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Thermal effect of laser beam on solid-state lighting application

Dimitrios Kyrginas
LAPLACE (Laboratoire plasma et conversion d'énergie)
Université Toulouse III - Toulouse, France
kyrginas@laplace.univ-tlse.fr

Benoît Glorieux
CNRS, ICMCB, Université de Bordeaux - Pessac, France
benoit.glorieux@icmcb.cnrs.fr

Gérald Ledru
LAPLACE (Laboratoire plasma et conversion d'énergie)
Université Toulouse III - Toulouse, France
gerald.ledru@laplace.univ-tlse.fr

Georges Zissis
LAPLACE (Laboratoire plasma et conversion d'énergie)
Université Toulouse III - Toulouse, France
georges.zissis@laplace.univ-tlse.fr

Abstract—Solid-state lighting devices become more common nowadays, taking the place of old conventional lighting sources such as incandescent lamps. A new, emerging and highly promising solid-state light source is the laser-driven phosphor conversion device. In this study, we investigate the thermal effect the laser beam has on the phosphor and specifically on the phosphor matrix, which in our case is based on silicon. Such a light source works by converting the laser beam to white light, using a suitable phosphor for the conversion process. Typical samples are phosphors like: YAG:Ce³⁺, GYAG:Ce³⁺ with nitride, with the excitation source being a blue 450 nm or a violet 405 nm laser diode. In this work, we simulate the thermal effect of the laser beam on a typical phosphor sample and how some beam characteristics like the beam radius affect the sample thermally.

Keywords— Solid-state lighting, laser diode, phosphor, thermal effects

I. INTRODUCTION

The last two decades have seen the rise of solid-state lighting devices, with the usage of LEDs being adopted in a variety of sectors ranging from automotive [1] to agriculture [2]. What makes high brightness LEDs attractive their small size, a long lifetime and more importantly their low energy consumption. White light generation by LEDs can be achieved by three particular methods: light color mixing of blue, green and red LEDs [3], phosphor conversion of a blue LED coupled with a yellow phosphor [4] and by coupling a violet or ultraviolet LED with a blue, green and red phosphor [5].

While LEDs are considered a staple both in industry and research, they are not an ideal solution. Their flaw originates from the decrease in external quantum efficiency which happens when the device operates under high current or high temperature and this effect is called efficiency droop [6]. There are many mechanisms responsible for the droop effect but it is mainly attributed to Auger effect where an electron-hole pair recombines without emitting a photon [7]. This affects the emitted light by shifting the peak emission wavelength and by broadening the emission spectrum. The result is a spectrum with a different ratio of emitted light, thus affecting the colorimetric parameters of the emitted light such as the Correlated Color Temperature (CCT) and the Color Rendering Index(CRI).

A solution to this predicament is the replacement of the LED source with a laser diode (LD). In this case, the loss in the external quantum efficiency does not happen due to the output power and external quantum efficiency of the laser diode following a linear increase with the operating current. This results in a color stable emission device and it also allows to exploit other laser characteristics such as its high brightness, its monochromaticity and the beam directionality in different applications.

The use of a laser diode solves on the one hand the efficiency problems caused by the LED but introduces a new parameter to consider, that of the material heating due to the interaction of the laser beam with the phosphor material. Knowing how the phosphor is affected thermally by the laser beam is crucial because it helps avoiding issues of overheating the material and causing degradation, therefore reducing the light conversion efficiency and the lifetime of the device. One first precaution is to operate the lighting system in a remote configuration, meaning that the laser and the material are placed in a distance, usually at 10 cm. In order to study how the material is heated by the laser beam, we simulate a simple laser-driven phosphor lighting system to observe the temperature distribution on the sample using FEM (Finite Element Method) analysis.

II. FEM ANALYSIS OF LASER HEATING

A typical phosphor conversion solid-state lighting device employing a laser diode, usually has the following configuration. An USHIO HL40085G violet laser diode, with an emitting wavelength of 405 nm and an optical power output of 1000 mW, is placed at 10 cm from the phosphor material. The sample in our case is a mix of three different phosphors, a blue BAM (BaMgAl₁₀O₁₇:Eu²⁺ Sigma Aldrich), a green cerium doped yttrium aluminum garnet (GYAG) of Intematix and a red nitride phosphor. All three phosphors are incorporated in the same silicon matrix. The thickness of the phosphor sample is 1 mm.

The emitted laser light is directed to the phosphor and excites it. As the sample is illuminated, it converts a part of the laser beam to white light due to the Stokes shift process. A glass filter can be used to cut any remaining laser light and then the generated white light is recorded by a spectroradiometer in order to characterize it photometrically. The constant illumination of the phosphor by the laser beam is responsible for a temperature buildup on the material.

Depending on the application, the accumulated heat on the sample can be either beneficial or detrimental to the device and its purpose.

The simulation and analysis of the incident heat flux from the laser as a spatially distributed heat source on the surface of the phosphor can be done by numerically solving the heat equation (1), in the time dependent form:

$$q = -k\nabla T \quad (1)$$

That way the transient thermal response of the phosphor wafer is obtained. This process is repeated several times for different heat transfer models. Each time the average, maximum and minimum temperatures as well as the temperature distribution across the entire silicon wafer is shown.

The first model to start with is the simpler approach of a 1 mm thick sample being illuminated by a 1000 mW laser beam, with the laser directed at the center of the wafer. We assume the system is under good thermal insulation from the environment. Fig. 1 shows the temperature distribution on the sample.

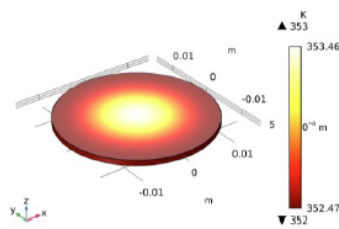


Fig. 1. Temperature variation across the phosphor wafer.

From Fig. 1 we observe that the temperature is maximum in the center of the sample and then is gradually decreasing towards the circumference of the phosphor. The shape of the heat distribution is the result of the laser beam shape. The above can also be verified through the isothermal contours graph (Fig. 2).

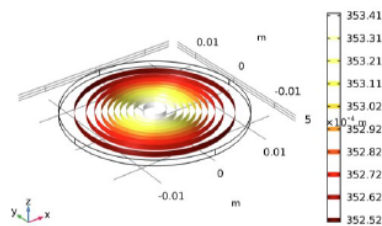


Fig. 2. Isothermal contours graph.

It should be noted that even though the temperature on the sample is not homogenous, the variation is not significant, ranging at 1 K from the center to the circumference. This is better depicted on Fig. 3 where the minimum, the maximum and the average temperatures are presented temporally.

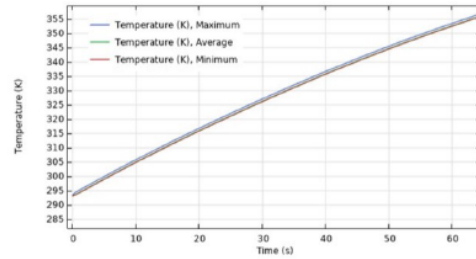


Fig. 3. Maximum, average and minimum temperatures as functions of time.

While their individual values are almost the same, the initial temperature of the sample with the one after 60 s is very different. All three temperature values start from 295 K (room temperature) and reach up to 355 K.

For the next model, the parameter of the laser beam radius is studied to see what its effect on the heat transfer on the wafer is. Four different radii for the laser beam were studied with the following values: 1 mm, 5 mm, 15 mm and 20 mm. The figure below (fig. 4) shows the temperature variation on the wafer for each case.

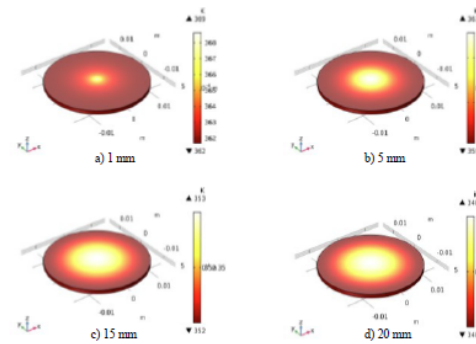


Fig. 4. Temperature variation across the phosphor wafer for different laser beam radii.

As it is expected, a narrower laser beam, i.e., smaller radius, results in a high temperature concentration in the center of the material. The more the laser beam radius increases, the more homogenous the heat transfer becomes, with the temperature distribution on the sample having the almost the same value both at the center and at points at the circumference. Furthermore, the variation between the maximum and minimum values for each case is different, ranging from 7 K for the 1 mm radius laser beam, down to 1 K for the 20 mm radius laser beam. All these values are summarized in the following table (Table I). The above findings suggest that an optimal laser beam is that that illuminates the entirety of the phosphor wafer, creating homogenous heat transfer conditions on the sample. With the use of appropriate optics components such as lenses, the conditions described above can easily be achieved, resulting in a homogeneously illuminated and heated sample. The

phosphor wafer, in this case will convert laser light to white light in a more efficient way due to the whole material contributing to the light conversion while on the same time the lifetime of the is expanded because of the better heat distribution as well as the lower temperature being developed on the material.

TABLE I TEMPERATURE RANGES FOR DIFFERENT BEAM RADII

Beam radius	1 mm	5 mm	10 mm	15 mm	20 mm
Temperature range (K)	362 – 369 K	359 – 362 K	352 – 353 K	352 – 353 K	339.5 – 340.5 K

The third and final model which is examined is the introduction of rotation in our system. More specifically, the phosphor wafer will be rotating with a certain frequency so that the laser beam will illuminate different points of the material during the heat transfer process. For this purpose, the laser beam is aimed 10 mm from the center of the wafer on the x-axis and the chosen beam radius is 1 mm. The rotational frequency of the sample is set at 10 rpm. As we did with previous simulations, the overall heat distribution, the variation of the maximum, minimum and average temperature along with the isothermal contours will be presented.

Fig. 5 shows the derived temperature distribution on the phosphor wafer. We may observe that the maximum temperature developed on the sample is 364 K whereas in the case of the non-rotating sample the maximum temperature achieved was 369 K. The 5 K decrease is significant, particularly if we consider that it is achieved just by introducing rotation to our sample and without adding any heat sink.

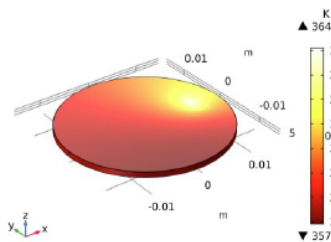


Fig. 5. Temperature variation across the phosphor wafer.

The following figure (Fig. 6) shows the isothermal contour plot of our model. In this case the contour lines change from the co-axial shape they had when the material was not moving.

The evolution of the temperature values during the heat transfer process presents some small variations due to the laser beam depositing different amount of heat on points closer to the center compared to points further away (fig. 7). This shows that the beam radius is still an important parameter as it is responsible for the heat deposition on the material. The rotating sample configuration seems to be a good approach in order to better handle the thermal buildup on the phosphor during the light conversion process.

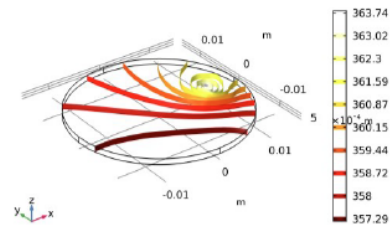


Fig. 6. Isothermal contour plot of rotating wafer.

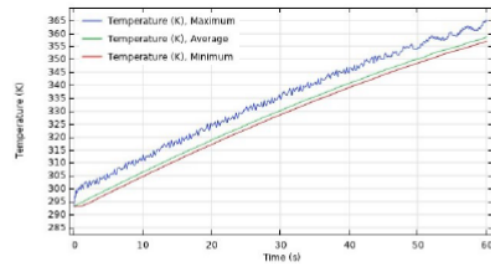


Fig. 7. Maximum, average and minimum temperatures as functions of time of rotating wafer.

III. CONCLUSIONS

We presented some simple models on how the phosphor wafer is heated in a solid-state light source based on a laser diode. The above models along with their results showed that the heating process of the phosphor material by the laser beam is an important factor on the thermal buildup and the temperature distribution on the wafer. Knowing the thermal effect of the laser beam on the sample is significant because it directly affects the lifetime and the conversion efficiency of the device. We presented the important role of the laser beam radius on how the heat is distributed on the phosphor. Moreover, we showed that a modification to the heating profile by introducing a rotating sample can help reduce the excess heat that is accumulated on the material. This leads us to assume that further investigation of other heating profiles is important to achieve smoother heating of the sample while avoiding any excessive temperatures which could damage the phosphor wafer.

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