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Krasnoshchoka, Anastasiia; Hansen, Anders Kragh; Thorseth, Anders; Marti, Dominik; Petersen, Paul Michael; Jian, Xu; Jensen, Ole Bjarlin

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Phosphor material dependent spot size limitations in laser lighting

ANASTASSIA KRASNOSHCHOKA,1 ANDERS KRAGH HANSEN,1 ©
ANDERS THORGENSETH,1 © DOMINIK MARTI,1 © PAUL MICHAEL PETERSEN,1 XU JIAN,2 AND OLE BJARLIN JENSEN1,1,*

1DTU Fotonik, Department of Photonics Engineering, Technical University of Denmark, 4000 Roskilde, Denmark
2Lab of New Energy Materials and Devices, School of Physics and Electronic Information, Henan Polytechnic University, Jiaozuo 454000, China
*ojen@fotonik.dtu.dk

Abstract: In laser lighting, a major benefit over other lighting techniques is the possibility to achieve very high luminous exitance. Focusing the exciting laser to a very small spot size on the phosphor, however, does not necessarily provide a very small emitting area for the white light. In this study we investigate experimentally and numerically the relationship between the white light spot size and the incident blue laser spot size. We show that the specific phosphor material properties have significant impact on this relationship and on the achievable minimum spot size. This constitutes a limitation on the minimum spot size achievable in laser lighting and has important implications in applications.

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1. Introduction

Solid-state lighting based on LEDs provides high efficiency and good colorimetric properties and has replaced incandescent light in most applications. Phosphor converted laser lighting is becoming a competitive alternative to other solid-state lighting technologies based on LEDs [1,2]. The ability to focus the excitation laser source to a small spot size results in white light emitted from a very small area. This, in turn, enables efficient collection and collimation of the white light, something that cannot be easily achieved with LEDs. This is the main reason that laser lighting is now being implemented in car headlights and projectors. Many studies have focused on investigating colorimetric properties and luminescence saturation in phosphors due to the high incident power density [3–8]. Only few studies have investigated the light distribution from the phosphor converted laser lighting and mainly with the focus of simulating the heat distribution in the phosphor materials [9–12].

Wierer et al. discussed the advantages of laser diodes in solid-state lighting. One of the main advantages mentioned was the possibility of highly directional emission due to the small emission area on the phosphor [2]. One way of assuring that the emission spot from the phosphor remains small is to limit the size of the phosphor. Masui et al. demonstrated a light source, where the blue laser light was focused onto a 650 µm diameter phosphor plate to achieve a high luminous exitance of up to 270 cd/mm² [13]. This approach, however, has limitations in terms of thermal handling.

Some efforts have also been put on modeling of light transport in phosphor materials and the impact on temperature distribution in the phosphors [11,14,15]. A similar model was used to simulate the temperature distribution in a laser excited silicone based phosphor with experimental verification [16]. Optimizing the beam shape of the laser beam to limit thermal quenching effects has been performed in a transmissive phosphor configuration with simulation and experimental verification [17]. Recently, Zheng et al. made some experimental investigations on the impact of
scattering on the shape of the generated luminescent spot [18]. They found that the pore structure of ceramic phosphors have great influence on the light distribution.

In this work, we experimentally and numerically investigate the light distribution in phosphor converted laser lighting. We find that the luminescent spot size depends strongly on the phosphor material properties and depends almost linearly on the input blue laser spot size. A minimum luminescent spot is achieved using highly absorbing and low scattering phosphors with polished surfaces. Surface roughness and material scattering increases the luminescent spot size. We find a good overall agreement between simulations and experiments.

2. Numerical model

When light is incident on a material, a number of scenarios are possible for the individual photons. A photon may be reflected at the entrance surface, transmitted through the material or scattered inside the material and either absorbed or transmitted. In a luminescent material, the absorbed photons give rise to emission of luminescent light.

Light propagation in the phosphor materials was modelled using the Monte Carlo method with implementation of fluorescence. Monte Carlo (MC) methods are generally considered accurate and flexible for modelling light transport in homogeneous and non-homogeneous materials by numerically solving the radiative transfer equation. One of the most widely used nonhomogeneous material models is the multilayered tissue model [19]. Here it is assumed that all the layers are flat and have uniform optical parameters along the layer, and it is often employed to model biological tissues or light propagation in LEDs [15,16,20]. Although the model in this paper is also multilayer-symmetric, we chose to use the new software suite MCmatlab in which no symmetries are assumed [21], as MCmatlab is capable of simulating fluorescence or other photoluminescence effects. The Henyey-Greenstein phase function was used to include the scattering anisotropy.

We used a two-layer model to simulate the phosphor samples used in this work. In this model, the first layer was the phosphor material and the second layer was either air or metal for transmitting or reflecting phosphor geometries, respectively. Blue light enters the phosphor layer from above, where it may undergo scattering or absorption. If the blue light is absorbed it may be re-emitted as luminescence. When the photons reach the bottom layer they may be transmitted in air or reflected at a metal surface, depending on the phosphor sample.

In the model, the following optical properties have to be defined: the absorption coefficients $\mu_a$ at the excitation wavelength $\lambda_e = 450 \text{ nm}$ and the luminescence wavelength $\lambda_l = 580 \text{ nm}$, the scattering coefficients $\mu_s$, assumed to be the same at both wavelengths and the anisotropy factor $g = 0.75$ [22], assumed to be the same for both wavelengths. The absorption of the luminescent light is assumed to be negligible. We further assume that the optical properties of the phosphor layer for the luminescent light are independent of wavelength, although the luminescent light itself is broadband, and use the optical properties at a representative wavelength of 580 nm. These assumptions were previously shown to be valid [15]. We have used different parameters for modelling the different phosphor materials with parameters extracted from the literature [22–24] and estimated values, see Table 1. Air was simulated as completely transparent, while the metal was modelled as a surface reflecting all photons.

In our model, shown as a flow chart in Fig. 1, we use the method of stochastic forward propagating photon packets in volumes with a set of specified optical properties of the phosphor material. The MC simulation follows the same steps as outlined in [8], with the difference that the launch position and direction of a photon packet is randomly generated according to the specified source distribution. The incident blue light is initialized such that the photon packets form a Gaussian beam profile on the surface of the phosphor, while the surface structure of the phosphor material determines which angular distribution the input light is initialized with. For materials with an optically plane surface, we used a Gaussian angle distribution of the input blue light,
Table 1. Phosphors investigated in the experiments with parameters used in the simulations

<table>
<thead>
<tr>
<th>Name</th>
<th>Material</th>
<th>Thickness</th>
<th>$\mu_a$/cm$^{-1}$</th>
<th>$\mu_s$/cm$^{-1}$</th>
<th>Front Surface</th>
<th>Rear surface</th>
</tr>
</thead>
<tbody>
<tr>
<td>SC</td>
<td>Single crystal Ce:YAG</td>
<td>500 µm</td>
<td>100</td>
<td>0.001</td>
<td>Polished</td>
<td>Air</td>
</tr>
<tr>
<td>TC</td>
<td>Transparent ceramic Ce:YAG</td>
<td>200 µm</td>
<td>100</td>
<td>0.001</td>
<td>Polished</td>
<td>Air</td>
</tr>
<tr>
<td>CC</td>
<td>Composite ceramic Ce:YAG</td>
<td>250 µm</td>
<td>40</td>
<td>100</td>
<td>Rough</td>
<td>Air</td>
</tr>
<tr>
<td>PiG</td>
<td>Ce:YAG phosphor in glass</td>
<td>150 µm</td>
<td>40</td>
<td>100</td>
<td>Rough</td>
<td>Air</td>
</tr>
<tr>
<td>Phoscera</td>
<td>Ceramic Ce:LuAG and Eu:nitride</td>
<td>65 µm</td>
<td>300</td>
<td>100</td>
<td>Rough</td>
<td>Air</td>
</tr>
<tr>
<td>Cryphosphor</td>
<td>Single crystal Ce:YAG</td>
<td>250 µm</td>
<td>70</td>
<td>0.001</td>
<td>Rough</td>
<td>Metal</td>
</tr>
</tbody>
</table>

while we used a Lambertian angle distribution for the rough, highly scattering surfaces. The result of this first Monte Carlo simulation run is the fluence rate distribution $F$ of the excitation light inside the phosphor material.

The distribution $n$ of photoluminescence emitters can then be calculated using the local luminescence power yield $Y$ and absorption coefficient $\mu_a$ by $n = Y \mu_a F$. The distribution of luminescence light is then found by running a second Monte Carlo simulation using the distribution of emitters as the source and by using the optical properties of the phosphor material at a characteristic luminescence wavelength $\lambda_l$ instead of the excitation wavelength $\lambda_e$.

The distribution of light inside the phosphor material can be calculated using the model. For this work, we are mainly interested in the outgoing photon distribution that an external observer such as a camera will see when looking at the phosphor surface.
For phosphors with rough surfaces, the angular distribution of exiting light will be Lambertian, so the 2D light intensity distribution on the top surface is sufficient to determine the luminous exitance and to describe what such an observer would see when imaging the surface of the phosphor. For phosphors with smooth surfaces, the angular distribution of photons leaving the phosphor is non-Lambertian, and an observer imaging the phosphor surface would see not just the intensity distribution on the surface but also light emitted in the bulk of the phosphor and not scattered at the surface. MCmatlab can also calculate the images formed from imaging such smooth surfaces with a given lens, although more statistics are then needed since relatively few photons are collected by the lens.

In each simulation, a sufficient number of photon packages were launched to reach a smooth distribution of photons at the observation plane. The size of the simulation volume was chosen individually for each phosphor material in order to ensure that only few photons exit at the side boundaries of the simulation volume.

3. Experimental setup

A schematic of the experimental setup is shown in Fig. 2. For excitation of the phosphor, a diode laser at 450 nm was used (Nichia). The beam was collimated and focused and the beam size along the focused beam was measured. In both the measurement and the modeling, the definition of spot size is important. We use the 1/e² beam width, which is also often used for characterizing laser beams. The laser beam profile was Gaussian and the spot size (diameter) was varied in the range 40 µm to 500 µm, which was limited by practical restrictions from access to the phosphor with the imaging system. The laser spot size on the phosphor was varied by changing the distance from the focusing lens to the phosphor. For the measurements, an optical power of 120 mW from the blue laser was used.

For characterization of the spot size of the luminescent light emitted from the phosphors a 4f imaging system was constructed using 2 achromatic lenses with 100 mm focal length. At the image plane, a CMOS camera (Thorlabs DCC1545M) was positioned. The imaging system was positioned to monitor the spot size in reflection mode, i.e. on the side of the phosphor where the laser light was incident. In order not to block the incident laser light, the imaging system was placed at an angle of approximately 30°. The resulting impact on the measurements was corrected numerically to an on-axis equivalent image. In the beam path of the imaging system, optical filters were placed to filter out residual blue light scattered off the phosphor surface and a neutral density filter was positioned in front of the camera to adjust the incident power level. Due to the limited depth of focus, the positioning was very important in order to obtain accurate spot size measurements. The pixel pitch of the camera was 5.2 µm, which limited the resolution for the smallest spot sizes measured.
We investigated different phosphor types in the setup, listed in Table 1. The phosphors were based on Ce:YAG or Ce:LuAG as the luminescent material. The main differences between the phosphors were their thickness, transparency and surface structure. The single crystal, transparent and composite ceramic Ce:YAG and the phosphor in glass were all single bulk materials without substrates or coatings and lateral dimension 10 mm × 10 mm, while the Phoscera (NTK Ceratec) was deposited on a 20 mm diameter sapphire substrate and the 5 mm × 5 mm Cryphosphor (Crytur) was bonded to a reflecting substrate. All phosphors were measured in reflection to allow comparison of the results. The methods used here can be translated to measure in transmission as well.

The phosphor materials used in the experiments had different material properties and the modeling had to take these differences into account. The transparent ceramic and single crystal Ce:YAG had high absorption and low bulk and surface scattering. The composite ceramic, phosphor in glass and Phoscera all had relatively high scattering and absorption. The Cryphosphor had high absorption, low bulk scattering and strong surface scattering as well as a mirror layer on the rear facet. The parameters used in the simulations are given in Table 1, with the absorption coefficient given at 450 nm and the scattering coefficient at both wavelengths. For the transparent phosphors, the absorption coefficient was measured while for the scattering phosphors, the absorption and scattering coefficients were estimated.

4. Results

The luminescent light was imaged onto the camera and the spot measured. The profile of the spot depended strongly on the phosphor material. In Fig. 3, the profiles of the luminescent spots are shown for three different phosphors at 40 µm and 320 µm spot size of the blue laser. Included in Fig. 3 are the simulated profiles of the luminescent spots for the same phosphors at 40 µm and 320 µm spot size of the blue laser. It is seen that there is good agreement between the experimental and simulated results. In Fig. 3, the intensities are normalized in order to compare the results. In absolute values, the intensities differ due to the different efficiencies of the phosphors and the different spot sizes.

![Fig. 3.](image)

**Fig. 3.** Measured (solid lines) and simulated (dashed lines) luminescent spot profiles at 40 µm and 320 µm incident blue laser spot sizes for (a) transparent ceramic Ce:YAG, (b) composite ceramic Ce:YAG and (c) Cryphosphor. Note the different x-axes scales.

From Fig. 3, it is evident that the profile varied strongly with a narrow spot for the transparent ceramic material, while the spot was enlarged to different degrees by surface roughness and scattering in the remaining two materials. Especially the shoulders of the profiles are enhanced making the luminescent spot Lorentzian-like. It is also evident that the spot size definition is important as for instance a 1/e or full width at half maximum (FWHM) definition would significantly underestimate the spot size in highly scattering materials because of the enhanced shoulders.
When the incident blue spot size was changed, the spot size of the luminescent light also changed. The dependence of the luminescent spot size on the incident blue spot size for the phosphors in Table 1 is shown as markers in Fig. 4. The samples with polished surfaces and low/no scattering had a luminescent spot size close to that of the incident blue laser beam. In contrast, the samples with high scattering and rough surfaces had a significantly larger luminescent spot than the incident blue laser. This indicates that there is a minimum achievable spot size for the generated white light even if the blue light is very tightly focused.

In the simulations, we varied the input blue laser spot size as in the experiments. The resulting simulated luminescent spot sizes for the different input parameters are shown as lines in Fig. 4. Note that the simulated results for the single crystal and transparent ceramic phosphors are nearly identical. As seen, there is an overall good agreement between the simulated and measured results. However, it has to be taken into account that the absolute values of $\mu_a$ and $\mu_s$ for the different materials were unknown and only estimated numbers were used.

Other topics of practical interest are the colorimetric properties, the color mixing and thermal and optical saturation in the phosphors. These topics are outside the scope of this work but it was generally noted that the color mixing in the transparent samples was very poor, while it was overall good in the scattering samples. The correlated color temperature (CCT) and color rendering index (CRI) for the Ce:YAG based phosphors were approximately 6000 K and 60-70 respectively, while they were approximately 4000 K and 85 for the Phoscerea phosphor. At the power level and power densities used in this work, no saturation was noticed by monitoring the spectrum during the experiments.

The dependency of the luminescent spot size on the scattering and absorption properties of the phosphor material can be investigated by varying these parameters in the model. We have in Fig. 5 plotted the simulated luminescent spot size as function of the absorption and scattering coefficients for a phosphor material with rough surface and 200 μm thickness. In Fig. 5(a) it is seen that the absorption coefficient has large impact on the luminescent spot size. The higher the absorption, the smaller the luminescent spot. In Fig. 5(b) the influence of the scattering coefficient is shown. Surprisingly, the scattering coefficient of the material seems to have only minor influence on the luminescent spot size. We also investigated the influence of the anisotropy on the resulting luminescent spot size. A representative result is shown in Fig. 6(a) for a 200
µm thick phosphor with rough surface and with a fixed value for the scattering coefficient, two different values for the absorption coefficient and two different spot sizes. It is evident that the anisotropy has significant influence on the resulting luminescent spot size. Finally, the influence of rear surface mirror coating on the luminescent spot size was investigated and the results are shown in Fig. 6(b). A 200 µm thick phosphor with a rough front surface with and without a rear surface mirror coating was studied at two different absorption coefficients. A clear enlargement of the luminescent spot size is evident for the simulated phosphors with rear surface mirror coating.

Fig. 5. Change of the luminescent spot size vs (a) absorption coefficient for fixed scattering coefficients and (b) scattering coefficient for fixed absorption coefficients for two input spot sizes of 40 µm and 320 µm into a 200 µm thick phosphor material with a rough surface.

Fig. 6. (a) Dependence of the luminescent spot size on the scattering anisotropy for a 200 µm thick phosphor material with rough surface and a scattering coefficient of 100 cm\(^{-1}\). The dependence is shown for two different absorption coefficients and two input blue spot sizes. (b) The influence of a rear side mirror coating on the luminescent spot size for a 200 µm thick phosphor material with rough surface and a scattering coefficient of 100 cm\(^{-1}\). The dependence is shown for two different absorption coefficients.

5. Discussion

The properties investigated in this work were the absorption and scattering coefficients, the scattering anisotropy and the use of a rear surface reflector. These properties influence the luminescent spot size in different ways as described in the following. Generally, the higher the absorption coefficient, the smaller a luminescent spot is achieved. This can be explained by the lower penetration depth and transverse diffusion distance of the blue light and thus the smaller volume from which the luminescent light is emitted.
The scattering coefficient of the phosphor material only has a small impact on the luminescent spot size. This may seem surprising but can be understood when looking at the distribution of the absorbed blue light and considering that the luminescent light is emitted isotropically. The lack of directionality of the luminescent light means that additional scattering only has little influence on the distribution of the light. Furthermore, high scattering tends to confine the light in a smaller volume instead of distributing it in a larger volume [22].

The scattering anisotropy of the phosphor material has significant impact on the luminescent spot size. However, for most commonly used phosphor materials, the size of the particles is significantly larger than the wavelength of the light. This means that Mie scattering is dominant and significant forward scattering will occur, meaning a scattering anisotropy in the range 0.5 to 0.9. In this range, the influence of the anisotropy is relatively modest with typically less than 10% variation of the luminescent spot size.

The rear surface reflectivity of the phosphor has significant impact on the luminescent light distribution. A reflecting surface increases the luminescent spot size as the isotropically emitted luminescent light incident on the rear surface will be reflected. Travelling the distance back to the input surface naturally increases the luminescent spot size.

The input surface structure also has significant impact on the luminescent spot size. At a smooth surface, the input blue light is transmitted straight through and absorbed in an apparent area almost the same size as the spot size on the surface. With a rough surface with a proper structure, the blue light is scattered isotropically in all directions making the distribution inside the phosphor material almost Lambertian. This means that the absorption volume of the blue light is significantly larger than for a smooth surface. The increased absorption volume increases the volume of emission of luminescent light, which increases the luminescent spot size.

The thickness also has large influence on the luminescent spot size. However, in most practical applications, the thickness will be optimized to ensure sufficient absorption of the blue light and at the same time allow for good thermal handling, as the thermal conductivity of most phosphor materials is relatively low. The enlarged spot size of both the blue and luminescent light in phosphors with a rough surface potentially helps reducing the thermal quenching in the phosphor material. The thermal load on the phosphor material is in this case distributed over a larger volume resulting in a lower local temperature in the phosphor thus resulting in lower thermal quenching.

6. Conclusion

We have investigated one of the major benefits of laser lighting over other light sources, namely the possibility to achieve a high luminous output from a small area resulting in high luminous exitance. The results of both our numerical and experimental investigations show that the achievable luminous exitance depends strongly on the properties of the luminescent material used. To various degrees, the luminescent spot will be larger than the incident blue laser spot.

The enlarged luminescent spot relative to the laser spot size will impact the performance of luminaires using laser lighting. A larger luminescent spot will result in larger divergence if the white light is to be collimated or result in reduced transmission through optical systems. One possible solution to minimize the impact of the enlarged luminescent spot is to cut the phosphor material to the desired lateral dimensions, thus effectively limiting the spot size. This solution may, however, result in worse thermal handling and lower efficiency.

Depending on the needs of the application, it will be necessary to develop and select phosphor materials based on these findings. As we have shown in this work, several parameters can be varied to have the desired light output.
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