Measurement of Crosstalk in an Energy-Harvesting Projector Utilizing a Uniform Luminescent Layer

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ABSTRACT

When a uniform luminescent layer is incorporated in the screen for an energy-harvesting projector, the crosstalk inside the screen limits its contrast ratio to 1 x 10^5. It would not degrade its spatial resolution if the pixel size were set adequately larger than the thickness of the luminescent layer.

1 INTRODUCTION

An energy-harvesting projector is essentially a combination of a luminescent solar concentrator (LSC) [1] and a laser phosphor display (LPD) [2]. A thin-film LSC consists of two transparent plates sandwiching a thin luminescent layer and solar cells attached to their edges. It harvests energy from sunlight and/or ambient light by converting the incident light to photoluminescence (PL) photons and wave-guiding them to the solar cells. An LPD modulates the intensity of a laser beam and scans it on a phosphor screen. Hence, by using an LSC as its screen, the dual functional device is realized [3]. The use of three-types of ceramic phosphors allowed us to demonstrate a color version [4]. In this experiment, however, a disk-shaped crosstalk pattern was observed when the light excited a single spot on the screen. The optical efficiency for recovering the incident optical power was only 0.8%. The crosstalk and this extremely low efficiency are both believed to be caused by the granular morphology of the ceramic phosphors: they scatter the excitation light as well as the PL photons inside the screen. The scattered light excites the phosphors nearby. The surrounding region emits PL photons. This is the origin of the disk-shaped crosstalk. Nevertheless, such crosstalk could degrade the contrast ratio of a displayed image. In addition, self-absorption of the PL photons and the subsequent reemission could also generate a crosstalk pattern. It could also blur the image. The scattered light also escapes the screen and does not reach the solar cells. This is the origin of the low optical efficiency for harvesting energy. Hence, characterizing the crosstalk event in the absence of the scattering events is important for assessing the ultimate performance of such a display.

In this paper, we report on the experiment with organic dyes. Section 2 briefly describes the simple model for the crosstalk [5]. Its characterization by experiment is described in Section 3. Implications of this effect on the image quality is discussed in Section 4.

2 SIMPLE MODEL

Suppose that a single spot on the uniform organic dye layer is excited by a narrow beam of light and that the emission is isotropic. As depicted in Fig. 1, the forward flux F_f and the backward flux F_b are emitted with the angle θ. They are reflected at the air-plate interface with the reflectance R_F given by the Fresnel equations. The dye layer partially absorbs the reflected PL photons and reemits the second-generation PL photons. Some of them reach our eyes and this results in the crosstalk.

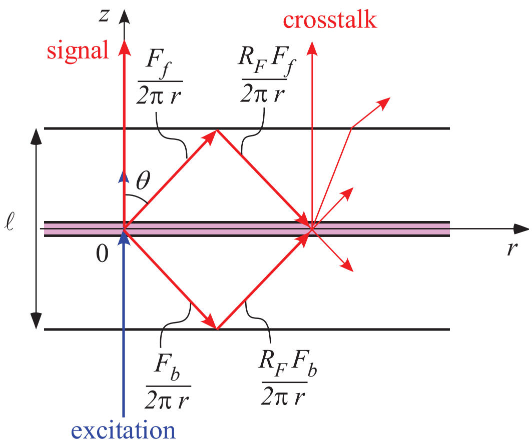

Fig. 1 Cross section of a non-scattering screen

Some of the PL photons are reflected back to the dye layer, which partially absorbs them and reemits.

The intensity of the crosstalk is proportional to that of the incident flux $\left(F_b + F_f\right)$ and R_F. Noting that the PL photons spread in the two dimensional space, the intensity of the crosstalk at a distance r from the excited spot is expressed as,

$$I_{Xtalk} \propto \frac{R_F}{2\pi r} \times \left(F_b + F_f\right). \quad (1)$$

The distance r is related to the emission angle θ by,

$$r = \ell \tan\theta, \quad (2)$$

where, ℓ is the thickness of the waveguiding structure as defined in Fig. 1.

The factor R_F / r has a peak at $r = \ell \tan\theta_c$, where θ_c is the critical angle for total internal reflection (TIR) [5].

3 EXPERIMENT

This section describes the experiment for observing the crosstalk from a uniform luminescent waveguide (LWG).

3.1 Fabrication of LWGs

The eight LWGs shown in Fig. 2 were fabricated by the same procedure described earlier [6] except for the followings. The area of the acrylic plates was 50 x 50 mm^2 and its thickness was either 2.0 mm or 5.0 mm. In addition to coumarin 6 (Sigma-Aldrich Co. LLC.), Lumogen F Red 305 (BASF Japan Ltd.), a popular luminescent dye for LSCs, was also used as the luminescent material. The transmittance of these LWGs were measured with a laser emitting at 450 nm (Z-Laser GmbH, Z30M18H-F-450-pe) and a power meter (Ophir Optronics Solutions Ltd., PD300-SH). Table 1 lists some properties of these LWGs.

(a) 4mm-thick LWG

(b) 10mm-thick LWG

Fig. 2 Photographs of the eight LWGs

Samples with higher dye concentrations appear more colored under room light illumination.

Table 1. Properties of the LWGs

dye	Conc. [wt%]	ℓ [mm]	T_{ex}	LWG #
C6	0.02	4.20	0.449	1
		10.23	0.420	2
	0.05	4.05	0.114	3
		10.20	0.105	4
Red305	0.2	4.16	0.563	5
		10.28	0.529	6
	0.5	4.23	0.064	7
		10.23	0.106	8

C6: courmarin 6 (Sigma Aldrich)
Red305: Lumogen F Red 305 (BASF)
Conc.: concentration of the dye in UV-curable resin
ℓ : LWG thickness measured by a vernier caliper
T_{ex}: transmittance measured at 450 nm

3.2 Observation of crosstalk

As illustrated in Fig. 3, a 12-bit monochrome camera (The Imaging Source Asia Co., Ltd., DMK23UP1300) faces the LWG squarely. A narrow laser beam (wavelength 450 nm, power 67.3 μW) is incident on it at 20°. The camera captures the PL photons emitted normally from its surface. The gamma value of the camera is set to unity such that the pixel value in an output image is proportional to the intensity of the incident light. The exposure time is adjusted to accommodate the wide intensity range for the PL photons leaving the LWG [4].

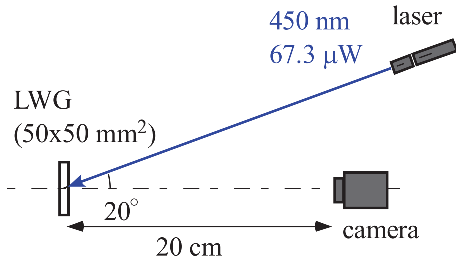

Fig. 3 Setup for observing a crosstalk pattern

A 12-bit monochrome camera faces an LWG to capture the PL photons emitted normally.

As an example, the images of the two 0.5 wt%-Red305 LWGs are compared in Fig. 4. In both cases, the pixel values at the central region are saturated at this exposure time T_E = 500 ms. In Fig. 4(a), a hollow pattern is clearly visible for the 4mm-thick LWG: the region immediately around the excited spot is darker than the surrounding region.

(a) 4mm-thick LWG (b) 10mm-thick LWG

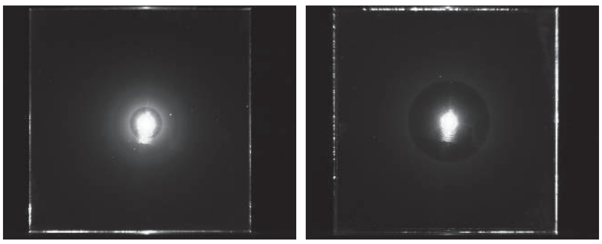

Fig. 4 Emission patterns of LWG #7 and #8

The exposure time is 500 ms for both cases. The pixel values around the excited spot are saturated.

The pixel values along the horizontal line including the excited spot were extracted from the images in Fig. 4. This process was repeated with T_E = 0.1 ms and the results are compared in Fig. 5. The secondary peaks become visible by setting T_E to 500 ms whereas the primary peaks are visible with T_E = 0.1 ms. The smaller peaks in these profiles are caused by some dirt attached on the surface of the LWG as evident from Fig. 4.

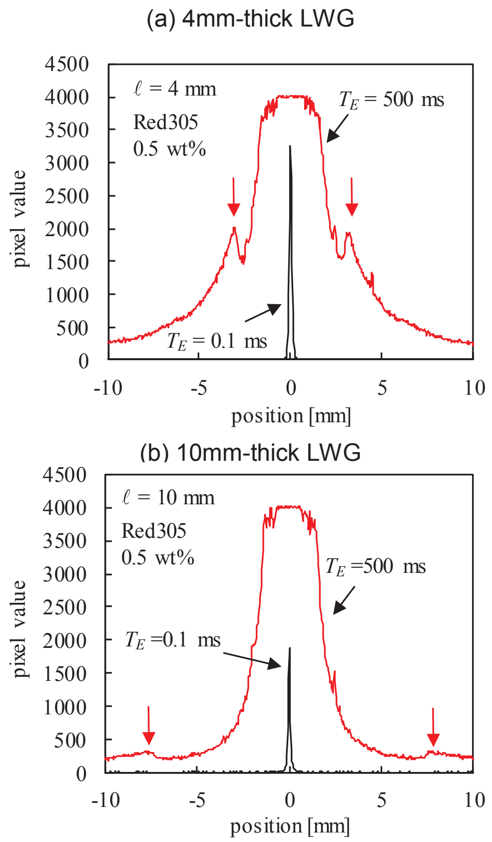

Fig. 5 Intensity profiles for the LWGs in Fig. 4

These profiles are extracted from the images taken with two exposure times (0.1 ms and 500 ms). The red arrows indicate the secondary peaks.

4 Discussions

Implications of the crosstalk on the image quality are discussed in this section.

4.1 Spatial resolution

The width of the primary peak sets the lower limit for the spatial resolution. The pixel values around the primary peak are normalized and the results for the 10mm-thick LWGs (#6 and #8) are compared in Fig. 6. The 0.2 wt% LWG (#6) has a slightly wider distribution. A full width at half maximum (FWHM) is calculated for each of the four LWGs and is listed in Table 2. The width of the laser beam is about 0.1 mm FWHM [7]. Because the values in Table 2 are clearly larger than 0.1 mm, there exist additional mechanisms for the spreading observed here. Also shown in Table 2 is the thickness of the Red305 layer calculated from the data in Table 1. It appears that the spreading of the primary peak is positively correlated to the thickness of the luminescent layer. Therefore, it is likely that the PL photons are partially absorbed before exiting the dye layer and that reemission events take place. At the lower dye concentration, the PL photons can penetrate further into the dye layer and extend the region for the reemission.

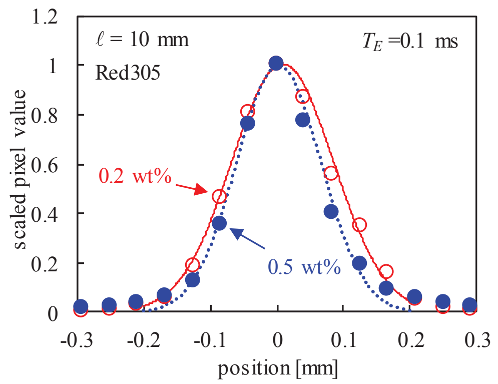

Fig. 6 Primary peaks for the 10mm-thick LWGs

The profile for the 0.2 wt% LWG is wider. The curves are approximations by a Gaussian function.

Table 2. Spreading of the primary peak

LWG #	FWHM [mm]	Thickness of the Red305 layer [mm]
5	0.152	0.16
6	0.180	0.28
7	0.147	0.23
8	0.149	0.23

In practice, the spreading of the primary peak does not limit the spatial resolution of a displayed image as long as the pixel size is set larger than this spreading.

4.2 Contrast ratio

The ratio of the pixel value to the exposure time is proportional to the intensity of the PL photons exiting the LWG. Hence, the ratio calculated from the primary peak represents the white level of a displayed image. The ratio calculated from the secondary peak corresponds to the black level. The contrast ratio is defined as the ratio of the white level to the black level. These numbers for the four Red305 LWGs are listed in Table 3. The LWGs with ℓ = 10 mm (#6 and #8) have a larger contrast ratio. The contrast ratio can exceed 1 x 10^5.

Table 3. Contrast ratio calculated from the two peaks

LWG #	White level (from the primary peak)	Black level (from the right secondary peak)	Contrast ratio
5	17460	1.424	1.23 x 10^4
6	35100	0.305	1.15 x 10^5
7	32670	3.798	8.60 x 10^3
8	18840	0.560	3.36 x 10^4

We have defined "radius of crosstalk" as the distance between the primary and the secondary peaks. The values calculated from the right and left peaks for each sample is shown in Fig. 7. The red marker represents the distance $\ell \tan\theta_c$ for each LWG. The measured radius is close to the simple model prediction. Further studies are needed to see if the discrepancy observed here is genuine.

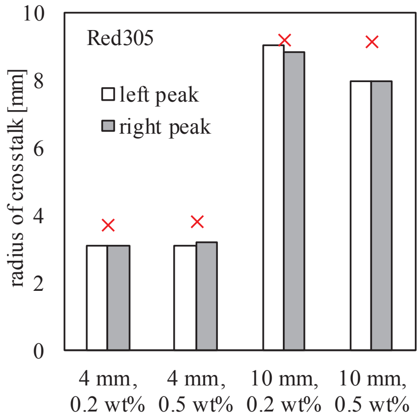

Fig. 7 Radius of crosstalk patterns

The radius calculated from the each secondary peak almost coincides each other. It appears that the simple model slightly overestimates this quantity.

As discussed so far, the reemission event can degrade the spatial resolution and the contrast ratio. Hence, further understanding of this phenomenon is important for an optimal design. In this regard, a closer observation of the emission pattern provides us a clue. As shown in Fig. 8, the images in Fig. 4 are enhanced by setting the gamma value to 0.40. Now, it is confirmed that the crosstalk pattern is concentric. The simple model does not explain this and a further theoretical study is needed.

(a) 4mm-thick LWG (b) 10mm-thick LWG

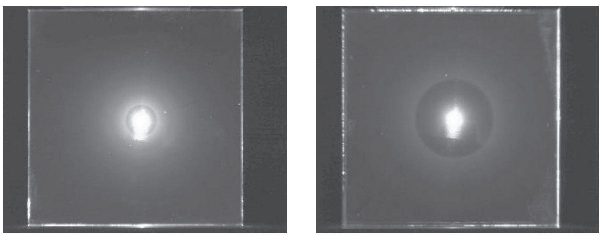

Fig. 8 Images enhanced by gamma correction

When the gamma value of the images in Fig. 4 is set to 0.40, a concentric emission pattern becomes visible.

5 CONCLUSIONS

Even in the absence of scattering events, self-absorption of the PL photons and subsequent reemission can degrade the quality of an image. Although this results in the concentric crosstalk pattern, the contrast ratio of a displayed image can exceed 1 x 10^5. The measured width of the emission profile for the excited spot ranges from 0.15 mm to 0.18 mm FWHM. Degradation of spatial resolution can be avoided by setting the pixel size adequately larger than this width. Further studies are needed to understand the reemission process.

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REFERENCES

[1] W. H. Weber and John Lambe, "Luminescent greenhouse collector for solar radiation," Appl. Opt. **15**(10), 2299-2300 (1976).

[2] Roger A. Hajjar, "Introducing scalable, freeform, immersive, high-definition laser phosphor displays," SID Digest, **43**, 985-988 (2012).

[3] Ichiro Fujieda, Shunsuke Itaya, Masamichi Ohta, Yuuki Hirai, Takamasa Kohmoto, "Energy-harvesting laser phosphor display and its design considerations," J. Photon. Energy **7**(2), 028001 (2017).

[4] Ichiro Fujieda, Takamasa Kohmoto, Kohei Yunoki, Mitsuhiro Shigeta, Yasuhiro Tsutsumi, "Fabrication and operation of an energy-harvesting color projector," SID Digest **50**, 394-397 (2019).

[5] Kohei Yunoki, Ryo Matsumura, Takamasa Kohmoto, Masamichi Ohta, Yasuhiro Tsutsumi, Ichiro Fujieda, "Crosstalk and optical efficiency of an energy-harvesting color projector utilizing ceramic phosphors," submitted to Applied Optics.

[6] Ichiro Fujieda, Masamichi Ohta, "Angle-resolved photoluminescence spectrum of a uniform phosphor layer," AIP Adv. **7**, 105223 (2017).

[7] Shintaro Ozawa, Masamichi Ohta, Shunsuke Itaya, and Ichiro Fujieda, "Measurement of photoluminescence spreading in an LC/dye cell," Proc. 23rd IDW, 180-183 (2016).