Chromaticity Performance Characterization of Curved OLED Light Sources

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ABSTRACT

Bending a planar OLED with flexible substrate or superstrate alters the optical structure of the device resulting in change of optical characteristics. In the previous publications by the author the effects of bending on the light emission through the substrate or superstrate were analyzed and the issues were extracted. The characteristics of two fabricated OLED samples with barrier layer thicknesses of 100 nm and 150 nm at curvature radii of $R_0=\infty$ mm (planar state), $R_2=143$ mm (cylindrically curved state) and $R_5=56.7$ mm (cylindrically curved state) were reported. In continuation of the previous work, the effect of bending radius of curvature on the characteristics of the OLED light source was theoretically and experimentally studied. The variations in optical characteristics of cylindrically shaped OLEDs, such as emission spectrum, chromaticity and luminous intensity distribution at specified directions were measured. The results were evaluated and discussed for the OLEDs in the planar and the cylindrically curved states..

1 Introduction

Flexible organic light emitting diodes (OLEDs) are used for illumination in recent years. The OLEDs are indispensable parts of the present and future power saving lighting technologies. These light sources are monolithic, segmented or block-wised such as integrated large size OLED. In the structures of the aforementioned light sources, a thin film glass or plastic film is used as substrate or superstrate which is flexible and bendable. Since the flexibility is an attractive characteristic, these non-planar OLEDs have been developed, and increased in the market, in the past few years.

In general, the flexible OLEDs are totally different in shape from the light sources that have been widely used so far. When a planar light emitting surface is bent or deformed, the optical properties of the device such as total luminous flux or other optical characteristics change. In contrast to planar OLEDs, the non-planar OLEDs (e.g. spherical, cylindrical, in general a curved light sources) introduce new measurement issues and challenges [1-6]. In this paper, the effect of bent substrate or superstrate of the OLED on the transmission or reflection of the emitted light is theoretically studied. In the next step, the optical characteristics of curved OLEDs are experimentally studied by fixing them on curved jigs to extract the issues of bent light sources. The analysis of the experiment results of curved OLEDs are discussed and showed how the curvature affects the optical characteristics such as the luminous flux, the angular luminous intensity distribution, and the emission spectrum. Furthermore the spectrum variations of cylindrically curved OLEDs along specified directions are measured and the comparison results with those of planar OLEDs are reported and discussed.

2 Fabricated OLED Panel Structure

In this study bendable OLEDs are employed to make a cylindrically curved light source (LS) and to estimate changes in characteristics in bent states. Therefore, a few OLED panels were prepared to study the effect of bending on the light emission characteristics. In the following paragraphs, the structure of prepared OLED panels are briefly explained.

In general an OLED consists of very thin layer as substrate as shown the structure in Fig.1. Few organic stacked layers are sandwiched between cathode and anode. The following materials are used in the structure. The Polyethylene naphthalate (PEN) is used as substrate. For planarization, an under coat (UC) layer is added. A Silicon-Nitrogen (SiN) is added as barrier layer. An Indium-Zinc-Oxide (IZO) is used as a transparent anode electrode. The light emitting part is the electroluminescence (EL) organic layers. As a cathode for EL layer, an Aluminum layer is added and coated by a film (F-film). As barrier film, an Al evaporated PEN (Al-PEN) is used. The thicknesses of the organic layers are normally several tens of nanometers and the thickness of an OLED panel including the substrate is less than 1 mm. The total thickness of the organic layers is negligible when compared to thickness of the sub/superstrate. Glass or plastic thin film is used as substrate. When a rigid glass sub/superstrate is used, the OLED panel cannot be bent. However, in the case of thin substrate plastic foil, the OLED can be bent or rolled, i.e., having a flexibility.

3 Theoretical Analysis

3.1 Light Emission Mechanism

The OLED panels are electric current driven light sources, in which the light emission is proportional to the number of electrons passing through the light-emitting layer. The light emission concept for a case of bent OLED is schematically shown in Fig.2. The light is generated in the organic layer (EL layer in the figure) that is sandwiched between the cathode and anode layers. Part of the light is emitted through the sub/superstrate. However, the rest of light is captured in the structure. The higher order emitted light rays that is the rays with large angles with respect to surface normal, are guided in the thick layers of the OLED. The trap of part of light rays results in changes of light radiation pattern and reduction in emitted luminous flux of the OLED [1-6]. To clarify the light transmission through a bend layer, the bending issues, e.g. the change of critical angles with curvatures radii, are theoretically analyzed.

3.2 Planar OLED Panel

A planar OLED with superstrate is shown in Fig.3. The emitted light is propagated through the superstrate and is emerged out of the superstrate. The total internal reflection occurs when the incident angle (θ_i) reaches the critical angle that depends on the refractive index of the superstrate. Here, an angle (θ_{ig}) is defined as a parameter that shows the complementary of the critical angle in the geometry of the light source, i.e., planar, spherical, or cylindrical shapes.

3.3 Spherical OLED Panel

A schematic diagram of a spherical OLED with a superstrate is shown in Fig.4. The light is generated in the inner part and emitted outward through the superstrate. The definition of the geometry dependent incident angle (θ_{ig}) and the critical angle (θ_{cg}) are the same as that of the planar OLED.

Since a sphere has a point symmetry structure, the cross section of the sphere can be used for analysis, that is, only the zenith angle, θ.

The transmission and reflection characteristics of the spherical OLED are affected only by the inner and the outer radii of the superstrate. Therefore the characteristics are analyzed in terms of R_1 and R_2.

3.4 Cylindrical OLED Panel

The geometry of a concave cylindrical OLED is shown in Fig.5. The cylindrical OLED emits light toward the outer surface. The difference between a cylinder and a sphere is that the analysis is based on the azimuth angle (ϕ), i.e., the position of the refracted ray on the inner or outer surface of the OLED cylinder. The transmission and reflection characteristics are expressed in terms of the inner and outer radii of the cylindrical OLED and the azimuth angle (ϕ).

3.5 Transmission/Reflection Coefficients: Bent OLED

A light ray travelling in a denser medium (n_s) strikes the surface of a less dense medium (n_a), i.e., $n_s > n_a$ where n_s and n_a : refractive indices of superstrate/substrate and air. Beyond a particular incidence angle known as the critical angle all light rays are reflected and the reflection coefficients are R_S=R_P=1. Here, the subscripts s and p stand for perpendicular and parallel polarizations. This is the case of total internal reflection, occurs at incidence angles for which Snell's law predicts that the sinusoid of the angle of refraction would exceed unity (whereas in fact $\sin\theta_i \leq 1$ for all real θ_i). The reflection and transmission characteristics of the superstrate for planar, convex and concave spherical OLEDs, are shown in Fig.6. The transmission (upper graphs, T_s, T_p) and reflection (lower graphs, R_s, R_p) coefficients are shown for planar OLEDs and concave/convex spherically bent OLEDs' superstrates with inner and outer radii of R_1 and R_2, respectively. The solid lines show the planar LS (up: T_s, T_p, down: R_s, R_p), the dotted lines show concave spherical LS (up: T_s, T_p, down: R_s, R_p), and the dashed lines show convex spherical LS (up: T_s, T_p, down: R_s, R_p). The changes of T_s, T_p, and R_s, R_p which depend on the geometry, e.g., planar and cylindrical (Φ=5°, 10°) are shown in Fig.7, where Φ is the angle viewed the emergent light ray position from the origin o-point.

The geometry dependent critical angles, θ_{cg}, were calculated for convex spherical and cylindrical OLEDs with superstrate (upper graphs) as shown in Fig.8. The lower graphs (below the "plane" shown in the figure) show the geometry dependent critical angle (θ_{cg}) for the concave spherical and cylindrical OLEDs.

4 Experiment Results

4.1 Fixtures: Planar, Convex, and Concave Jigs

To measure the characteristics of the samples in planar and cylindrically curved states, three jigs with cross sections shaped as segments of circles were designed and fabricated with radii of $R_0=\infty$ mm (a planar with a curvature of C_0=0 m^{-1}, and a sag of segment, H_0=0 mm), R_2=143 mm (with a curvature of C_2=17.637 m^{-1}, a sag of segment, H_2=2 mm) and R_5=56.7 mm (with a curvature of C_5=6.993 m^{-1}, and a sag of segment, H_5=5 mm) as shown in Fig.9 [1-6]. The planar jig was fabricated as a base for the comparison of the results.

4.2 OLED Samples

The following two OLED panels were prepared and used for measuring and evaluating their optical characteristics in flat and curved states. The sample S#1 had a barrier (SiN) thickness of t_1=100 nm, and the sample S#2 has a barrier thickness of t_2=150 nm. The substrate size was 48×46 mm^2 and the light emitting area was 26×26 mm^2 which was located at the center of a flexible substrate. The structure of the OLEDs were the same as shown in Fig.1.

4.3 Measured Spectrum: Bent OLED

The spectra of samples (S#1, S#2) on the jigs at surface normal axes (center of each curvature) are shown in Fig.10 for planar (H_0), and convex cylindrical

OLEDs, i.e., with H_2 and H_5. For comparison an OLED with glass superstrate was additionally fabricated. Its spectrum is shown in Fig.10. The spectra of S#1 and the OLED with glass superstrate were measured at directions of θ=0° (at surface normal), 20°, 40°, 60°, 80°. The variations of chromaticity with measurement direction and the bend curvatures are shown in Fig.11.

The chromaticity of samples S#1 and S#2 in the planar and cylindrically convex states were calculated using their spectra. For comparison, the variation of chromaticity for the sample S#1 is shown in Table 1. The variation of Δu'v' for S#2 in case of H_2 and H_5 are almost three folds of those of S#1. Furthermore, the characteristics of the sample S#2 with the barrier thickness of 150 nm, are similar to that of the OLED with glass superstrate.

5 Conclusion

The issues of bent OLED light sources, i.e., the effects of superstrate in light transmission and reflection on the characteristics of the OLEDs were studied theoretically. For the first time the coefficients of reflection and refraction (Figs. 6, 7) of the light in bent substrate or superstrate were analytically researched, formulated and calculated for the spherical and cylindrical bent light sources. Finally, the spectrum changes in the bent states were studied experimentally (Figs.10 and 12), for planar and cylindrical light sources. The results were compared with those of the planar OLED light sources.

As stated above, the bending of the OLEDs results in the change of directional emission characteristics. The convex bending of an OLED results in highly extraction of the light that benefits lighting design in some applications. This property can be counted as a new property for developing special lighting fixtures or display lighting devices.

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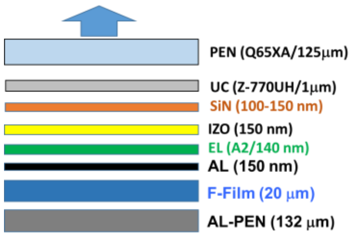

Fig.1 Structure of the fabricated OLED (Top emission)

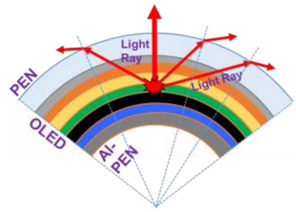

Fig.2 Schematic diagram of the OLED in bent state.

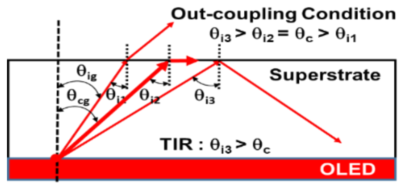

Fig.3 A planar OLED and the refraction/reflection of the emitted light in the superstrate.

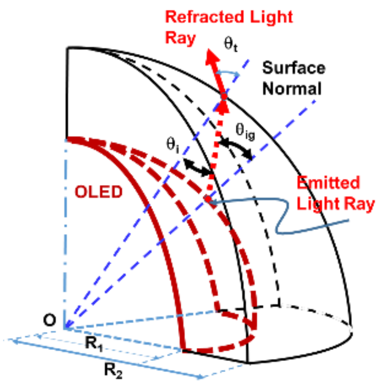

Fig.4 Geometry of the convex spherical OLED.

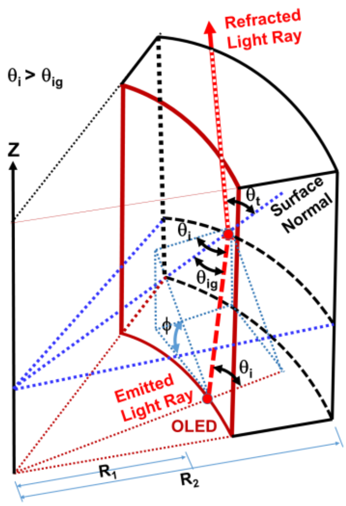

Fig.5 Geometry of the convex cylindrical OLED.

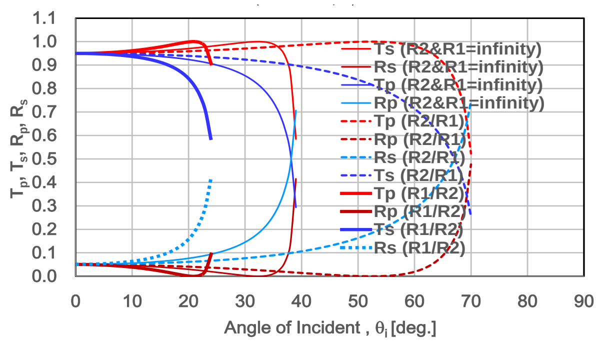

Fig.6 Transmission (uppers, T_s, T_p) & reflection (lowers, R_s, R_p) coefficients in the planar, the concave and the convex spherically bent OLED superstrate with inner and outer radii of R_1 and R_2.

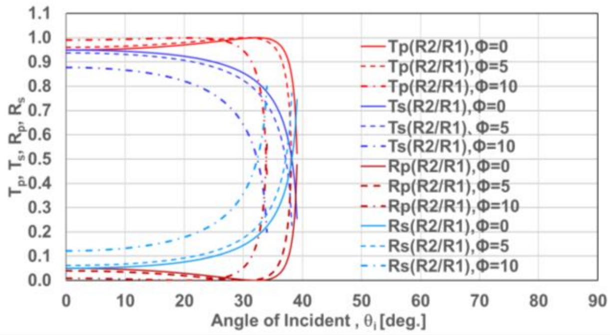

Fig.7 Reflection and transmission coefficients in the convex spherical (Φ=0), and the cylindrical convex (Φ>0) OLEDs with inner and outer radii of R_1 and R_2.

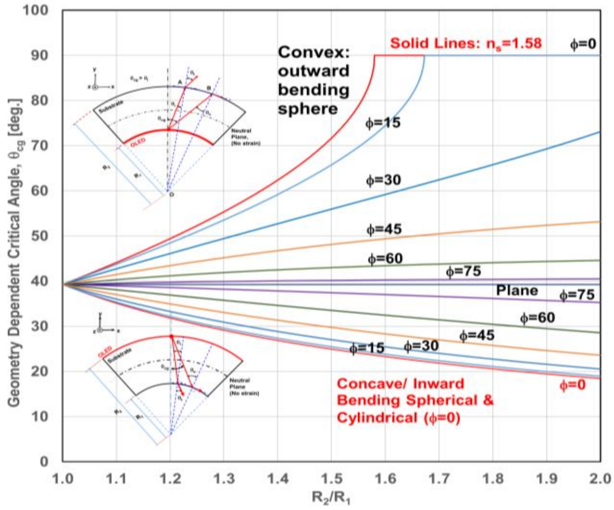

Fig.8 Variation of the geometrical shape dependent critical angle θ_{cg} with the inner and the outer radii of the bent superstrate (ϕ: azimuth angle in Fig.5).

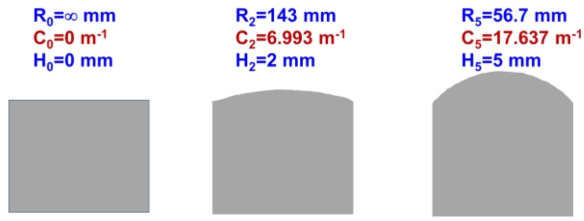

Fig.9 Jigs for bending the OLED samples. The sags of the jigs are H_0=0 mm, H_2=2 mm, and H_5=5 mm.

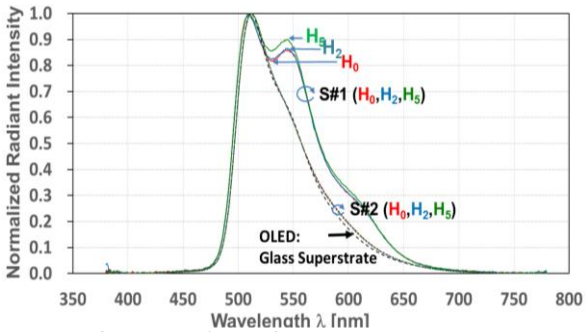

Fig.10 Spectra of two OLED samples with barrier layer of 100 nm and 150 nm, in the planar and the convex states, i.e., the sags of H_0=0 mm, H_2=2 mm, H_5=5 mm.

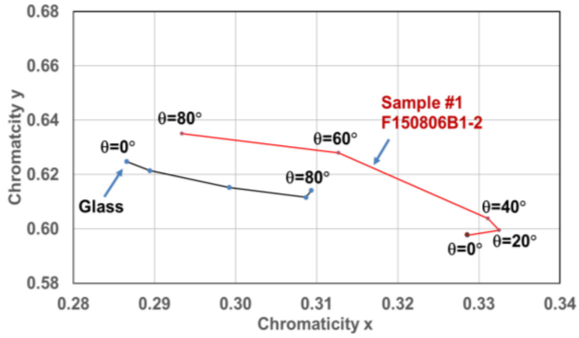

Fig.11 Chromaticity variations of OLEDs with glass and PEN superstrates (S#1) at different measurement angles.

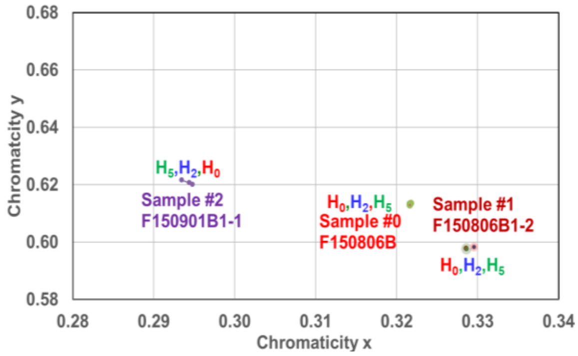

Fig.12 Chromaticity variations of OLEDs with PEN superstrates at the cylindrically curved states (on surface normal direction). S#0: for comparison.

Table 1 Chromaticity characteristics of S#1.

F150806B1-2 (S#1)			
	x	y	
H0	0.3286	0.5977	
H2	0.3286	0.5978	
H5	0.3296	0.5982	
	u'	v'	Δu'v'
H0	0.1381	0.5653	0
H2	0.1381	0.5654	5.7E-05
H5	0.1385	0.5656	4.2E-04