Phosphor converted LEDs with omni-directional-reflector coating

Jim-Yong Chi[1*,4], Ji-Siao Chen[2], Chuan-Yu Liu[3], Cheng-wen Chu[4], Kuo-Hsien Chiang[4]

[1]Institute of Opto-Electronics Engineering, National Dong Hwa University, Hualien, Taiwan 97401, R.O.C.
[2]Institute of Photonics Technologies, National Tsing Hua University, Hsinchu, Taiwan 30013, R.O.C
[3]Institute of Electronics Engineering, National Dong Hwa University, Hualien, Taiwan 97401, R.O.C.
[4]Electronics and Opto-Electronics Research Laboratories, Industrial Technology Research Institute, Hsinchu, Taiwan 31040, R.O.C.
**chij@mail.ndhu.edu.tw*

Abstract: A packaging scheme utilizing omni-directional reflective (ODR) optical coating is described to enhance the light extraction of near UV excited, phosphor-converted LEDs. A simple 1D model was developed to analyze the spectra of the extracted light measured with an integration-sphere as a function of phosphor layer concentration and thickness. Quantitative determination of the absorption coefficients at the pump and fluorescent light wavelength along with the conversion coefficient of phosphors were obtained. The reflection of the ODR film and the back reflector are also characterized. These parameters are then used for efficiency optimization of the present packaging scheme. A maximum enhancement of 40% can be expected with the materials and the configuration used in the present work.

OCIS codes: (230.3670) Light-emitting diodes; (230.5298) Photonic crystals.

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1. Introduction

High efficiency and high color rendering index of LEDs are the key performance indices to realize new applications from display to lighting. For the present, white light generation through color mixing of phosphor converted light is the most promising approach and efficiency surpassing the fluorescent light has been reported using blue LEDs to excite YAG:Ce phosphor [1]. The approach based on UV excitation of red, green, and blue phosphors [2–5], however, is hampered by the low phosphor conversion efficiency at the near UV wavelength range, despite the advantage of better color rendering index and higher power and efficiency around 400 nm [6]. We have reported a scheme to resolve this problem with

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omni-directional reflective (ODR) optical coating to recycle the UV light. Monte Carlo simulation was performed based on a theoretical phosphors scattering model [7]. A significant enhancement in efficiency is simulated. In the present work, experiment was performed to demonstrate the improvement using the ODR film. A phenomenological one dimensional model following reference 8 is constructed to analyze the measured results [8]. The absorption coefficients and conversion coefficient of the phosphor can be quantitatively determined using this simple approach. This model is then used to predict the optimal realistic performance using ODR with the determined coefficients. An enhancement of more than 40% is predicted by optimizing the thickness and concentration of the phosphor layer.

2. Sample preparing and experimental set up

To investigate the effect of the ODR films, a specially designed sample holder as shown in Fig. 1(c) is employed. The LED is mounted at the bottom of the holder and consists of nine GaN UV LED dies connected in series. The emission wavelength is around 395 nm with the power 24.4 mW at 20mA. The inside surface of the holder is coated with metallic reflector to reflect the back propagating light which can be blocked with a black paper mask that covers most of the surface except a small aperture around the dies. On top of the holder a glass piece coated with phosphor layers and/or ODR film can be placed. The phosphor layer is made with silicon resin (GE Plastics RTV615) mixed with green phosphors (Kasei Optonics, KX671). The thickness of the layer can be precisely controlled with a metal molding. An air gap is present between the die surface and the phosphor layer which is placed such that the phosphor layer is facing the dies. On the outer surface of the glass piece, an optical film with omni-directional reflective properties may be coated. The transmission spectra for the ODR film is such that the near UV light emitted by the LED is reflected for all angles and polarizations inside the escape cone and the visible light from the phosphor florescence can pass through with high transmission. For the present study, 40 pairs of SiO_2 and Nb_2O_5 multi-layers are used to obtain high reflectivity (>90%) for incident angles smaller than 45 degree and for both s- and p- polarizations at the around 400nm. For the visible light, the ODR film is transparent (>90%) as shown in Figs. 1(a) and 1(b). Such a reflective property will reflect back most of the incident UV light in the escape cone regardless of the incident angle and polarization, hence the name of omni-directional reflection and will let the visible light in the escape cone pass through the film with high transmission.

To study the properties of the ODR film, phosphor layers with varying concentration and thickness are made on the glass piece coated with the ODR film on the other side. For comparison, the same phosphor layers were also made on glass pieces without the ODR film. The spectra of the output light with the current through UV die set at 20 mA are measured with an integration sphere. A typical spectrum of the output light contains two well separated peaks as shown in Fig. 1(d). The primary power (P_1) and the secondary power (P_2) were determined by integrating the intensity of the spectrum above or below 430nm as indicated in the figure. Light output of the phosphor layer with six thickness and six phosphor concentrations with and without ODR films are measured. The same films are then measured again by blocking the reflection from the package using the black paper mask.

3. Data analysis

To analyze the data, a phenomenological one dimensional model was constructed. This 1D model extends the assumption of ref. 8 to include the effect of the ODR films. As shown in Fig. 2(a), the primary and the secondary light that are traveling in the + z and -z directions are described by the following equation,

$$\mathrm{dP}_1^+/\mathrm{dz} = -\alpha_1 \mathrm{P}_1^+ \tag{1}$$

$$\mathrm{dP}_1^-/\mathrm{dz} = \alpha_1 \mathrm{P}_1^- \tag{2}$$

$$\mathrm{dP}_2^+/\mathrm{dz} = -\alpha_2 \mathrm{P}_2^+ + \beta \mathrm{P}_1^+/2 + \beta \mathrm{P}_1^-/2 \tag{3}$$

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$$\mathrm{dP_2^-/dz} = \alpha_2 \mathrm{P_2^-} - \beta \mathrm{P_1^+}/2 - \beta \mathrm{P_1^-}/2 \tag{4}$$

where P_1^+ and P_1^- are the primary light that travel in the + and – z directions, while P_2^+ and P_2^- are that due to the secondary light.

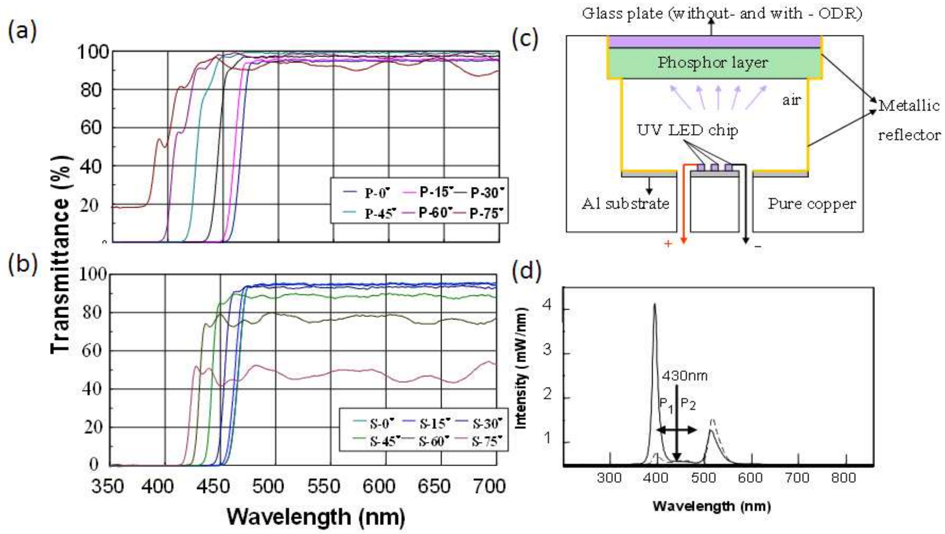

Fig. 1. The transmission spectra of the ODR film for the p-polarisation (a) and s-polarisation(b) at various incident angles used in the present work; (c) the schematics of the sample holds used for the present work; (d) the emission spectra for the UV excited LED with (dashed line)and without (solid) the ODR film. $P_1(P_2)$ is the integrated intensity for the area shorter (longer) than 430nm.

At the bottom of the phosphor layer $z = 0$, the λ_1 light, the light intensity generated by the LED chip reaching the phosphor layer, can be represented by $P_1^+(0) = I$, the intensity of the LED light. For the λ_2 light, the back travelled light P_2^- will leave the phosphors layer and be reflected back by the back reflector formed by the shinny surface inside the package. In the spirit of the present 1D approximation, this extra λ_2 light due to the back reflection can be represented by the boundary condition $P_2^+(0)=r_2 P_2^-(0)$,where r_2 is the reflectivity to be determined by analyzing the measurement data.

At the top of the phosphor layer $z = h$, the λ_1 light will be reflected back to the phosphor layer if ODR is present. This is described by $P_1^-(h) = r_1 P_1^+(h)$, where r_1 is the reflectivity of the ODR film at λ_1. At the λ_2, the reflectivity is very low and is approximated by the boundary condition $P_2^-(h) = 0$.

The above differential equation with the boundary conditions can be solved by assuming the solution of the following form.

$$\mathrm{P_1^+(z) = A_1^+ exp(-\alpha_1 z)} \tag{5}$$

$$\mathrm{P_1^-(z) = A_1^- exp(\alpha_1 z)} \tag{6}$$

$$\mathrm{P_2^+(z) = A_2^+ exp(-\alpha_2 z) + B_2^+ exp(-\alpha_1 z) + C_2^+ exp(\alpha_1 z)} \tag{7}$$

$$\mathrm{P_2^-(z) = A_2^1 exp(\alpha_2 z) + B_2^- exp(-\alpha_1 z) + C_2^- exp(\alpha_1 z)} \tag{8}$$

Substitute Eq. (5) through (8) into Eq. (1) through (4), the coefficients A’s B’s and C’s can be readily determined by matching coefficients of the exponential terms.

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This solution can then be used to determine the coefficients α_1, α_2 and β, r_1 and r_2, by least square fitting the four groups of measured data, those with and without the back reflection and those with and without the ODR films. The strategy to determine these parameters is as follows. First the UV data are analyzed using Eq. (5) to determine α_1 of the incident UV light. These data are then used in fitting all the other measured data. For the visible light emission, four groups of data are analyzed in sequence. (1)The absorption coefficients α_2 ad β are determined by fitting the measured data without ODR and the back reflection by setting $r_1 = 0$ and $r_2 = 0$; (2) the reflectivity, r_2, is determined next using the determined α_1, α_2 and β by fitting the group of data with the back reflection but without the ODR on top with the reflectivity r_1 set to zero; (3) these parameters are then used to determine the reflectivity of the ODR, r_1, by fitting the measured data with ODR film but without the back reflection with the reflectivity r_2 set to zero; (4) the last step is the *consistent* check by fitting the measure data with the ODR film and with the back reflection using all the parameters determined above.

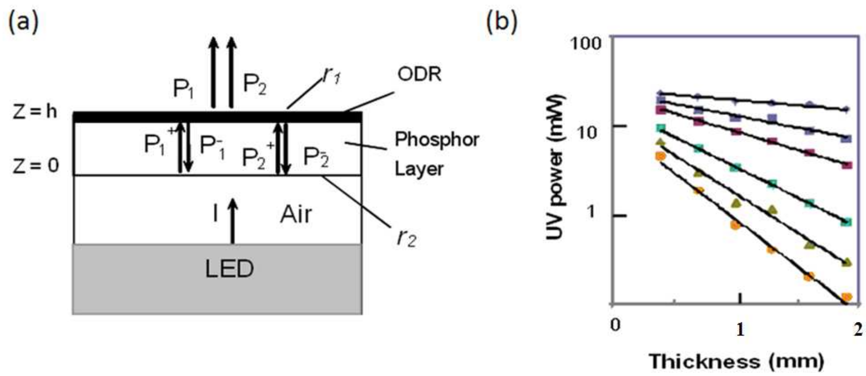

Fig. 2. (a) Schematics showing the parameters used in the 1D model. (b) Transmitted UV power vs. thickness and the phosphors concentration measured with an integration sphere. The corresponding concentrations are 1,3, 5, 10, 15, and 20wt% from the top line to the bottom.

4. Results and discussions

Figure 2(b) shows the UV power out, p_1, measured on samples without ODR film as a function of phosphor layer thickness. It can be seen that the data fall on straight lines when plotted on semi-logarithmic scale. The slope of the lines corresponds to the absorption coefficient of UV light. The absorption coefficient, α_1, can be determined by least square fitting these lines. As a check, the samples without the back reflection are also measured, it is found that the data exactly overlap with the previous data within the experimental accuracy, indicating that the UV light reflection due to either the boundaries of the phosphor layer or the package surface is negligible. With the determined α_1's, following the curve fitting strategy outlined above, the visible part of the light output, p_2, can be fitted to determine the other parameters. Figures 3(a) through 3(f) show the measured data and the fitting curves for six concentrations. It can be seen that the enhancement effect of ODR is evident. The curves labeled (1) through (4) in Fig. 3(a) correspond to the curve following each steps of the fitting process described above. The curves on the other figures can be similarly labeled following the same ordering sequence. As seen in the figures, the curving fitting of the measured data in general is satisfactory except at high concentrations where the scattering of the measured data prevent accurate fitting. The scattering of the data may also due to the clustering of the phosphor particles at high concentrations. The p_2 initially increases with the concentrations and thickness then deceases at high concentration and thicker layers. This behavior indicates the existence of an optimal concentration and thickness for maximum power output. The enhancement of ODR is also reduced at high concentration and thicker layers as expected since most of the UV light is absorbed in the phosphor layer and not reaching the ODR films on top.

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The results of the material parameters determined by the data analysis are summarized in Fig. 4(a) for coefficients α_1, α_2, and β and Fig. 4(b) for r_1 and r_2. It can be seen that the both the absorption of the primary and the secondary light increase with the phosphor concentration and so does β, in agreement with the expected trend. It can also be seen that the coefficients tend to saturate at high concentration. This trend can be accurately fitted with a second order polynomial to allow further analysis.

The reflection coefficient due to the ODR film, r_1, is close to one for most of the range except at the high concentration when most of the near UV light is absorbed in the layer to reach the surface. This high value of r_1 determined from the data corresponds well with the expected effect of the ODR film. For r_2, a value larger than one is obtained, indicating a significant portion of the light propagating backward into the package and reflected back by the metallic reflector on the inner surfaces. The r_2 parameter also provides a quantitative characterization of the back reflection.

The parameters determined above along with the analytical solution can be utilized to find the optimized condition for the maximum efficiency. Figure 5 shows the calculated efficiency contours for visible light output using the parameters shown in Fig. 4(a) for the case without the ODR (Fig. 5(a)) and with the ODR (Fig. 5(b)). The reflectivity used to obtain Fig. 5(a) is $r_1 = 0$. For that with the ODR cover (Fig. 5(b)), $r_1 = 1$ is used. The r_2 for both structures is set to 2 to take into account that the back reflection can be further improved from the present configuration. From the calculation, the maximum occurs at 13.0 and 18.2 mW respectively for the ordinary structure without the ODR cover and the ODR covered structure. The improvement is 39.7%. The optimal concentration occurs at 5 wt% for the ODR covered structure, lower than the 7% for the ordinary structure. The region of enhancement, i.e., the region with p_2 value above the maxima for the case without the ODR films, extends to the lower phosphor concentration and thinner thickness sides as indicated in the region encircled by the thick red line in Fig. 5(b). This observation indicates that the ODR covered structure can increase the visible power out put with lower concentration to lessen the deleterious effects that are normally encountered at high phosphor concentration. More phosphors can be more efficiently incorporated for color mixing which are needed for white light generation.

In summary, an enhancement scheme using optical coating to improve the efficiency of UV-excited, phosphors converted LEDs is presented. A one dimensional modeling is used to determine the absorption and conversion coefficients.

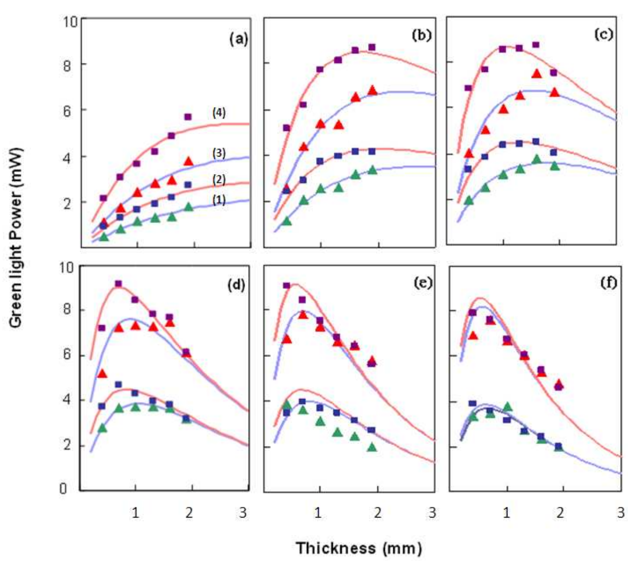

Fig. 3. Measured visible light output with and without ODRs and with and without the back reflectors. (1) and (2) are measured with the back reflector but with and without the ODR films. (3) and (4) are measured without the back reflector with and without the ODR film. The lines

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are the curve fitting to the experimental results according the present calculation. Parts (a) through (f) are for 1, 3, 5, 10, 15, and 20 wt % phosphors, respectively.

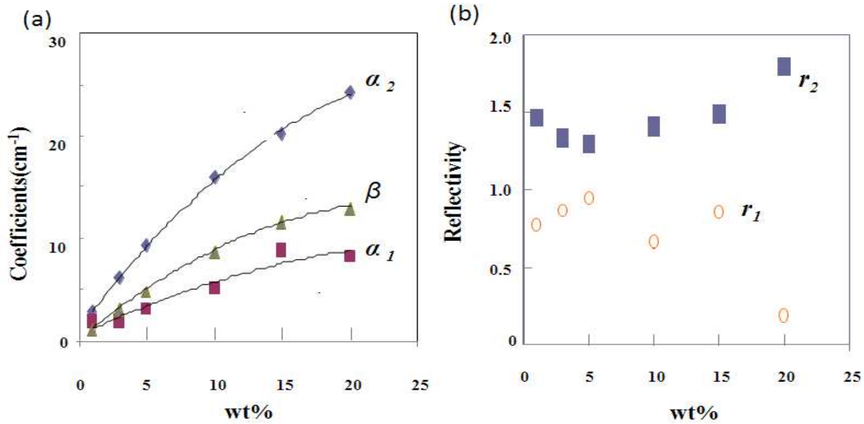

Fig. 4. (a)The absorption(α_1 and α_2) and conversion coefficients (β) determined from the measured data; (b) reflectivity parameters (r_1 and r_2) due to the ODR films and the back reflectors.

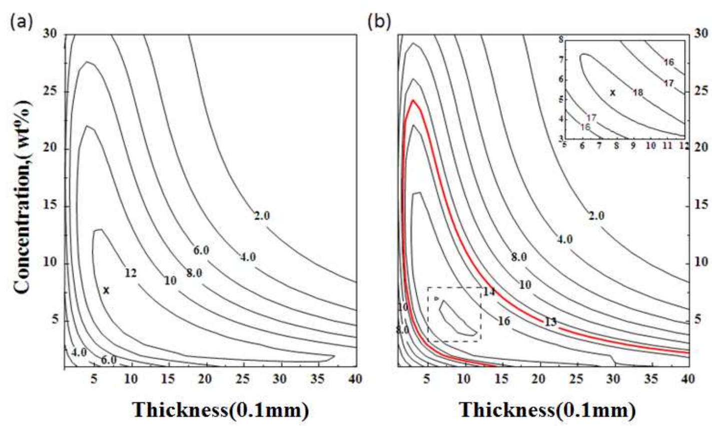

Fig. 5. The equal power contours based on the model and the material constants shown in Fig. 4 with the reflection coefficients are r_1 = 1.0 and r_2 = 2.0. The unit for the contour is mW. Part (a) corresponds to the case without ODR; Part (b) corresponds to the case with ODR. The thick red line in (b) is the contour with the maximum power value of the part (a). It represents the region of enhancement by ODR. The x's in (a) and (b) mark the location of the maxima. The inset in (b) is a magnified view of the region shown in the dashed box.

Using these parameters, it is determined that the optimal enhancement due to ODR is 40% over that without the ODR films. The optimal concentration can also be lower which is beneficial for lessening the deleterious effects at high concentration especially for the white light generation when more phosphors need to be added for color mixing.

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