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Luminance and chromaticity characteristics of different phosphor types in laser lighting

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Abstract
Laser lighting is emerging as a viable replacement for other light sources in applications requiring high luminance not achievable with LEDs. Phosphor materials for laser lighting are often optimized in terms of luminous efficiency and/or colorimetric properties, while the light homogeneity is often neglected. We present a thorough investigation of the homogeneity of the chromaticity and the luminance profile for the most common types of phosphors used in laser lighting. We find that the achievable luminance and homogeneity of the light spot depends significantly on the phosphor used to convert the blue laser light to white light. The findings of these investigations will present guidelines for optimal phosphor material parameters to achieve high luminance combined with homogeneous chromaticity.

1. Introduction
In recent years, laser lighting has emerged as a possible way of achieving very high luminance light sources. Lasers are not limited by the efficiency droop found in LEDs limiting their efficiency at high current densities [1]. The phosphor materials used for laser lighting are similar to the materials used in LEDs. However, the organic host materials used in LEDs cannot withstand the high power density achievable using lasers. Therefore, new inorganic host materials are used. The most common phosphor types are based on single crystals (SC), transparent ceramics (TC), composite ceramics (CC), phosphor in glass (PiG) or phosphor in glass films (PiGF) [2–11]. These different phosphor materials have different advantages and disadvantages concerning their efficiency, colorimetric properties, thermal dissipation, saturation threshold, ease and cost of fabrication and so on. These parameters are all important when selecting a phosphor material for a specific application.

Another parameter with high importance in applications of laser lighting is the achievable luminance and the homogeneity and shape of the emitted light. If the colors are not mixed properly in the phosphor, the emitted light will show a poor color homogeneity making it less attractive for some applications [2, 12]. Likewise, if the phosphors are unevenly distributed within the host material or the scattering is insufficient, the light emitted from the phosphor will have intensity variations over the surface of the phosphor. This uneven intensity distribution may lead to a similar uneven distribution in the light collected by the optics, which is undesirable in most applications. However, this phenomenon is rarely discussed and investigated. Deng et al investigated the light and correlated color temperature uniformity in PiGFs using different secondary phases increasing the scattering [13]. They concluded that the addition of secondary phases improves the light uniformity. A similar phenomenon exist for phosphor converted LEDs, where selection of phosphor material parameters and geometry influences the light uniformity [14].

A commonly mentioned phenomenon in laser lighting is the ‘blue spot’ or the ‘yellow ring’ [2, 15–17]. This stems from the Lambertian emission from the phosphor and the enlargement of the luminescent spot relative to the incident laser spot. This was investigated by Krasnoshchoka et al and Xu et al and they
Table 1. List of phosphor materials used in experiments.

<table>
<thead>
<tr>
<th>Name</th>
<th>Thickness (µm)</th>
<th>Substrate</th>
<th>Particle size (µm)</th>
<th>Backside coating</th>
</tr>
</thead>
<tbody>
<tr>
<td>SC1</td>
<td>150</td>
<td>Copper</td>
<td>—</td>
<td>Yes</td>
</tr>
<tr>
<td>SC2</td>
<td>500</td>
<td>None</td>
<td>—</td>
<td>Yes</td>
</tr>
<tr>
<td>TC</td>
<td>500</td>
<td>None</td>
<td>8</td>
<td>No</td>
</tr>
<tr>
<td>CC</td>
<td>500</td>
<td>None</td>
<td>8</td>
<td>No</td>
</tr>
<tr>
<td>PiGF1</td>
<td>30</td>
<td>Corundum</td>
<td>2</td>
<td>No</td>
</tr>
<tr>
<td>PiGF2</td>
<td>30</td>
<td>Corundum</td>
<td>5</td>
<td>No</td>
</tr>
<tr>
<td>PiGF3</td>
<td>30</td>
<td>Corundum</td>
<td>15</td>
<td>No</td>
</tr>
<tr>
<td>PiGF4</td>
<td>30</td>
<td>Corundum</td>
<td>25</td>
<td>No</td>
</tr>
</tbody>
</table>

concluded that the expansion of the luminescent spot is highly dependent on the phosphor properties [5, 18]. When the light is collected and, in many cases, collimated or imaged to a distance, the luminescent part of the emission will have a larger size than the part of the light mixed with the blue laser light.

In this work, we investigate the influence of the phosphor material on the homogeneity of the light emitted from the phosphors in a laser lighting system. A large difference is seen between phosphors with capabilities for strong and poor mixing of the light. The emitted light homogeneity is investigated in terms of luminance and chromaticity coordinates for a number of commonly used phosphor materials, highlighting the advantages and disadvantages of the different materials.

2. Materials and experimental setup

2.1. Materials

The phosphor materials used in this study and some of their main characteristics are listed in table 1. The material selection consists of single-crystal phosphors (SC1 and SC2) [19], transparent and composite ceramic phosphors (TC, CC) [3] and phosphor in glass films (PiGF1, PiGF2, PiGF3 and PiGF4) [5]. All phosphors are based on YAG:Ce. The single-crystal phosphors have a mirror coating on the back facet and the incident surface is structured to enable mixing of the light. The transparent and composite ceramic phosphors are polished on both surfaces. The investigated PiGFs have different phosphor particle sizes (2 µm, 5 µm, 15 µm and 25 µm) to investigate the influence on the light emission in luminance and color. The PiGFs are deposited on corundum substrates. More information on the phosphor materials including the morphology, efficiency and photoluminescent properties of the different phosphors can be found in the cited references.

2.2. Experimental setup

All phosphor materials are investigated in a reflective geometry and a sketch of the experimental setup is shown in figure 1. The phosphor material is attached to a heatsink with reflective surface. A fiber-coupled 442 nm diode laser (SLD Laser) is imaged onto the phosphor material using a telescopic lens system to a measured circular laser spot diameter of 1.0 mm. The laser is incident on the phosphor with an angle of approximately 30° inducing a slight ellipticity in the horizontal direction. In the experiments, the laser power is kept at 1 W to avoid luminescence saturation in the phosphors. An achromatic lens (Thorlabs AC508-075-A) with 75 mm focal length and 50 mm diameter is used to collect the light emitted from the phosphor. A screen coated with barium sulfate with a spectrally even reflectivity across the visible spectrum is placed 2.5 m from the lens. The lens is positioned to image the luminescent emission point on the phosphor on to the screen and the lens position is optimized for each phosphor material. This provides the highest possible luminance and provides details on how the structure of the emission point is at the phosphor. The barium sulfate coated screen is placed in the center of a near field goniophotometer (Technoteam, RiGo-801) by use of the integrated camera system. The integrated calibrated luminance and color camera (Technoteam, LMK98-4) is used to take high-dynamic range images using filters for the CIE 1931 color matching functions of the spot on the screen and simultaneously get full chromaticity details of the entire image. The angle between the light incident on the screen and the camera is approximately 18° and the distance from the screen to the camera is 1.5 m.

3. Results

3.1. Evaluation of experimental results

The experiments provide high dynamic range luminance images and color images of the spot on the screen. The color images can be shown and evaluated in multiple color spaces, e.g. CIE 1931 2 degree x, y.
chromaticity coordinates as used in this work. Examples of the resulting images from the experiments are shown in figure 2. On the figures, different regions are shown, which are used to evaluate the luminance and chromaticity properties of the spot. The luminance profile is evaluated along a vertical cross-sectional line labeled (1) in figure 2 and the results for all phosphors are shown later in figure 4. The line is positioned to pass the position of highest luminance. An ellipse (2) is shown, which encloses the spot region with a luminance of 50%–100% of the maximum luminance. Within this ellipse, the chromaticity coordinates (x and y) of all pixels are calculated and plotted in the CIE 1931 chromaticity diagram. To further evaluate the color difference across the entire spot, the chromaticity coordinates at the edge of the central spot (on the ellipse labeled 3) are extracted and plotted in the chromaticity diagram. Finally, to evaluate the effect of the ‘yellow ring’, an ellipse (4) is included, which is positioned significantly outside the central spot. The chromaticity coordinates of all pixels on the ellipse are calculated and included in the chromaticity diagram.
Figure 3. Luminance images of five different phosphors on a linear (top) and logarithmic (bottom) scale. The phosphors are: (a) SC2, (b) TC, (c) CC, (d) PiGF1 and (e) PiGF4. For a relative color scale, see figures 2(c) and (d).

3.2. Luminance distribution

The luminance at the screen is measured by the camera providing 2D images of the luminance distribution. Example luminance images are given in figure 3 for five different phosphor materials. It is seen that the luminance distribution is relatively similar for the different phosphor materials. However, there is a slightly increased inhomogeneity in the luminance image, when the phosphor surface is less homogeneous, for instance for the PiG film with large particle size in figure 3(e). Further it can be observed that the single crystal phosphor in figure 3(a) has a relatively high background light level. This was observed for both single crystal phosphors and is believed to be caused by internal reflections within the crystalline material coupling the light to the entire crystal. For the transparent ceramic phosphor in figure 3(b), the spot is highly confined due to the absence of scattering in the material or the surfaces. The low intensity spots seen in the logarithmic scale luminance image are caused by the reflecting surface of the heat sink. For the composite ceramic phosphor and the PiGFs, the luminance images in figures 3(c)–(e) are quite homogeneous and similar. This is due to the scattering in the material and at the surfaces.

Taking a vertical cross section through the luminance image at the position of maximum luminance as shown in figure 2 gives the luminance profiles and this can be seen for all the different phosphors in figure 4. The normalized luminance is given, as the absolute luminance depends on many other phosphor parameters such as the phosphor concentration and efficiency. In general, the measured luminance levels were similar for the CC and PiGF phosphors and somewhat lower for the TC and SC phosphors. There is a small difference between the different profiles but overall, they are quite similar. Two outliers are the transparent ceramic phosphor (TC) and the single crystal phosphors (SC1 and SC2). The transparent ceramic phosphor (TC) shows a more confined luminance profile. This is expected, since no scattering is present to enlarge the incident blue light and thus the emitted luminescence comes from a smaller volume. As also observed in figure 3(a), the structured single crystal phosphors (SC1 and SC2) have a wider tail in the luminance profiles. This is most likely caused by the structure on the surface in combination with the reflector on the rear side as well as by internal reflections in the crystalline material. The luminance images in figure 3(a) show that the entire phosphor lights up, which is causing the increased luminance outside the central region.

3.3. Chromaticity distribution

High dynamic range color images of the spot were acquired for all the phosphors and in figure 5, the images are shown for five different phosphor materials. It can be seen that the size of the spots is similar for all phosphors, when observed on a linear scale, while on a logarithmic scale, significant differences are seen. There are some obvious differences. For the single crystal phosphor (SC2) in figure 5(a), the central spot is very bluish, while the region outside the central spot is yellowish. The transparent ceramic phosphor (TC) (figure 5(b)) emits yellow light with almost no blue content and the spot is very confined as also seen in the luminance images in figure 3(b). For the composite ceramic phosphor (CC) (figure 5(c)) and the PiGFs (figures 5(d) and (e)), the central spot is almost white while the region around the central spot is yellowish. For PiGF4 with 25 µm particle size, a clear inhomogeneity can be observed in figure 5(e) with white and yellowish regions clearly separated. A minor inhomogeneity can also be observed in CC (figure 5(c)), which has a particle size of 8 µm, whereas almost no inhomogeneity is observed for PiGF1 with 2 µm particle size.
Figure 4. Cross-sectional luminance profiles for the different investigated phosphors on linear and logarithmic scales. (a) and (b) Single crystal, transparent ceramic and composite ceramic phosphors; (c) and (d) Phosphor in glass films with different particle sizes.

Figure 5. Color images of five different phosphors on a linear (top) and logarithmic (bottom) scale. The phosphors are: (a) SC2, (b) TC, (c) CC2, (d) PiGF1 and (e) PiGF4. The top images show a smaller region than the bottom images as illustrated in (a). This indicates that the particle size in the phosphor materials significantly affects the chromatic homogeneity of the emission spot.

From the high dynamic range color images in figure 5, the $x$–$y$ chromaticity coordinates can be extracted at different positions in the images as shown in figure 2. The variation of chromaticity coordinates within the spot can thereby be found for the different phosphors. Chromaticity diagrams for the different investigated phosphor types can be found in figure 6. It is seen that not only is there a large variation between the different phosphors but also for the individual phosphors, the chromaticity depends significantly on the position in the images. For the single crystal phosphors (SC1 and SC2), the central spot is quite bluish, while the region around is mostly yellow. For the transparent ceramic phosphor (TC), the entire spot is yellow as no blue light is mixed into the direction of the collecting lens. For the composite ceramic phosphor (CC) and
Figure 6. Chromaticity coordinates in the CIE 1931 chromaticity diagram for the four different phosphor types in the regions shown in figure 2. For the individual phosphors, the chromaticity coordinates are plotted for a region in the central spot (2), at the edge of the central spot (3) and in the yellow ring (4). The chromaticity coordinates are plotted for (a) SC1 (black dots) and SC2 (blue dots), (b) CC (black dots) and TC (blue dots), (c) PiGF1 (black dots) and PiGF2 (blue dots) and (d) PiGF3 (black dots) and PiGF4 (blue dots). In (b), all chromaticity coordinates for the TC (blue) are in the yellow spectral range and thus all within the ellipse showing region 4. In (d), the red ellipses encircle chromaticity coordinates for the two phosphors in region 3, while the blue ellipses encircle chromaticity coordinates for the two phosphors in region 4.

the PiGFs with small phosphor particles, the chromaticity within the central spot is fairly homogeneous, while they all suffer from a ‘yellow ring’ to some degree. For the PiGFs with 15 μm and 25 μm particle sizes, the chromaticity within the central spot varies significantly more than for smaller particles (figure 6(d)). This is most likely because the regions between phosphor particles are larger, causing less phosphor-glass interfaces and thus insufficient scattering.

It is important to state that by measuring the entire luminescence from the different phosphors using an integrating sphere, the chromaticity coordinates for all phosphors are quite similar and close to the Planckian locus, despite the large differences observed in figure 6. This is because an integrating sphere collects all the light independent of the scattering properties of the phosphor.
4. Discussion

In the investigations above, significant differences are found between the different phosphor materials. It was found that the central spot luminance profile is similar for all phosphor materials, although the absolute luminance obviously also depends on the luminous efficiency of the materials. The most significant difference in the luminance profiles is found outside the central spot, where the composite ceramic phosphor tend to be better at confining the light and the single crystal phosphors tend to show enlarged 'wings' in the luminance profiles. In most practical applications it is desirable to have the spot as confined as possible to obtain high luminance favoring the ceramic phosphor and the PiGFs also showing reasonably good confinement.

Considering the chromaticity, the differences between the phosphors are large. Especially the ability to mix colors and achieve a homogeneous chromaticity across the spot varies significantly. One extreme is the single crystal phosphors, that show a bluish central spot and the remaining material emitting yellowish light. This renders it challenging to achieve homogeneous white light in an application. On the contrary, the composite ceramic phosphor and PiGFs with small particle sizes show a fairly homogeneous chromaticity across the central spot, while they all show a yellow ring to different degrees. With such phosphors, it is less challenging to achieve good homogeneity in the chromaticity of the emitted light. From both the luminance and chromaticity investigations, it is clear that scattering inside the phosphor materials plays an important role in mixing the light in order to reach the desired lighting properties. Scattering not only ensures good color mixing but also aids in confining the light, which is most obvious for the single-crystal phosphors, where the absence of internal scattering enables the luminescent light to spread to the entire phosphor plate. However, the size of the scattering centers also plays a significant role in ensuring the desired properties. The scattering in the composite ceramic phosphor mainly takes place at interfaces between phosphor particles and secondary phases e.g. MgO or Al₂O₃, while for the PiGFs, scattering also occurs at small air bubbles trapped inside the material. If the mean scattering path is too long, as is the case for large particles, the light mixing becomes insufficient and especially the homogeneity of the chromaticity becomes inferior. However, the choice of phosphor material comes down to the requirements of the application and the production cost of the phosphors also plays a significant role for commercialization.

5. Conclusions

In this work, we investigated the influence of the phosphor material properties on the resulting luminance and chromaticity distribution in the light spot. Four different types of typical phosphor materials for laser lighting were investigated showing significant differences in the projected light. The luminance profiles of all phosphor materials show a similar central spot, while the luminance in the area surrounding the central spot depends critically on the phosphor type. The chromaticity also highly depends on the phosphor type, where especially the homogeneity of the chromaticity and the extent of the 'yellow ring' varies significantly between the different phosphor types. This work provides important information for selection of optimum phosphor materials for different applications of laser lighting.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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