by grinding and firing exhibit an unusually intense peak at 150 nm, which corresponds to formation of an STE in the host. We note a possible correlation between the intensity of this peak and the location of the Ln³⁺ ground state relative to YPO₄ valence and conduction bands, as well as a correlation with 4f⁰-5d⁰ energies calculated in prior publications. The peak at 150 nm decreases dramatically in samples prepared by co-precipitation. We suspect that this is due to the presence of an amorphous phase at the grain boundaries of materials prepared by co-precipitation, although it could also be due to surface defect states.

Using excitation and reflectance spectra, host-to-activator transfer efficiencies were calculated and modeled using first order competition kinetics. From this, we find that trapping efficiencies are especially high for excitation at the band edge in samples prepared by solid state reaction. At the band edge, Sm³⁺ and Eu³⁺ exhibit α/β ratios at least 10 times greater than Tb³⁺ in samples prepared by grinding and firing. The α/β ratio is calculated from fits to the model and is an indicator of e-h pair trapping efficiency. The difference in efficiencies among dopants may also be correlated with the energy level scheme, as was observed in YBO₄. The trapping efficiency decreases substantially in the smaller particles. Trapping efficiencies under 138 nm excitation, which corresponds to the formation of an e-h pair, are relatively insensitive to the preparation method.

For excitation at 150 nm, the kinetic analysis indicates that about 60% of e-h pairs are lost to the surface in the 20 nm material, while this number is 10–30% in the 330 nm material. This number is 30 – 40% under 138 nm excitation regardless of the preparation method.

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References

1. A. K. Parchur and R. S. Ningthoujam, RSC Advances, 2, 10859 (2012).
2. W. Jia, Y. Zhou, D. A. Keszler, J-Y Jeeong, K. W. Jung, and R. S. Meltzer, Phys. Stat. Sol. C, 48 (2005).
3. E. Nakazawa and F. Shiga, J. Lumin., 15, 255 (1977).
4. E. Nakazawa, J. Lumin., 100, 89 (2002).
5. H. Lai, H. Yang, C. Tao, and X. Yang, Phys. Stat. Sol. A, 204, 1178 (2007).
6. W. Di, X. Wang, B. Chen, H. Lai, and X. Zhao, Opt. Mat., 27, 1386 (2005).
7. L. van Pieterse, M. F. Reid, R. T. Wegh, S. Soverna, and A. Meijerink, Phys. Rev. B, 65, 045113 (2002).
8. L. van Pieterse, M. F. Reid, R. T. Wegh, S. Soverna, and A. Meijerink, Phys. Rev. B, 65, 045114 (2002).
9. V. N. Makhot, N. Yu. Kirinkova, M. Kirm, J. C. Kuipa, P. Ljubik, A. Lushchik, Ch. Lushchik, E. Nogodin, and G. Zimmerman, J. Phys. Chem C., 117, 045113 (2002).
10. T. Gryzb, A. Gruzesczak, and S. Lis, J. Lumin., 175, 21 (2016).
11. A. J. J. Bos, N. R. J. Poolton, J. Wallenga, A. Bessiere, and P. Dorenbos, Rad. Meas., 45, 343 (2010).
12. P. Dorenbos, A. J. J. Bos, and N. R. J. Poolton, Opt. Mat., 33, 1019 (2011).
13. A. J. J. Bos, P. Dorenbos, A. Bessiere, and B. Viana, Rad. Meas., 43, 222 (2008).
14. P. Dorenbos and A. J. J. Bos, Rad. Meas., 43, 139 (2008).
15. M. K. Wallace and A. L. Diaz, J. Lumin., 161, 403 (2015).
16. K. Olsen, A. Lawler, and A. L. Diaz, J. Phys Chem C., 115, 17136 (2011).
17. C. Waite, R. Mann, and A. L. Diaz, J. Solid State Chem., 198, 357 (2015).
18. W. O. Milligan, D. F. Mulllca, G. W. Beall, and L. A. Brainer, Inorg. Chimica Acta, 60, 39 (1982).
19. D. Wang, S. Xia, and Y. Min, J. Rare Earths, 26, 439 (2008).
20. R. Rabinovitz, K. Johnston, and A. L. Diaz, J. Phys. Chem. C, 114, 13884 (2010).
21. T. Waterous-Kelly, A. A. Diaz, and T. A. Dang, Chem. Mater., 18, 5310 (2006).
22. P. Dorenbos, J. Lumin., 111, 89 (2005).
23. K. C. Mishra and M. Raukas, J. Electrochem. Soc., 151, H105 (2004).