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# Light beam interactions and emission performance in powder phosphor materials: The role of the binder

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ABSTRACT

The light emission performance of powder phosphors, employed in a variety of imaging applications, is affected by their structural (i.e., the particle size and packing) and optical properties (i.e., the wavelength of the light rays and the refractive index of the grains). In the chemical synthesis and the corresponding construction development of phosphor layers, the binder plays crucial role though its contribution to the way that the grains are glued together in a packed spatial distribution. In the present work, the influence of the binder on optical diffusion models was examined by using Mie theory and Monte Carlo simulation. To this aim, phosphor layers were investigated assuming different set-ups of refractive indexes (i.e., four cases of phosphor grains and binder combinations). Results showed that the choice of the binder affects the amount and distribution of light mainly through the: (i) domination of light absorption with respect to light scattering, and (ii) the direction of the light beam when light scattering takes place. It is important to note that by changing the refractive index of the binding material the light spread was not considerably varied through the number of light-grain interactions.

## 1. Introduction

The light emission properties by certain materials are subject of research in a variety of imaging instrumentations and systems. Such systems usually incorporate material structures in granular form, that is, consisting of an ensemble of grains embedded within a binding material and coated in layers. Powder materials are employed in several applications, such as: particle characterization methods, microscopy techniques [1], fluorescent lamps, anatomical and functional imaging (e.g., medical imaging) [2], detecting tools of biological structures [3], white LED applications, and have an impact on various research areas [4]. The design of an imaging system has to take into account all the derived aspects and fulfill the overall requirements from analyzing the desired application. Toward to this direction, one of the most crucial factors of the imaging efficacy is the construction of appropriate materials (see Fig. 1).

Luminescence materials have been synthesized in different chemical composition (e.g., $Gd_2O_2S$, $La_2O_2S$, $Y_2O_2S$, $Y_2O_3$, ZnS etc): (a) emitting light in different wavelengths due to their corresponding activator dopant (e.g., Tb, Eu, Pr, Ce, Ag etc) (b) consisting of different values of conventional grain sizes (e.g., in the range from 3.5 μm up to 25 μm) and (c) presenting different refractive indexes for a given light wavelength [5]. The chemical compound [6], the light wavelength [7], the grain size [2], the complex refractive index [8], as well as the degree of particle packing density (or the residual porosity) [9] affect the optical diffusion and in turn the overall luminescence efficiency of the materials. These effects are directly associated with the light ray interactions with the phosphor grains. The grains play the role of optical scatterers" [10] within the chemical composition and provide a different interaction profile (scattering and absorption) of the optical beam within the layer (i.e., the interaction events affect the free path lengths of the optical photons and therefore light travels in different direction).

Beyond the impact of the aforementioned parameters on light transmission performance, another crucial factor is the binding material. The choice of the binder influences the synthesis of the material structure [11,12] and may change the compatibility of the voids ("empty" spaces in a material) between the grains resulting in an overall light spreading variation. In addition, the binder may contain a pigment (absorbing dye) which reduces the internal reflections from particle to particle and alters the imaging characteristics of the layer [13]. In the majority of the commercially available luminescent materials, the usage of the binder is not provided by the manufacturers and its role in optical diffusion has not been studied either quantitatively or qualitatively through computational modeling. The purpose of the present work is to examine this issue and in particular to: (i) assess the effect of the binder on Mie optical parameters (the light extinction coefficient $m_{ext}$, the anisotropy factor $g$ and the probability of light

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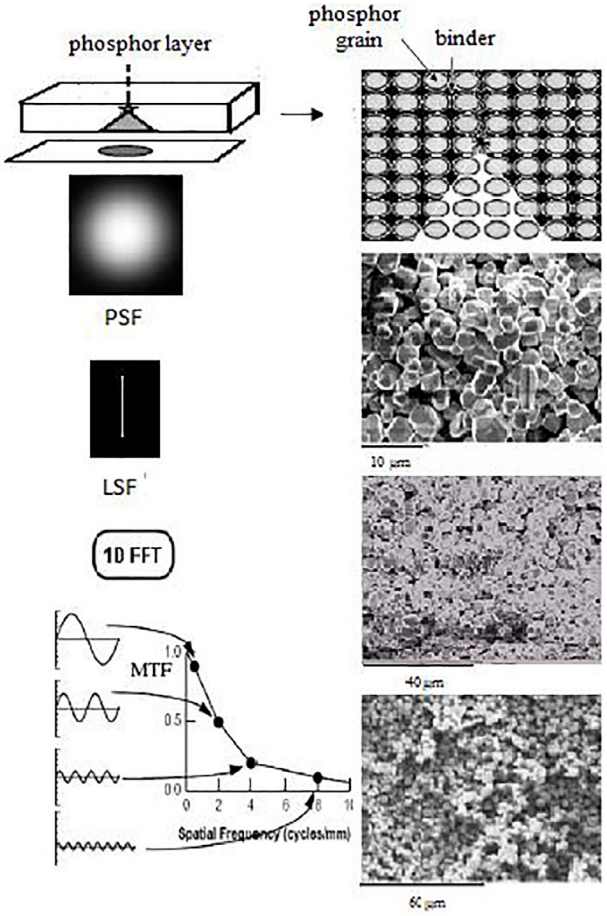


**Fig. 1.** The left part of the figure shows a phosphor layer where light is produced, diffused and emitted. A two dimensional PSF is obtained, the LSF is determined and finally the resolution is estimated from the predicted MTF. The right part of the figure depicts the powder luminescent material used in the computational model (it consists of phosphor spherical grains glued together by a binder) and corresponding real images of powder $Gd_2O_2S$ phosphor material of different grain structures taken by the electronic microscope (different scales of 10 nm, 40 nm and 60 nm are provided).

absorption $p$) and (ii) evaluate the distribution of light spread at the output of the layer which in turn affect the resolution of the image.

## 2. Materials and methods

### 2.1. The role of the binder in the computational evaluations

In the computational modeling, the binder influences significantly light spread within the powder structure though the variation of the optical parameters, such as (Appendix A in reference [2]): the light extinction coefficient $m_{ext}$, the probability of light absorption $p$ and the optical anisotropy factor $g$, which affect the intrinsic mechanisms of optical diffusion, correspondingly. The aforementioned intrinsic processes were provided by Mie scattering theory via three stages (Appendix B in reference [2]): (i) the free path length followed by the optical photon after production and before interaction, (ii) the decision of the type of interaction (absorption or scattering) and finally (iii) the evaluation of the new direction of the optical photon (in case of scattering) or the termination of the optical photon history (in case of absorption). The mathematical equations of Mie theory that describe the physical processes include a series of factors which are affected by the refractive index of the binder $n_{binder}$. These factors are connected with the following expressions (Appendix A in reference [2]): (i) the Mie coefficients $a_n$ and $b_n$, (ii), the Riccati-Bessel functions $\psi_n(x)$ and $\zeta_n(x)$,

**Table 1**
This table summarizes the input data required to feed the computational model. Data include: (i) the phosphor thickness, (ii) the powder packing density, (iii) the grain diameter, (iv) the light wavelength and (v) four cases of refractive index values (phosphor and binder). It is important to note that the imaginary part of the phosphor complex refractive indexes was considered to be $10^{-5}$.

| | |
|---|---|
| **Phosphor layer properties** | |
| Thickness (μm) | *200* |
| **Structural properties** | |
| Packing density (%) | *50* |
| Grain diameter (μm) | *7* |
| **Optical properties** | |
| Light wavelength (nm) | *420, 545, 610* |
| **Set of refractive indexes** | |
| **Case (i)** | |
| Refractive index of the phosphor grains | 1.8 |
| Refractive index of the binder | 1.1–1.5 |
| **Case (ii)** | |
| Refractive index of the phosphor grains | 2.0 |
| Refractive index of the binder | 1.1–1.5 |
| **Case (iii)** | |
| Refractive index of the phosphor grains | 2.2 |
| Refractive index of the binder | 1.1–1.5 |
| **Case (iv)** | |
| Refractive index of the phosphor grains | 2.4 |
| Refractive index of the binder | 1.1–1.5 |

(iii) the extinction factor $Q_{ext}$, (iv) the first element of the so-called Mueller matrix $S_{11}(\theta)$ as well as (v) the complex elements of scattering matrix $S_1(\theta)$ and $S_2(\theta)$. Two parameters are directly dependent on the refractive index of the binder, the relative complex refractive index $m$ and the size parameter $x$, as given below:

$$m = n_{grain}/n_{binder} \quad (1)$$

and

$$x = \pi d n_{binder}/\lambda \quad (2)$$

where $\lambda$ is the light wavelength and $d$ is the diameter of the grain. According to the refractive index of the binder, the result could be a strongly scattering phosphor where light photons travel over a nearly diffusive distance in the layer, or in other case light photons travel in a transparent layer with long mean free paths.

### 2.2. Numerical data used in the computational model

#### 2.2.1. Input data

The evaluation of the optical parameters $m_{ext}$, $p$ and $g$, was carried out by considering optical and structural properties summarized in Table 1. The computational model considered a granular layer with thickness value 200 μm consisted of phosphor particles glued together with a binder. The diameter of the particles (grains) was chosen to be 7 μm and the corresponding packing of the grains 50%, which are considered common values for powder phosphors. In addition, the light wavelength was chosen to take three different values 420 nm (blue emission), 545 nm (green emission) and 610 nm (red emission) which correspond to a phosphor accordingly doped by different types of activators, such as Ce, Tb and Eu, respectively [7].

The most crucial parameters in the model were considered to be the refractive indexes of the phosphor material and of the binder. Finding refractive index values for powder materials is considerably difficult since there is a lack of numerical data in the literature [5], the measurement approaches are not sufficiently precise [14] and for further calculation performance different empirical methods or fitting procedures are employed [5]. Furthermore, in most of the cases, data sheets of commercial phosphors do not mention the refractive index of the material and sometimes in such materials, the presence of additional