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Involvement of scattered UV light in the generation of photoluminescence in powdered phosphor screens

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Abstract. In powdered phosphor screens, a large fraction of incident UV light is reflected from the surface of individual particles, with the remainder penetrating the phosphor surface to generate photoluminescence. The reflected UV photons entering the screen are randomly scattered throughout the particulate structure, resulting in photoluminescence down to, for example, 10 layers deep from the surface. An optimum number of layers within a screen for luminance in reflection and transmission modes can be calculated after determination of the absorption and scattering coefficients per layer in a practical phosphor screen. Good agreement has been obtained between the calculated and experimental results.

1. Introduction

Powdered phosphor screens are widely used in fluorescent lamps and plasma display panels (Weber 1985), as a transducer of the energy of invisible UV light into visible light. Photoluminescence is generated in individual phosphor particles in the screen as a consequence of the absorption of incident UV light. Although absorption of incident UV light by individual particles in the screen is important to obtain optimum luminance of phosphor screens, one may encounter a great number of difficulties because the luminance of phosphor screens varies with the packing conditions of the phosphor particles (Ozawa 1994, Donofrio and Rehkopt 1979). The packing conditions in screens vary with the quality of phosphor powder used and with the screening technique used with the phosphor slurries (Ozawa 1990, Sluzky and Hesse 1988). The variation in screen quality makes a scientific study difficult, even though phosphor screens have been in practical use for more than 50 years; there is no scientific report known to us in the literature. The optimum screen thickness for photoluminescence has been determined empirically by individual users (Busselt and Rane 1988, Donofrio and Rehkopt 1979), resulting in different thicknesses of screen being used.

In this report, we have analysed optical properties of UV light incident onto a phosphor screen. Penetration of incident UV light into a deep layer in the screen is achieved using scattered UV light on the surface of the particles, even though phosphor particles have strong absorption properties. The number of phosphor particles, which generate photoluminescence in the screens, can be counted under UV light irradiation. Although introduced absorption and scattering coefficients per layer are determined empirically with the given phosphor screens, equations used to calculate photoluminescent intensities of the screens in either reflection or transmission mode have been derived. A close fitting was obtained between the calculations and experimental results.

2. Experimental procedure

Phosphor particles dispersed perfectly in a dilute PVA solution. Phosphor screens of Y_2O_3:Eu particles (average particle size 4 μm by surface area) in various layers were then made on a flat substrate (5 cm^2) with application of sedimentation. Change in concentration of phosphor solutions was used to control the number of phosphor layers. After the sedimentation process, the screens were dried at 120 °C for 20 min. The number of layers in these screens could be calculated by

$$L = 1.65w/\rho d \tag{1}$$

where L is the number of phosphor layers, w is the screen weight, ρ is the density of phosphor particles and d is the mean particle size (Ozawa 1990). In addition, the Y_2O_3:Eu phosphor screens were irradiated with visible light (for example 500 nm) that was not absorbed by the screens in order to determine the scattering coefficient (β). The same screens were also irradiated with 254 nm UV light to obtain the value of $\alpha + \beta$, where α is the absorption coefficient. In addition the Y_2O_3:Eu powder compact was pressed under a high pressure (3000 psi) at 1000 °C for 1 h. The obtained sintered Y_2O_3:Eu bulk was transparent to light, like the single crystal. Therefore, α of the phosphor crystal at 254 nm could be obtained by using a Cary 14 spectrophotometer with UV light irradiated on the Y_2O_3:Eu bulk.

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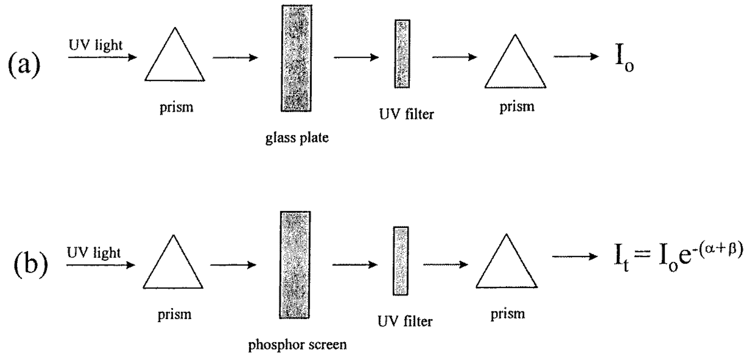

Figure 1. Schematic explanation of determination of (*a*) I_0 and (*b*) I_t.

Figure 1 indicates the determination of I_0 and I_t using a double-prism spectrometer (Hitachi, spectrofluorescent meter MP4). Due to the absorption of the glass plate, UV light was irradiated on a glass plate to obtain I_0, shown in figure 1(*a*). The same UV light was then irradiated on the Y_2O_3 : Eu phosphor screen to obtain I_t (figure 1(*b*)). The light intensities of both transmission and reflection modes of the powdered phosphor screens were measured by using a photodetector (Minolta, CS-100) with a UV filter.

3. Results and discussion

3.1. Specific surface area of phosphor particles in screens

In order to discuss quantitatively photoluminescent intensities from phosphor screens, we must know about the particles in which luminescence is generated in phosphor screens. Since phosphor particles have a large index of refraction (Ozawa 1990), a large fraction of the incident UV light reflects off the surface of a particle, and the residue penetrates into the particle to generate photoluminescence. The reflected UV light reaches another phosphor particle on which a large fraction of the light again reflects off the surface and the residue penetrates into the particle. In this way, reflected UV light reaches phosphor particles deep in the screen. Because the properties of reflected UV light in the screen are correlated with the total surface area of particles in the phosphor screen, we will first discuss the surface area of particles in phosphor screens.

One gram of phosphor powder contains about 10^{11} particles (Higuchi 1961) whose sizes are not equal but which are distributed with a log-normal probability (Ozawa 1990). Particle sizes of phosphor powder are usually expressed by an average size or a median size of the log-normal distribution. Then, we can estimate the average surface area of particles in a phosphor screen by using the average particle size. Although the surface area is the average surface area of the particles involved, we express it simply as surface area in the following discussions.

It is believed that the total surface area of phosphor particles in screens increases as particle size decreases. However, the total surface area of particles in screens is a function of the number of layers of particles, and is independent of the particle size (Ozawa and Hersh 1974). The specific surface area S_{sp} of particles arranged in a single layer on unit substrate area is given by

$$S_{\text{sp}} = n\pi d^2 \ (\text{cm}^2). \tag{2}$$

where d is the average particle size and n is the number of particles arranged on unit substrate area, that is given by d^{-2}. Therefore

$$S_{\text{sp}} = d^{-2}\pi d^2 = \pi = \text{constant} \ (\text{cm}^2). \tag{3}$$

For a screen of L layers, the total surface area of particles on unit substrate area S_{tot} is given by

$$S_{\text{tot}} = Ls\pi \ (\text{cm}^2). \tag{4}$$

Thus, the properties of reflected UV light in a phosphor screen should be expressed as a function of the number of layers L in the screen. It should be noted that L is the average number of layers estimated from average particle sizes of the log-normal distribution.

3.2. Penetration depth of incident UV light into a phosphor particle

Photoluminescence in individual particles is generated in the volume V in which the UV light is absorbed. The absorbing volume in the particle is given by the product of the exposed surface area of a particle S_p and the penetration depth p of the UV light

$$V = kpS_p \tag{5}$$

where k is a constant.

The penetration depth can be estimated from the α value, which can be obtained from the measurement mentioned in section 2 above. The experimentally determined α of practical phosphor crystals for fluorescent lamps for 254 nm UV light was 4×10^5 cm^{-1}; for example $\alpha > 10^5$ cm^{-1} which shows a close agreement with reported results (Ozawa 1990). The penetration depth of the UV light into phosphor particles is given by $1/\alpha$ (i.e. < 0.1 μm), which is shorter than the particle sizes (4 μm) we used. Thus, penetrated UV light undergoes multireflection inside the walls of the particles. Hence we neglect the penetration depth of UV light into a phosphor particle.

Although the volume V in which the photoluminescence is generated is a small volume in the particle, the emitted

Table 1. Measurement results of photoluminescent intensities of Y_2O_3 : Eu phosphor screens with different numbers of layers.

Phosphor screens (number of layers)	Relative luminescent intensities (%)
2	60
15	100

light in V emerges from the particle after being multiply reflected on the inside wall of the particle (Ozawa 1990). With multiple reflection of emitted light, the particle becomes a light source having the size of the particle. Then, the luminescent intensities from phosphor screens can be treated as a function of the number of layers of phosphor particles in the screen.

3.3. Penetration of scattered UV light into deep phosphor screens

The simplest case for evaluation of the luminescent particles in a screen is a screen in which the reflected UV light is neglected. In this case, the number of luminescent particles is limited to the particles exposed directly to the irradiated UV light. The number of exposed particles in the screens is the same for both thin and thick screens. Therefore, the same luminescent intensities are expected for thin and thick screens. However, as shown in table 1, different luminescent intensities in reflection mode were obtained with a different thickness of phosphor screen; a thick layer results in a higher luminescent intensity. We thought that with a thick screen the emitted light from the exposed particles might be reflected from the deep layers of particles, and that this reflected light might be included in the measured luminescent intensities, while such reflected light would not occur in the thin screen, resulting in the lower measured intensity. Experimentally, the thin phosphor screens were then made on an aluminium film deposited on a reflecting glass plate (about 90% reflection) (Giancaterini and Pacifici 1984). The luminescence was indeed enhanced for the thin phosphor screens deposited on aluminium film. However, we obtained different luminescent intensities for the thin phosphor screens on Al films and the thick screens directly on the glass plates. More luminescence was still obtained from the thick screens. Those results definitely indicate that the behaviour of the luminescent particles in phosphor screens is not limited to the exposed particles. The phosphor particles in deep layers are also excited by the incident UV light, and the photoluminescence from the particles in deep layers contributes to the measured luminescence intensities of the thick phosphor screens.

Since phosphor particles having different shapes and sizes are packed randomly in the screens, directions of the reflected light on particle surfaces are well randomized in phosphor screens (i.e. scattered light). Some scattered UV light, within the phosphor screen, may penetrate into other phosphor particles in the screen to generate photoluminescence. If we know the absorption and scattering coefficients of the UV light in the screens, we may calculate the luminescent intensities. As already mentioned, the scattering and absorption of UV light in phosphor screens is a function of the number of layers of particles. Then the measured I_t from the screens can be expressed by

$$I_t = I_0\,\mathrm{e}^{-(\alpha+\beta)L} \tag{6}$$

where α and β are respectively the absorption and scattering coefficients per layer of particles. It should be noted that the values of α and β differ from the absorption and scattering coefficients determined with continuous media (such as single crystal) that are given by values per unit length, instead of per layer.

If the screen does not absorb the light (for example emitted light), the measured I_t can be expressed by

$$I_t = I_0\,\mathrm{e}^{-\beta L}. \tag{7}$$

This is because some light scatters horizontally in the screen even if the light is not absorbed in the screen.

3.4. Determination of α and β

Since the mean free path of the scattered light in screens changes with the quality of phosphor screens, the values of α and β in equations (6) and (7) change with the screens, which are prepared with different phosphor powders and using different screening technologies. Therefore, the values should be determined experimentally for each phosphor screens under given conditions. If phosphor particles disperse perfectly in the phosphor slurries, the phosphor powders will be densely screened without defects.

The determined β was 0.26 per layer. By irradiation of the 254 nm UV light, a value of 0.52 per layer was obtained for $\alpha + \beta$. Assuming that the determined β is applicable to UV light, we may evaluate the value of α from the measured $\alpha + \beta$ by subtraction of β on a logarithmic base. The value of $\alpha = 0.26$ per layer was evaluated for 254 nm UV light. The large value of $\alpha + \beta$ indicates that the scattered UV light possibly penetrates into the phosphor particles and this penetrated light undergoes multiple reflection. The simultaneous excitation of the same particles may result in a brilliant luminescence from a powdered phosphor screen.

3.5. Luminescent intensities as a function of number of layers

Using the determined α and β values, we may calculate the UV light absorbed by the phosphor screens in various layers of particles. As illustrated in figure 1(*b*), when light of intensity I_0 irradiates the phosphor screen, the absorbed UV light in the phosphor screen (I_a) is given by subtraction of the transmitted light intensity (for example $I_0\,\mathrm{e}^{-(\alpha+\beta)L}$) from I_0. Then, we have

$$I_a = kI_0(1 - \mathrm{e}^{-(\alpha+\beta)L}) \tag{8}$$

where k is a material constant. Equation (8) gives a net absorption of the UV light by the phosphor screen.

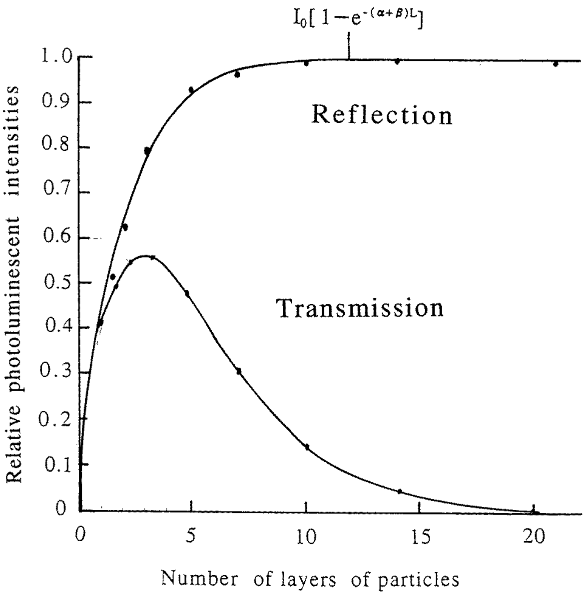

Figure 2. Calculated (full curves) and experimental (symbols) photoluminescent intensities from the phosphor screens in transmission and reflection modes, as a function of the average number of layers of particles.

3.5.1. Luminescent intensities in reflection mode. We assume that a UV photon absorbed by the phosphor particle generates a luminescent photon. If the luminescence intensities on the screens are measured in the reflection mode, luminescent light emitted in the phosphor screen can be collected by a photodetector. If this is the case, the luminescent intensities in the reflection mode are given by equation (8). The calculated curve in reflection mode on the basis of equation (8) (full line) is shown in figure 2. This figure shows that the experimental data (●) for Y_2O_3:Eu phosphor screens fit the calculated curve well. The luminescence intensities increase with the number of layers of particles up to a saturation level, which is given by 10 layers of particles. The measured luminescent intensities of a two-layer screen were 60% of that of a 15-layer screen, as shown in table 1. The luminescent intensity calculated from equation (8) is $64/100 = 0.64$, showing a close fit between the calculation and experiments. This means that the measured luminescent intensities in the reflection mode are proportional to the UV light absorbed by the phosphor screen.

3.5.2. Luminescent intensities in transmission mode. If the luminescent intensities are measured with transmitted light from the phosphor screen (I_{trans}), the emitted light in the screen loses its intensity with horizontal scattering in the phosphor screen. The horizontally scattered light is not included in the measurement of I_{trans}. In the measurements of I_{trans}, we determine the light intensity which is made up of (a) the light intensity emitted in the given phosphor layers and (b) the scattering loss of the emitted light by the layers between emitted and output layers. If the screen is constructed with three layers of particles, the measured I_{trans} will be the emitted light intensity generated by absorption of the UV light by particles in three layers minus the scattering loss of the emitted light at the first and second layers. This can be expressed by the following equations:

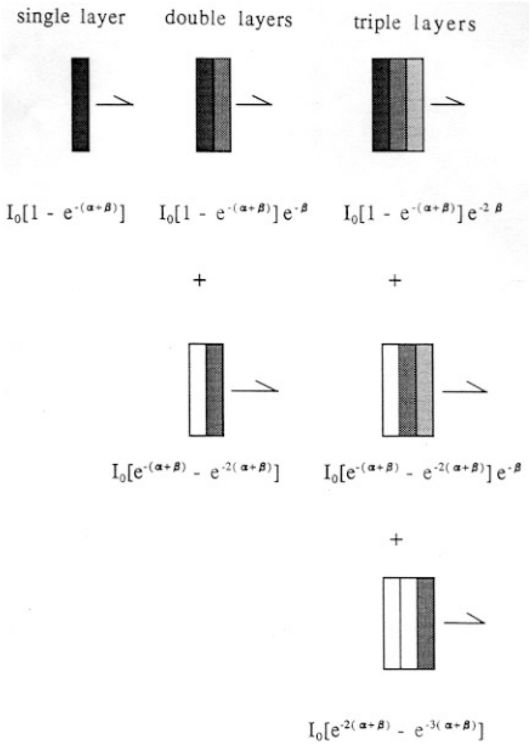

Figure 3. Schematic explanation of the transmitted photoluminescent intensities of screens having single, double and triple layers. The different shadings in the first row of this figure show various amounts of light emission for each layer. The deeper the colour of the layer, the more lights it emits. The second and third rows stand for the loss by scattering. The shaded part is the place yielding the scattering loss. Similarly, the deeper the colour of the layer, the more losses it has.

(i) Screen with a single layer

$$I_{\mathrm{trans}} = kI_0(1 - e^{-(\alpha+\beta)}). \tag{9}$$

(ii) Screen with two layers

$$I_{\mathrm{trans}} = kI_0(1 - e^{-2(\alpha+\beta)}) - kI_0(1 - e^{-\beta})(1 - e^{-(\alpha+\beta)}). \tag{10}$$

(iii) Screen with three layers

$$I_{\mathrm{trans}} = kI_0(1 - e^{-3(\alpha+\beta)}) - kI_0(1 - e^{-\beta})[(1 - e^{-2(\alpha+\beta)}) + (1 - e^{-(\alpha+\beta)})e^{-\beta}]. \tag{11}$$

Figure 3 illustrates the models described above. The transmitted luminescent intensities I_{trans} for a screen of L layers may be expressed by

$$I_{\mathrm{trans}} = kI_0[1 - e^{-L(\alpha+\beta)}] - kI_0(1 - e^{-\beta}) \times [(1 - e^{-(L-1)(\alpha+\beta)})e^{-(L-L)\beta} + (1 - e^{-(L-2)(\alpha+\beta)}) \times e^{-(L-L+1)\beta} + \cdots]. \tag{12}$$

The first term of equation (12) is the same as equation (8), that is an function incremental with the number of phosphor layers. The loss of the emitted luminescent light is by scattering. The scattering loss increases as the number of layers increases. Therefore, the transmitted luminescence intensity initially increases with the screen layers to a maximum, and then decreases with the screen layers. Figure 2 gives the curve of the luminescent intensities in transmission mode (full curve). The experimental data (●) fit well on the calculated curve. The optimal number of layers for the transmitted luminescent intensity is three layers of particles. Since the experimental phosphor screens were made using well dispersed particles, the quality of the phosphor screens might be close to ideal.

If the phosphor screens contain voids, which act as a path of light conductance in the screens, the values of α and β will be sensitively changed with the size and number of voids in the screens. The voids are generated in screens having aggregated particles, large particles, irregularly shaped particles and a wide distribution of particle sizes. The size and number of voids markedly change with the screening technique used with the phosphor powders. All of those factors give small values of α and β, resulting in a high optimal number of layers.

It was a very hard to control the number and sizes of voids in screens made with commercial phosphor powders, resulting in a poor experimental reproducibility. A smooth screen was only obtained when the sizes of the phosphor particles were distributed in a narrow range, and when the particles were well dispersed in slurries, resulting in a high reproducibility.

4. Conclusions

It has been shown that scattered UV light penetrates into the deep layers of a phosphor screen. Consequently, the phosphor particles in the deep layers generate photoluminescence. The scattered UV light in the screen may have a chance to undergo multiple reflection inside the same particle, resulting in a high luminescent intensity of the powdered phosphor screen. Powdered phosphor screens with a high luminance are widely used in fluorescent lamps and plasma display panels.

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