Enhanced Utilization of Ambient Light by Optical Films Coupled to a Luminescent Waveguide

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ABSTRACT

Ambient light is converted to photoluminescence photons in a luminescent waveguide. A reflector placed below increases the upward flux by a factor of 1.7. A light-diffusing film attached to its bottom surface improves this factor to 2.2. The ambient light redirected by these films would narrow a color gamut.

1 INTRODUCTION

Ambient contrast ratio (ACR) of a liquid crystal (LC) cell stacked on a luminescent waveguide (LWG) remains at about 10 when illuminance is increased up to 222 klx [1]. This is smaller than 23, the value for the reflective liquid crystal display (LCD) reported in 2019 [2]. The black-state luminance of a display is proportional to the intensity of the light scattered by its surface and the components inside. In this regard, a display utilizing non-scattering luminescent materials has a potential advantage over a reflective LCD because no color filters are needed. The white-state luminance of such a display is proportional to η, the quantum efficiency of its luminescent layer [1]. That of a reflective LCD is proportional to the reflectivity of the pixel electrode, which can be made close to unity. Hence, it is eminent to increase η for enhancing ACR of a display based on luminescent materials.

In this paper, we study the effect of optical films on ambient light utilization.

2 AMBIENT LIGHT UTILIZATION

Let us consider the process of extracting light from an LWG. First, a luminescent material absorbs an incoming radiation and emits a photoluminescence (PL) photon. This probability η_{QY} is a material parameter and is called internal quantum efficiency. Second, some PL photons are trapped in the LWG via total internal reflection (TIR) as illustrated in Fig. 1(a). Denoting this probability as η_{trap}, the light extraction efficiency is equal to $1-\eta_{trap}$. Hence, the quantum efficiency η of an LWG is expressed as follows.

$$\eta = \eta_{QY}\left(1-\eta_{trap}\right). \qquad (1)$$

For example, in case of isotropic emission, a simple geometrical calculation reveals that η_{trap} is equal to $\cos\theta_c$ where θ_c is the critical angle for TIR. The expression for dipole emission is a little more cumbersome [3].

We consider two optical films for enhancing ambient light utilization. First, a reflector is placed below an LWG as shown in Fig. 1(b). The PL photons emitted forward can propagate toward an observer after reflection. The ambient light with longer wavelengths passes through the LWG without being absorbed. The reflector redirects it. If untreated, this component could be troublesome for a color display as will become clear in Section 3. We will discuss some optical measures to solve this problem in Section 4. We regard it a future topic for the moment.

Second, we consider minimizing η_{trap} by attaching a light-diffusing film to the bottom surface of the LWG as depicted in Fig. 1(c). It scatters the PL photons together with the transmitted ambient light. Some of them are directed toward the observer. Some of the light scattered downward is redirected toward the observer by the reflector. It is worth noting that light extraction is hindered by TIR in an organic light emitting diode (OLED) as well. Optical films enhance light extraction by breaking the TIR condition at its air-substrate interface [4].

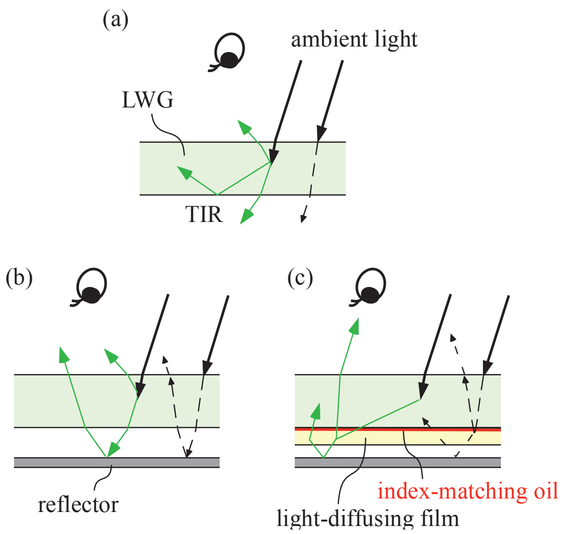

Fig. 1 Optical films enhance ambient light utilization.

3 EXPERIMENT

To quantify the effect of the optical films on the light utilization efficiency, we carried out the following experiments.

3.1 Monochromatic Excitation

For simplicity, we excited an LWG with a monochromatic light from a laser. A laser pointer emitting at 405 nm was held above an acrylic plate containing unknown luminescent materials (50 x 50 x 2 mm, purchased from a local shop). As shown in Fig. 2(a), it appeared green under room light. It was placed on a black paper. An optical fiber head was placed 3 cm above the LWG to guide the photons to a spectrometer (Brolight, BM6001). As shown in Fig. 2(b), an aluminum foil was used as a reflector. A light-diffusing film developed for backlight applications (Tsujiden, D114) was attached to the bottom surface of the LWG with index-matching oil (refractive index 1.49). This was the same film used in [4].

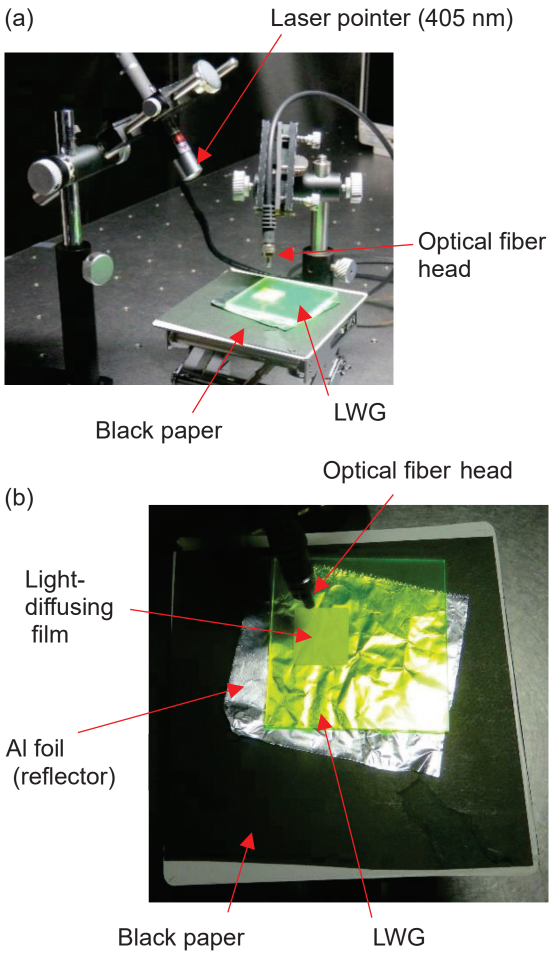

Fig. 2 Photographs of the setup and the device under test for the monochromatic excitation.

The power of the laser light was measured to be 2.5 mW. The integration time of the spectrometer was set to 5 ms. The spectra recorded under this condition are compared in Fig. 3. Each curve corresponds to the configurations depicted in Fig. 1. The number of photons emerging from the LWG is proportional to the area under of these curves. The reflector increases the upward photon flux by a factor of 1.7. Adding the light-diffusing film improves this factor to 2.2.

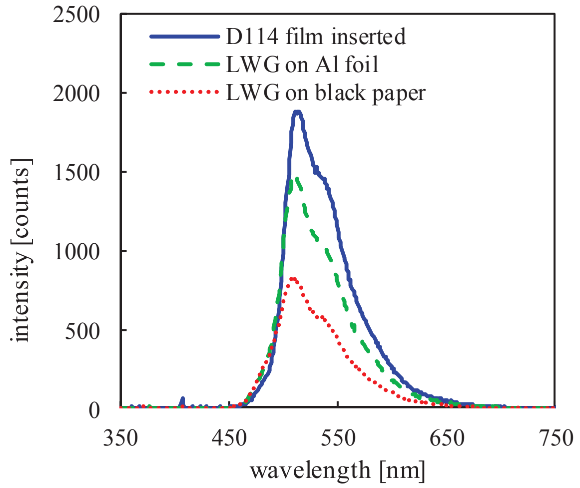

Fig. 3 Spectra recorded with a fixed integration time for the configurations depicted in Fig. 1.

A closer observation of Fig. 3 reveals the mechanisms behind this enhancement. Each spectrum is normalized by its peak intensity and the results are compared in Fig. 4. The intensity between 450 nm and 500 nm decreases when these optical films are added. This is caused by self-absorption. The forward flux suffers from redshift more than the backward flux [5]. The reflector adds this flux to the backward flux. The light-diffusing film scatters the PL photons, causing them to travel longer distances inside the LWG. These events result in larger redshifts.

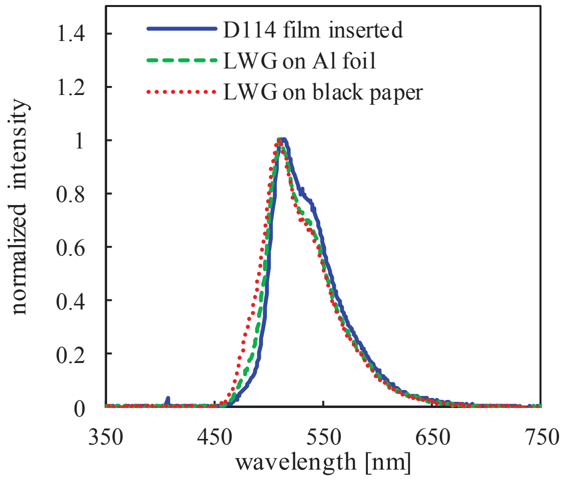

Fig. 4 Normalized spectra show redshifts caused by self-absorption inside the LWG.

A small peak appears around 405 nm only when the light-diffusing film is added. This is due to the excitation light scattered by this film after transmitting the LWG.

3.2 Excitation by White Light

In this experiment, the laser pointer was replaced by an LED flashlight and the spectrum recording was repeated for the three configurations in Fig. 1. Two types of flashlights were used. The spectra in Fig. 5 were obtained by removing the LWG and the light-diffusing film in Fig. 2. Hence, these are the product of the spectra and the reflectivity of the Al foil which has little dependency on wavelength. Both flashlights appear to combine LEDs emitting around 450 nm and yellow phosphors. Flashlight Type B emits yellowish light due to the larger intensity beyond 500 nm.

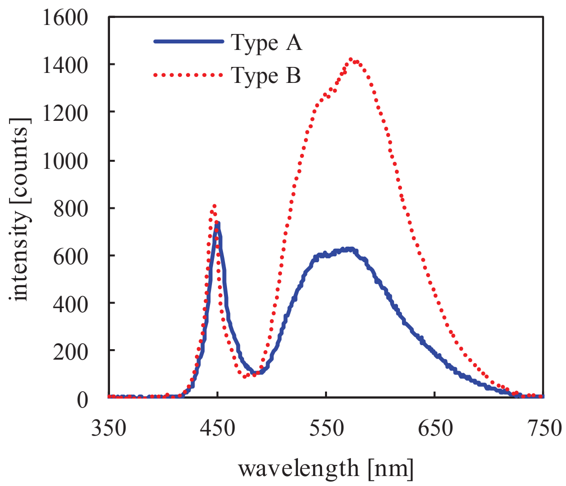

Fig. 5 Emission spectra of the two LED flashlights used in this experiment to mimic ambient light.

A photograph of the LWG illuminated by Type A flashlight is shown in Fig. 6. The light-diffusing film is attached to its bottom surface. This is placed on the Al foil and the black paper. Note that the area covered by the light-diffusing film appears white rather than green.

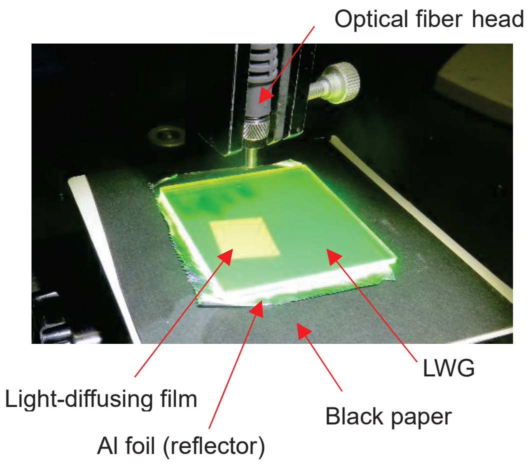

Fig. 6 Photograph of the device under test for the white light excitation.

The spectra recorded with the two flashlights are shown in Fig. 7. The LWG absorbs the blue light around 450 nm almost completely in both cases. The ratio of the areas under the three curves is $7.2:4.0:1$ for Type A flashlight in Fig. 7(a) and $6.9:5.7:1$ for Type B flashlight in Fig. 7(b). These enhancement factors are much larger than the ratio for the monochromatic excitation in Fig. 3 $(2.2:1.7:1)$. In Fig. 7, the centroid of the distribution shifts to longer wavelengths as the optical films are added. On the other hand, the emission peak remains at around 510 nm in Fig. 3. A separate measurement shows that the transmittance of the LWG is about 0.95 beyond 510 nm. These facts suggest that the observed spectral change beyond 510 nm in Fig. 7 is dominated by the ambient light reflected by the Al foil. Although this component enhances ACR, it would contract the color gamut of a color display. A low-pass filter would eliminate this component.

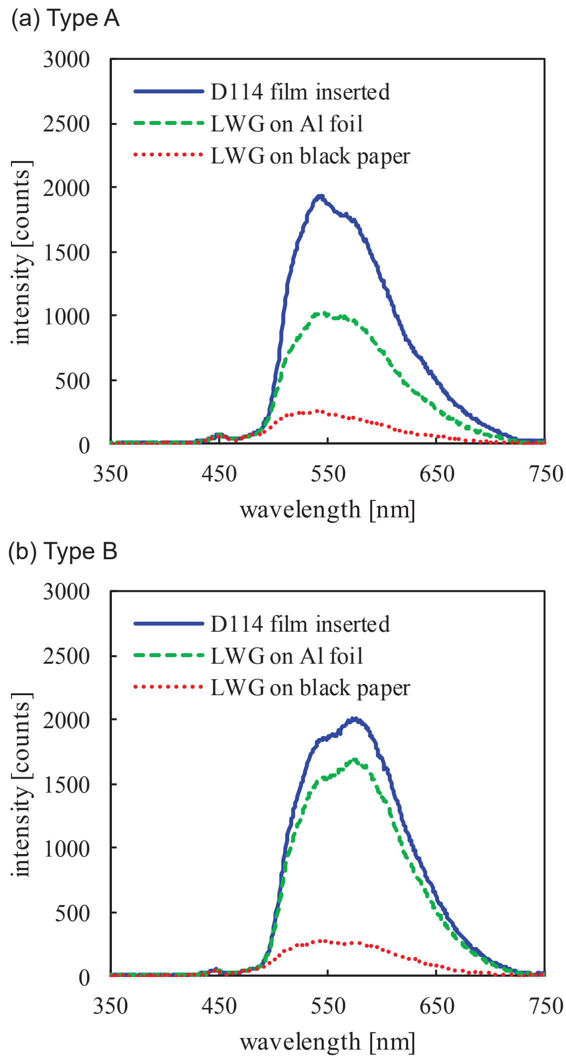

Fig. 7 The effect of the optical films depends on the spectrum of an LED flashlight.

4 DISCUSSION

Optical films allow one to utilize the light more efficiently by redirecting the light emitted in the wrong direction and by extracting the light trapped in the LWG. However, ambient light with longer wavelengths passes through the LWG. When this component reaches an observer, the gamut of a color display shrinks. In addition, a thick LWG would cause parallax error for a high-resolution display. We discuss what would be an ideal configuration for mitigating these problems and which technologies are available for fulfilling this goal.

As illustrated in Fig. 8, the low-pass filter above the corresponding luminescent layer passes the PL photons in the visible range and absorbs the ambient light with longer wavelengths. The light-scattering layer below the luminescent layer prevents waveguiding of the PL photons. The reflector below the light-scattering layer redirects the scattered light upward. For securing visibility in dark, a backlight unit emitting in ultraviolet is required to excite the luminescent materials from behind. For this reason, the reflector above it needs to pass the ultraviolet light. The color filter technology might be modified to form these filters. In addition, other in-cell technologies are required to avoid parallax error. In-cell polarizer has been already reported [6]. There is a continuing interest in this technology for improving the contrast ratio of an LCD [7].

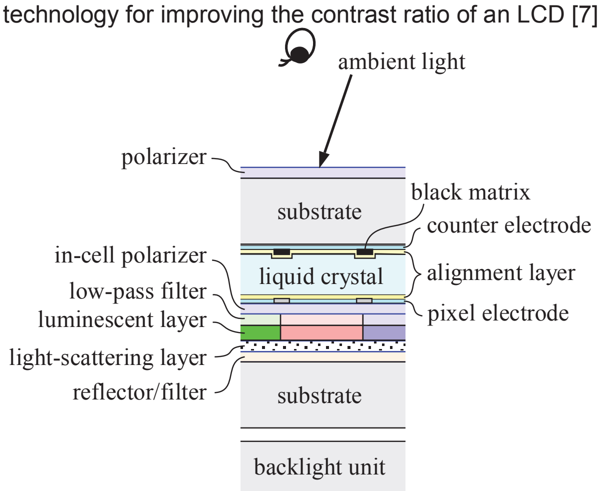

Fig. 8 A cross-section of a pixel structure for utilizing ambient light efficiently.

The low-pass filter can be moved to the upper substrate to ease burdens on fabrication. Note that Fig. 8 is not drawn to scale. Because the liquid crystal layer is much thinner than the pitch of the sub-pixels, there would be no optical crosstalk between sub-pixels.

One might be tempted to incorporate the light-scattering mechanism in a luminescent layer. Ceramic phosphors have granular morphologies and PL photons are extracted efficiently. However, such a layer would scatter the ambient light passing through the low-pass filter, leading to a smaller color gamut. Therefore, this mechanism should be provided by a separate layer as shown in Fig. 8.

5 CONCLUSIONS

Optical films enhance light utilization as follows. A reflector placed below a luminescent layer redirects the downward photon flux toward an observer. Light-diffusing mechanism placed near or built in the luminescent layer extracts the photons trapped inside.

In the first experiment, a monochromatic light from a laser excited an LWG. An Al foil placed below the LWG increased the upward flux by a factor of 1.7. This enhancement factor increased to 2.2 by attaching a light-diffusing film to the bottom surface of the LWG. In the second experiment, an LED flashlight replaced the laser. Although the light utilization was further enhanced, the reflected ambient light dominated the observed spectra.

A low-pass filter would prevent the ambient with longer wavelengths to reach the reflector, thus avoiding the shrinkage of a color gamut. For suppressing parallax error in a high-resolution display, some in-cell technologies need to be developed.

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