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Simulation and analysis on visibility enhancement for laser beam projected on display panels using black matrix with scattering particles☆

Dong-Kyun Shin, Jin-Young Lee, Gi-Eun Kim, Jongwoon Park*

Korea University of Technology and Education (KOREATECH), School of Electrical, Electronics & Communication Engineering, 1600, Chungjeol-ro, Byeongcheon-myeon, Dongnam-gu, Cheonan-si, Chungcheongnam-do 330-708, Republic of Korea

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ABSTRACT

With an attempt to enhance the visibility of laser beam projected on a display panel, we investigate the single-layered black matrix (BM) structure where light scattering particles are embedded in BM and the double-layered BM structure in which the scattering layer is separated from BM. By a ray tracing tool, we perform simulations, and then calculate the scattered ray distribution and detected power for those BM structures. It is observed from the results for both structures that the visibility is enhanced with increasing scattering particle density, but lowered with increasing oblique incidence of the laser beam. It is also demonstrated that the double-layered BM structure shows higher visibility than the single-layered BM structure. However, there exists a trade-off between the visibility of the projected laser beam on display panels and color mixing among pixels on the selection of those BM structures. Although color mixing is still unavoidable, our study shows that the scattered power into the active pixel area (pixel aperture) is as low as 1% of the incident laser power.

1. Introduction

Large-sized liquid crystal display (LCD) monitors have often been used in place of a beam projector and a screen for presentation in conferences or seminars [1,2]. The contents displayed on the monitor are highlighted using a laser pointer. The small width of the laser beam shows a point of light when striking an opaque surface. Due to reflection and absorption of light, however, the visibility of the laser beam projected on display panels is much lower than that on a normal projection screen. This phenomenon is more pronounced when the laser beam is projected obliquely from the side of the monitor. This is attributed to the layer structure and material property of the display panel. It is composed of a cover glass/color filter (C/F) substrate (glass)/black matrix (BM)/common electrode/LC/thin-film transistor (TFT) backplane in order from the outside to the inside of the panel [3]. Reflection and absorption of some laser beams occur on a cover glass or C/F substrate, but significant absorption takes place in the BM with very low light transmittance (typically about 3%). BM is used for shielding of direct light exposure to the TFT and to clearly distinguish the pixel boundaries [4]. It is made of a resin in which shielding agents such as carbon black or titanium nitride particles are diffused for light absorption (~95%) [5,6]. Normally, resin BM is fabricated by reverse printing method. The laser beam, which is not absorbed by the BM and enters the panel, is mostly absorbed by other materials.

To enhance the visibility of the laser beam projected on display panels, therefore, strong light scattering should be involved. Mie scattering has been widely utilized to extract more light from organic light-emitting diodes (OLEDs) [7–11]. Light-scattering strength is affected by the properties of particles, such as the refractive indices of the particle and the medium, the size of the particle, and the wavelength of the light that the particle scatters [12]. Rutile TiO_2 particles with diameters of roughly one-quarter micron have been used to maximize light scattering [13,14]. Considering the transparency and haziness of the display panel, those scattering particles should be incorporated into the non-emission area (i.e., BM) of the panel. In this work, we have investigated two different BM structures; the single-layered BM structure where light scattering particles are embedded in BM and the double-layered BM structure in which the scattering layer is separated from BM. To optimize the structure and maximize the visibility, we have performed simulations of a model similar to the actual panel using a ray tracing tool (LightTools 7.0 [15]). We have first analyzed the visibility of the projected laser beam on the panel by varying the scattering particle density, BM transmittance, and refractive indices of the particle and the medium. The dependence of the visibility on the incident angle

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* Corresponding author.
E-mail addresses: speed21c@koreatech.ac.kr (D.-K. Shin), dlwlsdud9203@koreatech.ac.kr (J.-Y. Lee), rlarldmsrns@koreatech.ac.kr (G.-E. Kim), pjwup@koreatech.ac.kr (J. Park).

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of the laser beam has also been investigated. Furthermore, we have studied the inter-pixel color mixing induced by scattering particles.

2. Methods

2.1. Experiment method

We experimentally investigate the possibility of light scattering and thus the enhancement of the visibility of the laser beam projected on display panels. In reality, a resin BM composition in which TiO_2 is dispersed would be printed or coated and then patterned on a C/F glass for the single-layered structure. For the double-layered structure, a patterned polymer medium embedding TiO_2 nanoparticles (i.e., the scattering layer) could be first formed on a C/F glass, and then a patterned BM is formed on it. Such a fabrication process requires a high-accuracy printing technology and/or wet etching process. Instead of it, we performed a simple experiment on light scattering at low cost. We coated TiO_2 (purchased from Sigma Aldrich) on a cover glass. The size of TiO_2 nanoparticles is smaller than 150 nm. The TiO_2 dispersion in H_2O was spin coated at the speed of 3000 rpm for 30 sec and dried on a hot plate at the temperature of 80° for 20 min. The TiO_2-coated glass was attached to a LCD panel and the laser beam was incident on it at an angle of 45° with respect to the normal. A digital camera was used to capture scattered light in a dark room. To demonstrate the strong dependence of the visibility on the incident angle of the laser beam (θ_i in Fig. 1), we also measured the luminance of the laser beam appeared on a TV monitor using a luminance meter (CS-100, Konica Minolta) in a dark room. The luminance meter is positioned to measure the luminance of the laser at a vertical distance. We used the laser pointer (3M, JC-2300) with the maximum power less than 1mW at the wavelength of 650 nm.

2.2. Simulation method

Presented in Fig. 2 is the schematic view of the layer structure of a display panel with a single- or double-layered BM structure used for ray tracing simulations. The total thickness of glass (cover glass + C/F glass) is chosen to be 1.4 mm, its refractive index to be 1.54, and its transmittance to be 90% for the thickness of 0.7 mm. The BM placed on the C/F glass has the thickness of 1.5 µm, refractive index of 1.6, and transmittance of 3%. Its structure is designed in such a way that the display panel has a resolution of 67.78 PPI, corresponding to a 65 in. 4 K ultra-high-definition (UHD) television. Namely, there exist three sub-pixels with the active area of 88 µm × 281 µm in a dot with the area of 370 µm × 370 µm. The width of the horizontal and vertical lines of BM is 88 µm and 35 µm, respectively. In the single-layered BM structure, scattering particles with the refractive index of 2.4 and diameter of 1 µm are embedded in the BM to induce Mie scattering. In the double-layered BM structure, the scattering layer is separated from the BM layer so that the incident laser beam from outside can be scattered by the scattering layer and the light from the inside of panel can be

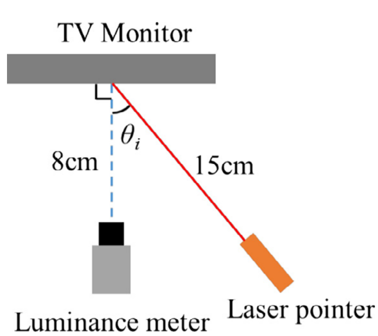

Fig. 1. Measurement setup for the luminance of laser beam on a TV monitor at different incident angles (θ_i) using a luminance meter.

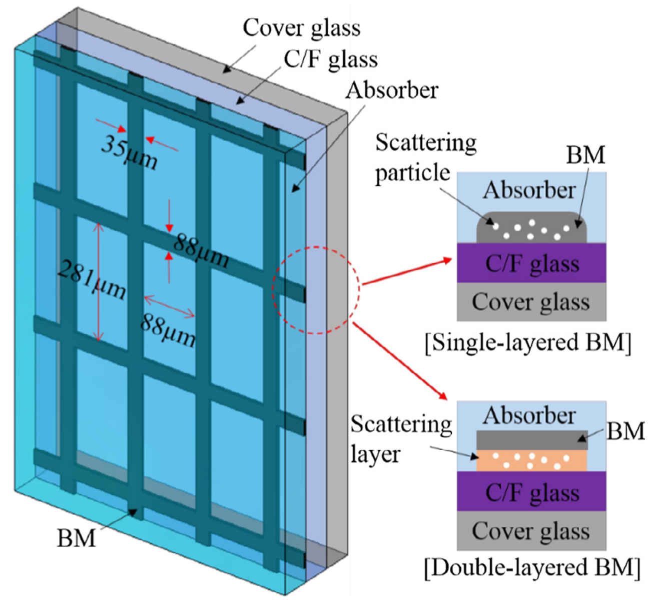

Fig. 2. Schematic view of the layer structure of a display panel with a single- or double-layered BM structure used for ray tracing simulations.

absorbed by the BM layer. The refractive index and thickness of the medium (the scattering layer in the double-layered BM structure) are set to be the same as those of BM, but its transmittance is assumed to be 100%. We have varied the scattering particle density within the range between 10^7 mm^{-3} and 10^{10} mm^{-3}, and observed its effect on light scattering. In Fig. 2, other parts of the display panel such as LC, TFT backplane, and back light unit (BLU) are replaced by a simple absorber with the refractive index of 1.7 and thickness of 0.7 mm in order to capture light scattering induced purely by those single- and double-layered BM structures. A round-shaped laser source (corresponding to a laser pointer) has the ray emitting area of 4.5 mm^2 and is set to have the radiation power of 100 mW. The total number of rays is 3 million. Unless otherwise specified, the laser beam is incident on the display panel at an angle of 0° with respect to the normal (i.e., normal incidence). The receiver detecting the scattered rays is place right on the cover glass. It is divided into 30 × 30 bins over the area of 20 mm × 20 mm to capture the scattered ray distribution. The visibility of the laser beam projected on the panel is evaluated by the number and power of scattered rays detected by the receiver.

3. Results and discussion

3.1. Experiment results

Fig. 3 shows the red-colored bright spot and scattered light of the laser beam measured with and without the TiO_2-coated glass attached to a LCD panel. Without the TiO_2-coated glass, a small but oval-shaped bright spot is observed because the incident angle of the laser beam is about 45° with respect to the normal. However, a round-shaped bright spot is observed with the TiO_2-coated glass at the same incident angle. Furthermore, stronger light scattering is observed around the central and bright spot. This simple experiment result implies that the visibility of the laser beam projected on display panels can be boosted once light scattering is incorporated into the BM structure. Meanwhile, red-colored light along the perimeter of the TiO_2-coated glass is due to the glass-air interface (refractive index difference). We have also measured the luminance of the laser beam appeared on a TV monitor without any light scattering particle involved and summarized the results for different incident angles (θ_i) in Table 1. It is evident that the luminance (visibility) varies depending sensitively on the incident angle of the laser beam. The luminance is reduced more than half even at the