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Published in:
Journal of the Electrochemical Society

DOI:
10.1149/1.1391684

Published: 01/01/1999

Citation for published version (APA):
Eu-Doped Barium Aluminum Oxynitride with the β-Alumina-Type Structure as New Blue-Emitting Phosphor

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Attractive new blue-emitting phosphors for use in low-pressure mercury gas discharge lamps are synthesized by Eu-substitution in the barium aluminum oxynitride host lattice with the β-alumina-type structure. The emission spectra of these phosphors for 254 nm excitation show a band at about 450 nm with a shoulder at higher wavelength. The maximum quantum efficiency of these materials is about 85-90% just like commercial BaMgAl10O17:Eu with the β-alumina type structure. The nonoptimized oxynitride phosphors are more sensitive to oxidation (at 873 K) and to short-term depreciation due to 185 nm irradiation compared to commercial BaMgAl10O17:Eu. However, the maintenance of the oxynitride phosphors in single component fluorescent lamps is improved. Calculations indicate that by using these phosphors in tricolor fluorescent lamps instead of BaMgAl10O17:Eu with the β-alumina type structure, the color rendering index will improve while the lumen output remains high.

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Manuscript received May 15, 1998.

Fluorescent lamps are very important lighting sources since they have a high efficiency, a good color rendering, adjustable color temperature, and a long lifetime. It was predicted by Koedam and Opstelten1 as well as by Thornton2 that a fluorescent lamp with a high efficacy and color rendering index (CRI) can be obtained by combining three phosphors which emit in narrow wavelength intervals centered around 450 (blue), 550 (green), and 650 (red) nm. Such a lamp was realized a few years later, based on rare-earth activated phosphors and is called the tricolor lamp.3–5

A commonly used blue-emitting phosphor in tricolor lamps with a CRI of about 85 is Eu2+–doped BaMgAl10O17.3–5 The material BaMgAl10O17 has the β-alumina-type structure (space group P63/mmc) and can be derived from sodium β-alumina by replacing (NaAl)4+ with (BaMg)4+. So substituting Al3+ by Mg2+ is necessary for charge compensation when Na+ is substituted by Ba2+.6

In the BaO-Al2O3 system such a charge compensation is not possible, so the β-alumina material observed in this system has a defect structure. The material is named barium aluminate phase I and has an ideal composition of Ba0.75Al1.175O2.25. In this case Na+ is substituted by (Ba0.75Al1.175O2.25)4+ and the defects in this structure are called Reidinger defects. These Reidinger defects consist of a Ba vacancy, an O interstitial, and two Al Frenkel defects. The exact composition of Ba aluminate phase I is not clear since the reported composition of this material ranges from a Ba/Al ratio of 0.058 to 0.094.6–21 Also an O interstitial, and two Al Frenkel defects. These Reidinger defects consist of a Ba vacancy, an O interstitial, and two Al Frenkel defects. The exact composition of Ba aluminate phase I is not clear since the reported composition of this material ranges from a Ba/Al ratio of 0.058 to 0.094.6–21

The general composition of the samples is

\[ \text{Eu}_x(0.83+0.17)\text{Ba}_{1-x}(0.83+0.17)\text{Al}_{10}\text{O}_{17}\text{N}_y \]

with \( x: 0, 0.01, 0.05, 0.10, 0.15, 0.40, 0.70, \) and 1.00 and \( y: 0, 0.17, 0.55, \) and 1.

We also prepared a magnesium-containing sample with the composition of \( \text{Eu}_{0.1}\text{Ba}_{0.9}\text{MgAl}_{10}\text{O}_{17} \).

The powders were wet-mixed in isopropanol (>97%) for 2 h in an agate container with agate balls on a planetary mill. After mixing the isopropanol was evaporated. The powders were dried in a stove for one night at 433 K and subsequently ground in an agate mortar.
The powders were fired in a molybdenum crucible under a mildly flowing N$_2$/H$_2$ (90/10) gas mixture. Reactions were performed in a vertical high-temperature tube furnace at 1973 K for 2 or 4 h (heating/cooling rate 3 K/min). Eu$_{0.1}$Ba$_{0.9}$MgAl$_{16}$O$_{17}$ is fired for 4 h at 1973 K.

The properties of the synthesized powders are compared with commercial Eu$^{2+}$-doped BaMgAl$_{16}$O$_{17}$ (Philips Lighting, U716), which contains about 10% Eu. In this work we refer to this commercial material as BAM.

**Characterization**

The phases, present after reaction, were determined by powder X-ray diffraction (XRD). Continuous scans were made with Cu Kα radiation from 5 to 75° (2θ), with a scan speed of 1° (2θ)/min (Philips 5100). Step scans, with a step size of 0.01° (2θ) and a counting time of 6 s/step, were made from 68 to 75° (2θ) in order to determine the presence of traces of AlN. For Eu-containing specimens, Fe Kα radiation was used instead of Cu Kα, to prevent fluorescence which increases the noise of the spectra. The lattice parameters were calculated by using the following reflections: 2 0 14, 2 2 0, 2 0 13, 3 0 4, 2 0 11, 2 1 7, 1 0 11, 2 1 8, 2 0 6, 2 0 5, and 1 0 10.

The powder morphology was studied by scanning electron microscopy (SEM), JEOL-840A. The powder samples were suspended in isopropanol and droplets were put on a brass sample holder. After evaporation of the isopropanol, a thin gold layer was sputtered on the samples to avoid charging.

The particle size and distribution was determined with a laser diffraction system, CILAS HR 850.

**Luminescence**

The luminescence measurements were performed at room temperature, using three kinds of spectrophotometers. The first type is a Perkin-Elmer LS50B spectrophotometer with a xenon flash lamp. The lamp spectrum is corrected with a deuterium lamp. The second type is a SPEX spectrophotometer, using a deuterium lamp. For both spectrophotometers the emission spectra are recorded using excitation radiation with a wavelength of 254 nm. Furthermore, the emission spectra are recorded using a double photomultiplier. The lamp spectrum is corrected with a deuterium lamp. The third type is a SPEX spectrophotometer, using a deuterium lamp.

**Results and Discussion**

**Powder characterization.**—In our previous work we have shown that the $c/a$ ratio is a reliable measure for observing the incorporation of nitrogen in Ba-$\beta$-alumina. According to XRD measurements the unit cell dimensions change ($a$ increasing, $c$ decreasing) with increasing nitrogen content, resulting in a decreasing $c/a$ ratio as is shown in Fig. 1 for samples doped with Eu ($x = 0.1$). This phenomenon was observed previously for samples without Eu, so it can be concluded that it is possible to incorporate nitrogen.

The shape of the $c/a$ curve for samples with Eu ($x = 0.1$) is comparable to the curve reported for samples without Eu fired at 1973 K. Only the absolute $c/a$ values appear to be somewhat lower. Therefore we have determined the influence of the Eu-incorporation on the $c/a$ ratio. The $c/a$ ratio of both Eu-doped Ba aluminate phase I and BaAl$_{11}$O$_{16}$N is decreasing with increasing Eu content (see Fig. 2), which is expected since the ionic radius of Eu$^{2+}$ is smaller than that of Ba$^{2+}$. At Eu-contents of $x = 0.4$ and higher EuAl$_{12}$O$_{19}$, with the magnetoplumbite-type structure ($c/a$ ratio of 3.953), is observed as a secondary phase. This indicates that the...

![Figure 1](https://example.com/figure1.png)

**Figure 1.** $c/a$ ratio as a function of the nitrogen content ($y$) in Ba aluminium oxy nitride with the $\beta$-alumina-type structure doped with Eu ($x = 0.1$) and fired at 1973 K for 2 h.
maximum percentage of Eu-incorporation in Ba β-alumina is in between $x = 0.15$ and 0.4.

Scanning electron microscopy (SEM) pictures reveal that the powders of all Eu-doped Ba β-alumina’s consist of hexagonal shaped platelets (Fig. 3 and 4). The powder morphology of the commercial powder BAM is more regularly shaped (Fig. 4) and seems to have a more uniform grain size distribution compared to the samples synthesized in this work.

As expected on the basis of the SEM pictures the grain size distribution of commercial BAM is indeed narrower than of the other Eu-doped Ba β-alumina powders (Fig. 5). These differences are ascribed to fluxes, used in the synthesis of commercial BAM to obtain a more uniform powder morphology, and that after-treatment was applied to obtain a narrower grain size distribution.

**Luminescence properties.**—The luminescence properties are only determined for the single-phase materials but not for the samples with high Eu-concentrations ($x = 0.4$, 0.7, and 1.0).

In Fig. 6 the emission and excitation spectra are shown of Ba aluminate phase I, BaAl$_{11}$O$_{16}$N, and BaMgAl$_{10}$O$_{17}$ substituted with Eu ($x = 0.1$). In all emission spectra of the samples fired for 2 h at 1973 K, except for commercial BAM, a very small amount of Eu$^{3+}$ emission (around 610 nm) is observed. This indicates that Eu$^{3+}$ from the Eu$_2$O$_3$ starting material is not yet completely reduced to Eu$^{2+}$.

The most striking difference in the emission spectra is the presence of a shoulder in Eu-doped Ba aluminate phase I and BaAl$_{11}$O$_{16}$N and the absence of this shoulder in the spectrum of Eu-doped BaMgAl$_{10}$O$_{17}$ (Fig. 7). This is in accordance with our previous results. The differences in emission spectra between Eu-doped Ba aluminate phase I and BaAl$_{11}$O$_{16}$N is only slightly different. This indicates that nitrogen is not coordinated to europium which we have indeed proved by neutron diffraction. The significant influence of
coordination with N\(^3\)– ions was shown for a similar luminescent ion (Ce\(^{3+}\)) in Y-Si-O-N host lattices.\(^{40}\) The presence of the shoulder indicates the presence of two Eu-sites in Eu-substituted Ba aluminate phase I and BaAl\(_{11}\)O\(_{16}\)N. In a subsequent paper we focus on the luminescence properties of the two Eu sites in BaAl\(_{11}\)O\(_{16}\)N and the possibility of energy transfer between them and compare this to Ba aluminate phase I and BaMgAl\(_{10}\)O\(_{17}\).\(^{41}\)

The emission wavelength at maximum intensity of Eu-doped Ba aluminate phase I shifts to higher wavelengths with increasing europium content (Fig. 7), which is caused by an extended intensity of the shoulder. The emission wavelength of maximum intensity of Eu-doped BaAl\(_{11}\)O\(_{16}\)N only increases for low Eu concentrations. As expected, the UV-absorption becomes larger with increasing europium content approaching an asymptotic value of about 90% (Fig. 8). The UV-absorption of the Eu-doped samples fired for 4 h is higher than that of Ba aluminate phase I and BaAl\(_{11}\)O\(_{16}\)N with the same Eu concentration of \(x = 0.1\) which are fired for 2 h. This is ascribed to the longer firing time (4 h instead of 2 h) resulting in a slightly higher particle size. The UV-absorption of commercial BAM is higher, which is caused by the smaller fraction of grains below 2 \(\mu\)m. In the laboratory-made powders a significant number of the particles is smaller than 2 \(\mu\)m resulting in a lower UV-absorption due to increased scattering.

From the measured UV-absorption (\(A\)), the ratio of absorption coefficient (\(a\)) and scattering coefficient (\(s\)) was calculated using the Kubelka-Munk formula\(^{42}\):

\[
\frac{a}{s} = \frac{A^2}{2(1-A)}
\]  

(3)

As expected from the Lambert-Beer law for direct excitation of the Eu center, the calculated ratio between the absorption coefficient and scattering coefficient of Eu-doped Ba aluminate phase I is linearly dependent on the europium content and intersects the zero point (Fig. 9). However, the linear curve of the \(a/s\) ratio for Eu-doped BaAl\(_{11}\)O\(_{16}\)N does not intersect the zero point but crosses the y axis at a value of about 0.15 (Fig. 9). This is caused by the host-lattice absorption. The \(a/s\) value of \(x = 0.01\) is about 0.3 for Eu-doped BaAl\(_{11}\)O\(_{16}\)N, indicating that at this concentration about half of the photons is absorbed by the host-lattice followed by non-radiative losses. This corresponds very well with the quantum efficiency for this material that is also about half of the maximum value observed for Eu-doped BaAl\(_{11}\)O\(_{16}\)N (Fig. 10).

The large \(a/s\) ratio of Eu\(_{0.1}\)Ba\(_{0.9}\)MgAl\(_{10}\)O\(_{17}\) and commercial BAM is ascribed to the larger particle size of these powders, resulting in a smaller scattering coefficient and thus in a larger \(a/s\) ratio when the same \(a\) is assumed. This also holds for the Eu-doped powders with \(y = 0\) and \(y = 1\) as is shown in Fig. 9.

In general all samples show high quantum efficiencies (Fig. 10). The nitrogen concentration does not influence the quantum efficiency at high europium concentrations: all oxynitride samples with varying nitrogen content and substituted with \(x = 0.1\) Eu have a quantum efficiency around 80% for samples fired for 2 h and about 85% for samples fired for 4 h (Table I). As is shown in Fig. 10, the...
quantum efficiency of BaAl$_{11}$O$_{16}$N: Eu is reduced at low Eu contents. This might be caused by the presence of host-lattice absorption in BaAl$_{11}$O$_{16}$N as is shown by reflection measurement (Fig. 11). The quantum efficiency of commercial BAM is higher compared to the materials which are fired for 2 h. It is interesting to note that the quantum efficiency of samples fired for 4 h is already equivalent to commercial BAM, while these phosphors are not optimized indicating that even better values can be expected. Up to $x = 0.15$ no concentration quenching of the luminescence occurs.

Increasing the firing time from 2 to 4 h at 1733 K improves the quantum efficiency and UV absorption for the oxynitride phosphors (Table I), making the values comparable to those of commercial BAM. An increase of the particle size due to the longer firing time is expected, which results in a smaller scattering coefficient $x$ and therefore in a larger UV-absorption A (see Eq. 3). The improved quantum efficiency is ascribed to a better crystallinity of the host-lattice and to a full reduction of Eu$^{3+}$ to Eu$^{2+}$, since Eu$^{3+}$ emission is diminished after 4 h at 1733 K.

The influence of the oxidation test on the quantum efficiency, UV-absorption, and emission wavelength with maximum intensity ($\lambda_{\text{em},\text{max}}$) is given in Table II. It is clear that the quantum efficiency of the samples containing nitrogen is decreased after the oxidation test, while the quantum efficiency of the other samples is unaffected. This indicates that the nitrogen containing samples are somewhat affected by the heat-treatment in air. Since no weight losses nor peaks are observed in TGA and DTA measurements, it can be concluded that the amount of bulk oxidation is negligible. However the limited oxidation is strong enough to influence the quantum efficiency and the emission color of the samples. According to the available literature

![Figure 10. Quantum efficiency of various Eu-doped Ba $\beta$-alumina's as a function of the europium content ($x$).](image)

![Figure 11. Reflection spectra showing competitive absorption around 250 nm in BaAl$_{11}$O$_{16}$N.](image)

Table I. Quantum efficiency ($QE$) and UV-absorption ($A$) for 254 nm excitation of various Ba $\beta$-alumina phosphors doped with Eu ($x = 0.1$), Eu$_{y}$Ba$_{1-x}$Al$_{11}$O$_{16}$N$_{y}$ and commercial BAM as well as Eu$_{y}$Ba$_{0.9}$MgAl$_{1.7}$O$_{17}$. Data are shown for samples fired for 2 and 4 h at 1733 K.

<table>
<thead>
<tr>
<th>Powder type</th>
<th>$QE$ (%)</th>
<th>$A$ (%)</th>
<th>$QE$ (%)</th>
<th>$A$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Commercial BAM</td>
<td>87</td>
<td>89</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Eu$<em>{0.1}$Ba$</em>{0.9}$MgAl$<em>{1.7}$O$</em>{17}$</td>
<td>—</td>
<td>—</td>
<td>73</td>
<td>87</td>
</tr>
<tr>
<td>$y = 0$</td>
<td>83</td>
<td>81</td>
<td>85</td>
<td>84</td>
</tr>
<tr>
<td>$y = 0.17$</td>
<td>80</td>
<td>82</td>
<td>87</td>
<td>84</td>
</tr>
<tr>
<td>$y = 0.55$</td>
<td>82</td>
<td>79</td>
<td>85</td>
<td>89</td>
</tr>
<tr>
<td>$y = 1$</td>
<td>79</td>
<td>82</td>
<td>82</td>
<td>84</td>
</tr>
</tbody>
</table>

Table II. Quantum efficiency ($QE$), UV-absorption ($A$), and emission wavelength at maximum intensity ($\lambda_{\text{em},\text{max}}$) at 254 nm excitation of various Eu-doped Ba $\beta$-alumina’s (fired at 1733 K for 2 h) before and after oxidation test at 873 K for 10 min in air. The sample composition is Eu$_{y}(0.83+0.17)x$Ba$_{1-x}(0.83+0.17)y$Al$_{17.33-1.33y}$N$_{y}$.

<table>
<thead>
<tr>
<th>Sample</th>
<th>$x$, $y$</th>
<th>$QE$ (%) Before</th>
<th>$QE$ (%) After</th>
<th>$A$ (%) Before</th>
<th>$A$ (%) After</th>
<th>$\lambda_{\text{em},\text{max}}$ (nm) Before</th>
<th>$\lambda_{\text{em},\text{max}}$ (nm) After</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.05, 0</td>
<td>75</td>
<td>79</td>
<td>75</td>
<td>75</td>
<td>447</td>
<td>446</td>
<td></td>
</tr>
<tr>
<td>0.05, 1</td>
<td>78</td>
<td>72</td>
<td>73</td>
<td>73</td>
<td>456</td>
<td>453</td>
<td></td>
</tr>
<tr>
<td>0.10, 0</td>
<td>83</td>
<td>82</td>
<td>83</td>
<td>83</td>
<td>450</td>
<td>450</td>
<td></td>
</tr>
<tr>
<td>0.10, 1</td>
<td>76</td>
<td>73</td>
<td>84</td>
<td>83</td>
<td>456</td>
<td>456</td>
<td></td>
</tr>
<tr>
<td>0.15, 0</td>
<td>77</td>
<td>76</td>
<td>88</td>
<td>88</td>
<td>456</td>
<td>456</td>
<td></td>
</tr>
<tr>
<td>0.15, 1</td>
<td>80</td>
<td>74</td>
<td>87</td>
<td>87</td>
<td>456</td>
<td>456</td>
<td></td>
</tr>
<tr>
<td>Commercial BAM</td>
<td>87</td>
<td>86</td>
<td>89</td>
<td>89</td>
<td>451</td>
<td>451</td>
<td></td>
</tr>
</tbody>
</table>

Table III. Short-term depreciation (combined 185 and 254 nm) of various Eu-doped Ba $\beta$-alumina’s fired at 1733 K for 2 h.

<table>
<thead>
<tr>
<th>Sample</th>
<th>$QE$ (%) Before</th>
<th>$QE$ (%) After</th>
<th>$A$ (%) Before</th>
<th>$A$ (%) After</th>
<th>$\lambda_{\text{em},\text{max}}$ (nm) Before</th>
<th>$\lambda_{\text{em},\text{max}}$ (nm) After</th>
<th>STD (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$x = 0.05$, $y = 0$</td>
<td>0.2</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>$x = 0.05$, $y = 1$</td>
<td>5.0</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>$x = 0.10$, $y = 0$</td>
<td>1.2</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>$x = 0.10$, $y = 0.17$</td>
<td>1.7</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>$x = 0.10$, $y = 0.55$</td>
<td>2.1</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>$x = 0.10$, $y = 1$</td>
<td>3.2</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>$x = 0.15$, $y = 1$ (only 185 nm)</td>
<td>4.0</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Commercial BAM</td>
<td>0.0</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
</tbody>
</table>
toward green/white luminescence (Table IV). Also the lumen output decreases in time. To take into account the influence of the observed shift in the emission color, the lumen output was compared by taking the lumen/Y values. In Fig. 12 the lumen/Y values are shown as function of the operation time. The commercial BAM phosphor shows the highest lumen/Y output but also the strongest degradation. Therefore, the difference in lumen/Y output between BAM and the oxynitride phosphors becomes less for longer operation times.

From the emission spectrum measured for the single-component fluorescent lamp (Fig. 13) the CRI and lumen output of a tricolor lamp were calculated using these materials as the blue-emitting phosphors. \( Y_2O_3:Eu \) was taken as the red and \((Ce, Tb)MgAl_{11}O_{19}\) as the green emitting phosphor as is the case in a commercial tricolor lamp (Fig. 13) the CRI and lumen output of a tricolor fluorescent lamp (Fig. 13) the CRI and lumen output of a tricolor fluorescent lamp compared to BAM can be ascribed to the lower quantum efficiency of these materials. To take this effect into account we have performed simulations based on the assumption that oxynitride phosphors actually tested in the fluorescent lamp have the same quantum efficiency as the maximum value achieved for the barium \( \beta \)-alumina oxynitride phosphors (Table I). This results in tricolor lamps with a calculated lumen output almost equal (88 lm/W) to tricolor lamps with BAM as blue-emitting phosphor (89 lm/W) while the color rendering index improves. A possible improvement in color rendering index without loss in lumen output was predicted by Yamamoto et al.\(^4\) for blue-emitting phosphors by shifting the emission wavelength more to 480 nm. So it can be stated that novel Eu-doped Ba \( \beta \)-alumina oxynitrides are very interesting materials for use as blue-emitting phosphors in tricolor fluorescent lamps.

### Conclusions

Novel Eu-doped barium alumina oxynitride phosphors with the \( \beta \)-alumina-type structure were prepared by solid-state reactions. As expected, the \( c/a \) ratio of the \( \beta \)-alumina-type unit cell of these materials decreases with increasing nitrogen and europium content. The oxynitride phosphors show two emission bands for 254 nm excitation, similar to Eu-doped Ba aluminate phase I. The maximum quantum efficiency of the oxynitride phosphors is about 85-90% just like commercial BAM. The nonoptimized oxynitride phosphors are more sensitive to oxidation at 873 K and to short-term depreciation compared to Eu-doped Ba aluminate phase I and commercial BAM. However, the maintenance of the oxynitride phosphors is better compared with commercial BAM. The oxynitride materials are very attractive for use as a blue-emitting phosphor in tricolor fluorescent lamps, since the CRI of these tubes increases with preservation of a high lumen output.

### Acknowledgment

The authors would like to thank Slobodan Markovski for making the SEM pictures and Dick van de Voort (Philips Lighting) for his help with the luminescence measurements, calculations, and discussions.

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### Table IV. Color coordinates \((X, Y)\) and lumen output of single component TL-lamps with oxynitride phosphors

<table>
<thead>
<tr>
<th>Sample</th>
<th>(X/Y)</th>
<th>Lumen</th>
<th>(X/Y)</th>
<th>Lumen</th>
<th>(X/Y)</th>
<th>Lumen</th>
</tr>
</thead>
<tbody>
<tr>
<td>(x = 0.10)</td>
<td>0.1821/0.1876</td>
<td>240</td>
<td>0.1835/0.1910</td>
<td>223</td>
<td>0.1839/0.1929</td>
<td>156</td>
</tr>
<tr>
<td>(x = 0.15)</td>
<td>0.2012/0.2477</td>
<td>318</td>
<td>0.2026/0.2498</td>
<td>282</td>
<td>0.2026/0.2514</td>
<td>196</td>
</tr>
<tr>
<td>Comm. BAM</td>
<td>0.1593/0.0873</td>
<td>159</td>
<td>0.1591/0.0899</td>
<td>137</td>
<td>0.1590/0.0907</td>
<td>95</td>
</tr>
</tbody>
</table>

---

### Table V. Simulated performance of a tricolor fluorescent lamp as a function of the blue-emitting phosphor

<table>
<thead>
<tr>
<th>Sample</th>
<th>Calculated CRI</th>
<th>Calculated lumen output (lm/W)</th>
<th>Calculated lumen output (lm/W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oxynitride (x = 0.10)</td>
<td>89</td>
<td>82(^a)</td>
<td>88(^b)</td>
</tr>
<tr>
<td>Oxynitride (x = 0.15)</td>
<td>91</td>
<td>83(^a)</td>
<td>88(^b)</td>
</tr>
<tr>
<td>Commercial BAM</td>
<td>83</td>
<td>89</td>
<td></td>
</tr>
</tbody>
</table>

\(^a\) Based on real quantum efficiency measured for these phosphors. 
\(^b\) Based on maximum quantum efficiency achievable for these phosphors.
Eindhoven University of Technology assisted in meeting the publication costs of this article.

References