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Improved Human Factors of Electroluminescent Displays using Optical Interference Effect

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Abstract

We discuss main techniques to improve legibility of electroluminescent displays. Emphasis is placed on use of destructive optical interference to cancel ambient light reflected from the back electrode of the device. Basic optical principles and material composition of the optical interference contrast-enhancing stack (CES) are presented. We also describe the improved human factors of electroluminescent devices assisted with a CES. Achromatic contrast is the most important contributor to display's legibility. In some conditions color contrast may also be important. Contributing to both luminance and color contrast enhancement, the contrast-enhancing stack may play an important role in various display applications.

Keywords : electroluminescence, human factors, contrast, optical interference.

1. Introduction

Despite the domination of liquid crystal displays in the flat-panel display (FPD) industry, there is increasing demand for alternative display technologies. This is primarily determined by the industry pull for an inexpensive, easy-to-make, and legible device. Electroluminescent displays were commercialized more than two decades ago in form of alternating-current thin-film EL (TFEL) devices [1, 2]. Recent progress of ELDs is mainly associated [3, 4] with organic light-emitting diode (OLED) displays (Fig. 1). One of the key advantages of electroluminescent displays over their LCD counterparts is their emissive nature, which makes them more pleasant to the eye and eliminates the need for a backlight illumination. Among other advantages are internal ruggedness, wide viewing angle, low power consumption, and great potentials to be manufactured by inexpensive ink-jet process [5].

In many applications a display is used in changing environments, from complete darkness to direct sunlight. Ideally, the display must have good legibility, a complex characteristic, which is primarily determined by image contrast and some other factors, including background color and brightness, diffuse and specular reflectance, etc. [6]. The key challenge for ELDs in achieving high contrast has been the use of reflective metals, such as aluminum, for the counter electrode. This material selection is determined by the ability of Al to prevent the destructive pixel breakdown in case of TFEL devices [7] and provide a stable and reproducible cathode in case of OLEDs [8]. The downside of using shiny electrodes is mirror-like reflection from the display, when most of the ambient light is being superimposed on the image, resulting in poor legibility.

This paper discusses the most important ways to enhance contrast and other human factors of electroluminescent displays.

2. Contrast Enhancement

One of the solutions to increase contrast is to make a display transparent, so there is no reflected light. Universal Display Corporation has addressed this

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through their patented Transparent OLED (TOLED) technology [9], comprising a thin Mg:Ag work-function-matching layer in combination with ITO as the transparent cathode. Efficiency of the transparent cathode, however, as well as efficiency of transparent organic electron-ejecting materials is not sufficient for their wide use.

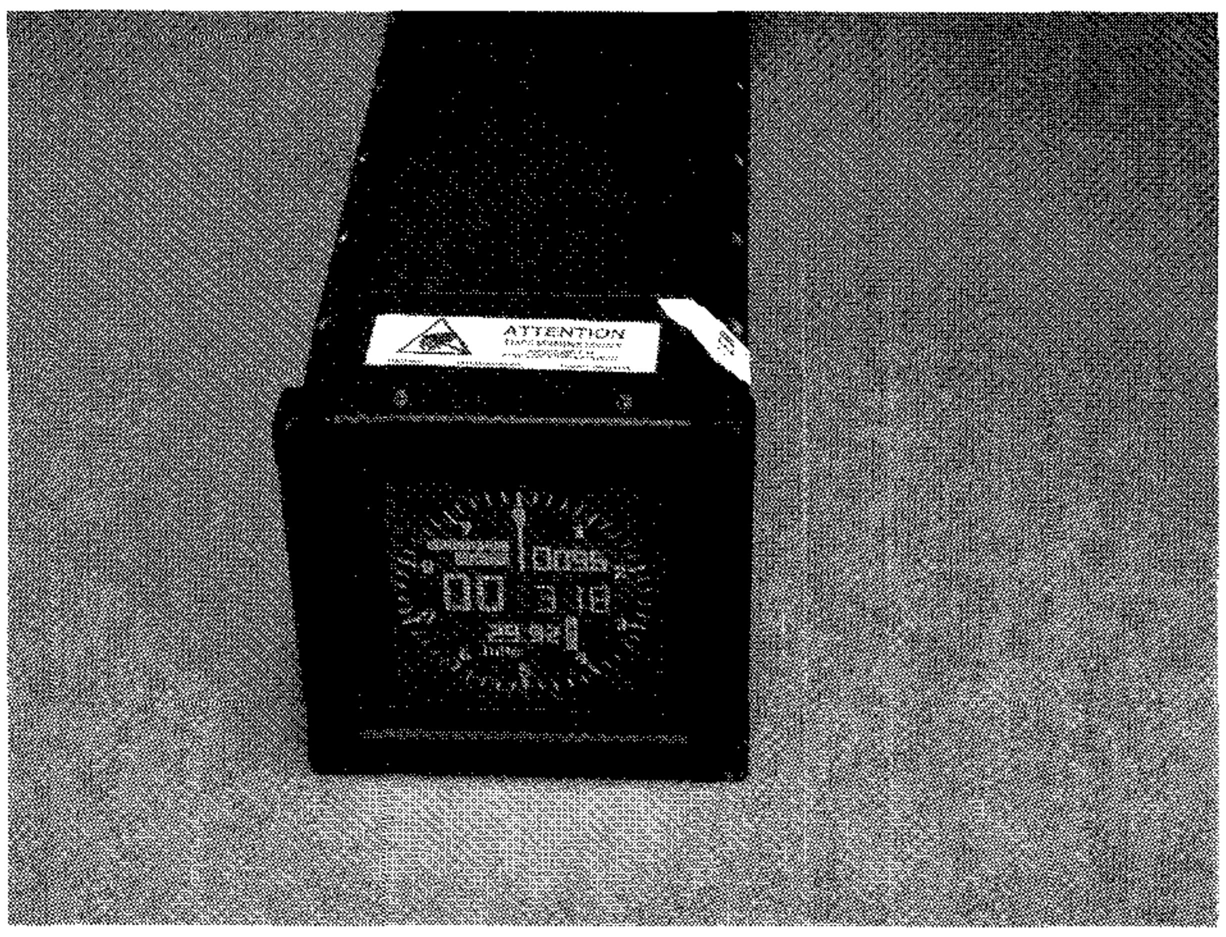

Fig. 1. A 3ATI OLED module.

A preferred way to achieve high contrast is cancellation of ambient light reflected from the back electrode and other interfaces in the display [6], which can be done using several methods. All these methods can be divided into external and internal.

2.1 External methods

The cancellation of light reflected from the front surface of the display is usually accomplished by using an antireflection coating, a method similar to that developed in 1935 by A. Smakula in Carl Zeiss [10]. A thin dielectric or metallic film (or a combination of such films) is applied on front of the device substrate to reduce the reflectance and thereby increase the transmittance through the refractive index matching. Antireflection coatings can be applied by means of vacuum deposition or in a form of laminating films, often also combining antiglare properties.

The most common and successful method to reduce the reflectance from an electroluminescent device is the use of a traditional circular polarizer (a combination of a laminate of a linear polarizer and a 1/4 wavelength optical retarder) in front of the display [11]. Once passed through the linear polarizer, ambient light becomes linearly polarized. The retarder ensures further circular polarization of the light. After being reflected from the rear electrode of the device, the light experiences a second circular polarization by the retarder. Now it is polarized along an axis perpendicular to the axis of the polarizer and is unable to pass through it. At the same time, the emitted light, although polarized, exits the device. Circular polarizers are available from such companies as 3M, Sumitomo, etc. and require no internal changes to the device. Despite their good optical performance, the polarizers absorb a significant portion (~62 %) of the emitted light. They are also quite costly and do not eliminate the effect of pixel blooming (increased pixel size at high luminance), associated with the use of the reflective electrode. Also, this technology has some temperature limitations and is restrictive in use with promising flexible OLEDs [11].

2.2 Internal methods

The simplest internal method to eliminate the reflected light is the use of a light-absorbing material behind the light-emitting layer. Despite its seeming simplicity, the absorbing solution requires tough materials selection. iFire used a thick high-K dielectric in an “inverted” device design [13] to increase the electric field across the light-emitting layer and to prevent the device from a breakdown. It has been found that rough surface of the dielectric reduces the specular reflectance from the device, thus increasing contrast. Extreme Photonix has recently improved this approach in their experimental device by blackening the thick dielectric [14]. Xerox has recently applied a light-absorbing metal-organic layer at the rear of small-molecule based OLED devices to enhance their contrast [15].

Early attempts to improve contrast of TFEL devices through absorbing techniques included work of Sharp to incorporate a light-absorbing layer between the electroluminescent material and the rear electrode [16] and the use of dark dielectrics, such as $Pb_xCd_{1-x}Te$:In [17-19]. It is hard, however, to achieve high levels of contrast through a straightforward use of absorbing materials, since a decrease in the spectral component of the reflectance in this case is always accompanied by an increase in its diffuse component. Besides of that, all wavelengths, including infrared light, are absorbed, which may result in an extra heating of the device if used under direct sin light.

Among other internal contrast-enhancing approaches, which have found commercial applications in TFEL displays is the use of an index-varying dielectric layer at the rear of the device [20]. It implements a thin-film layer, having a gradually or discretely changing complex refractive index, between the rear dielectric and the counter electrode to absorb the ambient light thus to increasing contrast. The concept has been employed by Planar since 1996 in the form of an integrated contrast-enhancement layer.

3. Use of Optical Interference to Improve Contrast

3.1 Basic principles

It is a textbook knowledge that the speed of light in vacuum is independent of the wavelength of light λ. The velocity of propagation of electromagnetic waves through a solid does depend on the wavelength of the radiation and is given by the complex refractive index

$$N = n - ik ,$$

where the real part, n is related to the wave velocity, and k is the extinction coefficient, related to the damping of the oscillation amplitude. The extinction coefficient determines the extent to which light is slowed down in the material.

By selecting the extinction coefficient and thickness of the media, it is possible to control the phase shift between the incident and the lagging waves. If now the original wave is broken down into two parts by a semi-transparent film (Fig. 2), the phase shift between the two parts will increase with the thickness of the solid. If the lagging wave is now reflected by a reflective surface in the opposite direction, it will interfere with the original wave reflected from the first surface. The phase shift of 180° between the two reflected waves will mean the destructive optical interference. Selecting the amount of the reflected and transmitted light through the first layer, it is possible to make the two reflected waves being of the same magnitude, but propagating out of phase, which means their cancellation.

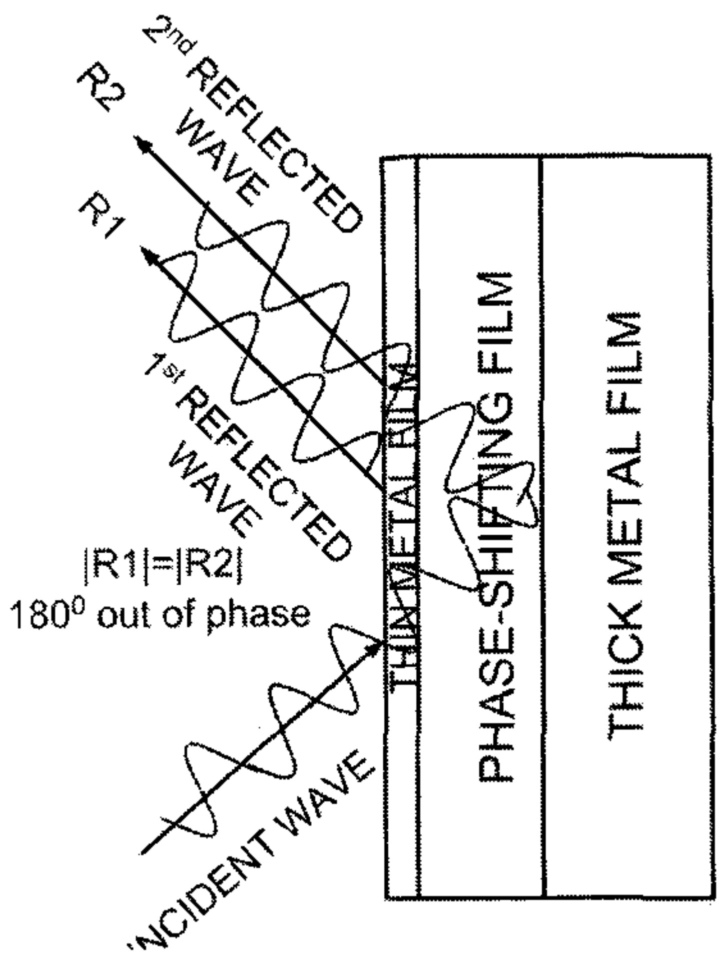

Fig. 2. Basic principles of operation of the optical interference contrast-enhancing stack.

3.2 Black layer™

In 1991 Luxell Technologies Inc. in collaboration with the National Research Council of Canada used this principle to develop a new concept [21] of eliminating the reflected light from an electroluminescent display. The concept interposes a destructive optical interference stack (Black Layer™) between the light-emitting part of the device and the Al electrode. Later the stack was applied to OLED devices [22]. This contrast-enhancing stack (CES) has a combination of an ultra-thin (~20-50 Å) semi-absorbing metal layer, a phase-shifting layer of a transparent conducting oxide (such as ITO, ZnO:Al, SiO-based materials, etc.), and a thick reflective metal layer (such as Al). The ultra-thin metallic film causes partial reflection of the ambient light. The whole stack is treated as an optical interference filter. A computer analysis is based on the calculation of the characteristic matrix of each layer, a component of this stack [23-25]. Thickness of the individual films are chosen such as to provide a 180° phase shift between the two reflected waves of the same magnitude, which causes the cancellation of the reflected light.

First two layers are the most crucial elements for a proper tuning of the CES. Best results have been achieved with the use of Cr as the first metal layer and CrSiO as the phase shifter. CrSiO is deposited from sintered pieces (Cr/SiO wt% ratios 60/40-70/30) at room temperature using electron beam evaporation. The deposition is performed in a vacuum system at a base pressure of 8 X 10^{-6} Torr at rates of 1-10 Å/s. The extinction coefficient of the material is measured with an ellipsometer and is kept at about 0.2 - 0.5.

The optical properties of CrSiO are strongly dependent on deposition rate and composition of the material. Films deposited at higher rates exhibit lower sheet resistance, presumably due to an increased hopping conductivity [26] between Cr-based inclusions. The concentration of this inclusions increases with the increased deposition rates due to different vapor pressures of Cr and SiO.

3.3 CES and flexible OLEDs

Being an integrated part of the device, the contrast-enhancing stack has several important advantages over its circular polarizer counterpart. It does not add to the thickness and weight of the device, and is very cost-effective. Compared to circular polarizers, the CES can be tuned for a better device performance and has an advantage to be used with emerging flexible OLEDs [27, 28].

To match the inorganic contrast-enhancing stack with delicate OLED structure, a good mechanical and chemical compatibility must be achieved. Flexible devices bring an additional requirement to the CES, i.e. the ability to withstand intrinsic mechanical stress caused by bending. By optimizing thicknesses and Young's moduli of the individual components, the contrast-enhancing stack can be produced mechanically compatible with a flexible device.

Experiments suggest [29] that the multi-layer CES prevents penetration of moisture and other aggressive elements into the organic film within the pixel area. This may largely be due to the excellent environmental stability of CrSiO, a component of the CES.

4. Human Factors of Ces-Assisted Displays

4.1 Reduced reflectance

Fig. 3 demonstrates the reflectance spectra from OLED devices deposited on different substrates. Due to the discussed optical interference nature of the contrast-enhancing stack, its best performance can be achieved for a particulate wavelength of light. Typically 555 nm (green light) is selected, since the human eye is most sensitive in this spectral region. At the same time, the blue and the red components of the ambient light are partially reflected. Tuning the thickness of each individual layer of the device allows further minimization of the reflected light, making it quite broadband and bringing it down to less than 2 % of specular reflectance from a TFEL display and less than 1 % for an OLED (compared to a 75-90 % reflectance from a regular device). The residual reflectance in the red and blue causes a dark-purple coloration of the display.

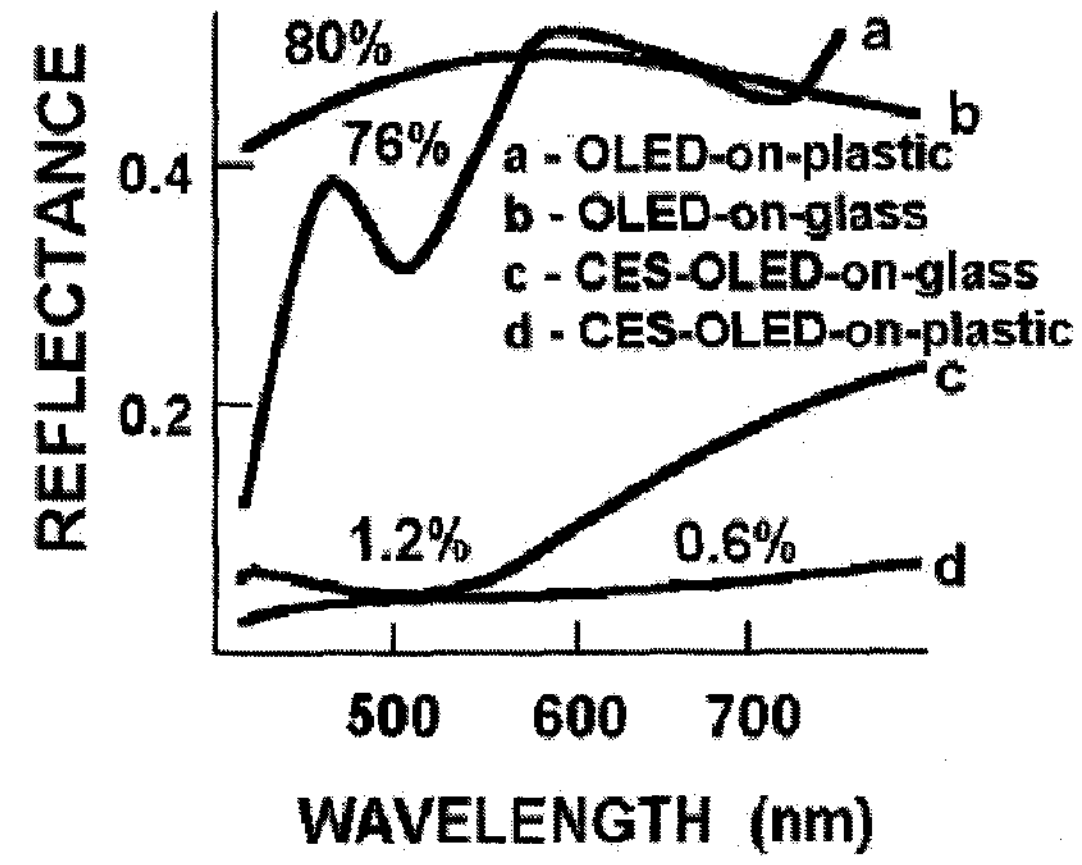

Fig. 3. Reflectance spectra from OLEDs deposited on various substrates.

While canceling the reflection of ambient light, the display remains reflective to the near-infrared light, which is a significant advantage over absorbing solutions in terms of solar loading when exposed to direct sunlight.

4.2 Improving both achromatic and color contrast

The effective use of an ELD as the final link in the machine-human interface requires deep understanding of the device's optical properties as well as the physiological aspects of the human vision. Each particular application demands specific requirements from the display. A device, which is perfectly legible in an indoor environment, may become useless in a cockpit exposed to direct sunlit. For instance, such companies as Raytheon, Lockheed Martin, BAE Systems require contrast of 1.5:1 or higher at 10,000 fL for monochrome applications. In some cases, a simple increase of luminance can provide sufficient legibility. In others, color contrast becomes important. The reasons for such "selectiveness" are the specific distribution of the receptive cells [30] in the eye and the change of the receptor sensitivity depending on the surrounding illumination and the viewer's physiological conditions. In the human eye achromatic rods occupy primarily the eye periphery, while chromatic cones are located in the very central region of the retina. A high luminance contrast, therefore, is especially important for peripheral "at-a-glance" image recognition of side-view displays, while color contrast should be taken into account when dealing with direct-view displays. There is always, however, a minimum display luminance, below which it is impossible to achieve good legibility by simply reducing the amount of the reflected light. At the same time, it is difficult to make a device highly legible in high ambient illumination by just increasing luminance, because at high luminance the pupil starts to shrink, causing eyestrain.

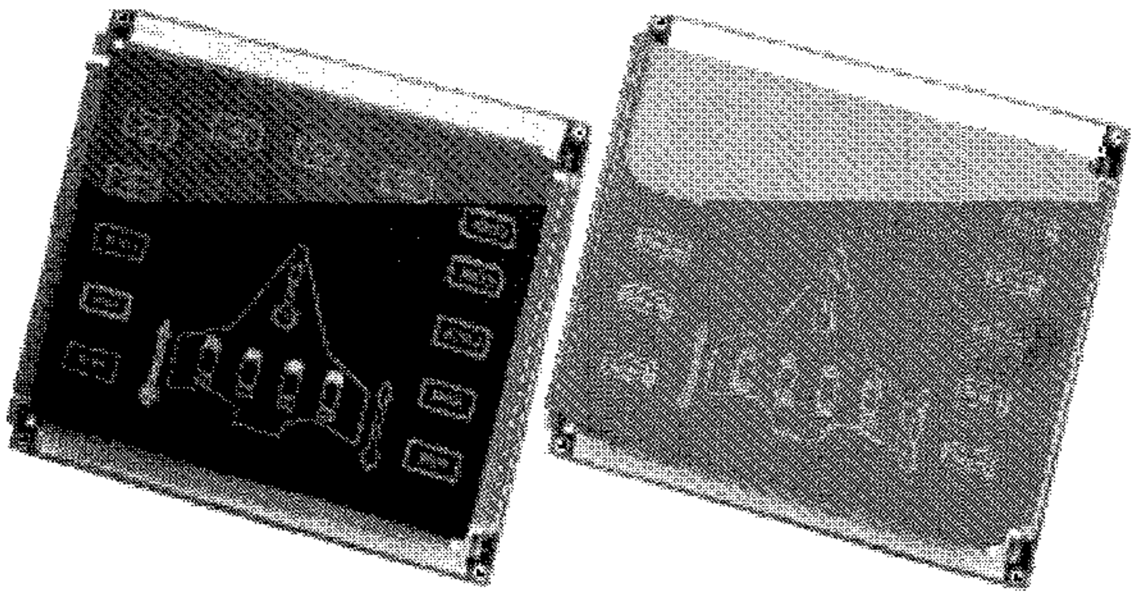

Fig. 4. Side-by-side comparison of CES-assisted TFEL (a) and conventional (b) TFEL devices.

In some applications, especially military, the eye is often subjected to alternating exposure to dark and bright ambient in short time intervals, the condition known as transient adaptation. During the dark (scotopic) adaptation, which lasts for several minutes, the rods are less sensitive receptors and the role of chromatic contrast becomes important. Some extreme conditions, such as high aircraft acceleration, may result in suffering from a lack of oxygen (hypoxia), which causes the rods to further reduce their sensitivity. The time required for dark adaptation in this case increases, and so does the significance of color contrast.

Contributing to an increase of both achromatic and color contrast, the contrast-enhancing stack improves the overall device legibility compared to its conventional counterpart (Fig. 4).

4.3 Contribution to other human factors

According to the Herring's Opponent Process Theory, human vision employs achromatic (black-white) and two chromatic (red-green and blue-yellow) systems to build a vision signal bridge between the retina and the brain. The dark-blue is always interpreted as a sign of distance, while its antagonist yellow or most other unsaturated colors appear closer. This results in enhanced foreground-background separation and is one of the reasons why CES-assisted displays improve the viewer's aesthetic satisfaction. A dark background improves also the perceived brightness of an unsaturated image through the effect known as inhibitory simultaneous contrast. This helps to improve legibility of the device without increasing brightness at the expense of power. To increase both luminance and color contrast of the yellow monochrome image, the optical-interference CES is tuned to create a saturated dark-bluish background (CIE color coordinates x=0.11; y=0.14). Because a dark-blue background is preferred for most colors, there are also great opportunities for applying the contrast-enhancing solution to multi- and full-color electroluminescent displays.

5. Conclusions

We have reviewed the main concepts and techniques to increase legibility of electroluminescent displays. Use of optical interference contrast enhancing stack between the light-emitting layer and the rear electrode allows a significant increase in contrast due to the elimination of the reflection from the device. It also eliminates environmental concerns, such as thermal and humidity sensitivity. The main advantage of the CES is that it is an integrated part of the device. This allows the whole stack to be optically tuned for a better device performance.

Based on a subjective evaluation, the contrast-enhancing stack has been found to contribute to the improved human factors of a device. It also brings a new competitive advantage over circular polarizers for emerging flexible OLEDs.

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