



(51) International Patent Classification:
G02F 1/1337 (2006.01)

(21) International Application Number:
PCT/US2016/012333

(22) International Filing Date:
6 January 2016 (06.01.2016)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:
62/100,347 6 January 2015 (06.01.2015) US

(71) Applicant: CORNING INCORPORATED [US/US]; 1
Riverfront Plaza, Corning, New York 14831 (US).

(72) Inventors: GREENE, Raymond Geroe; 94 Autumn
Ridge Circle, Ithaca, New York 14850 (US). ISHIKAWA,
Tomohiro; 133 East 4th Street, Corning, New York 14830
(US). VEPAKOMMA, Krishna Hemanth; 17 Michael's
Way, Painted Post, New York 14870 (US).

(74) Agent: HARDEE, Ryan T.; Corning Incorporated, Intel-
lectual Property Department, SP-TI-03-1, Corning, New
York 14831 (US).

(81) Designated States (unless otherwise indicated, for every
kind of national protection available): AE, AG, AL, AM,
AO, AT, AU, AZ, BA, BB, BG, BH, BN, BR, BW, BY,
BZ, CA, CH, CL, CN, CO, CR, CU, CZ, DE, DK, DM,
DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT,
HN, HR, HU, ID, IL, IN, IR, IS, JP, KE, KG, KN, KP, KR,
KZ, LA, LC, LK, LR, LS, LU, LY, MA, MD, ME, MG,
MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM,
PA, PE, PG, PH, PL, PT, QA, RO, RS, RU, RW, SA, SC,
SD, SE, SG, SK, SL, SM, ST, SV, SY, TH, TJ, TM, TN,
TR, TT, TZ, UA, UG, US, UZ, VC, VN, ZA, ZM, ZW.

(84) Designated States (unless otherwise indicated, for every
kind of regional protection available): ARIPO (BW, GH,
GM, KE, LR, LS, MW, MZ, NA, RW, SD, SL, ST, SZ,
TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, RU,
TJ, TM), European (AL, AT, BE, BG, CH, CY, CZ, DE,
DK, EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU,
LV, MC, MK, MT, NL, NO, PL, PT, RO, RS, SE, SI, SK,
SM, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ,
GW, KM, ML, MR, NE, SN, TD, TG).

Published:

— with international search report (Art. 21(3))

(54) Title: METHODS FOR MURA MITIGATION IN CURVED LIQUID CRYSTAL DISPLAYS

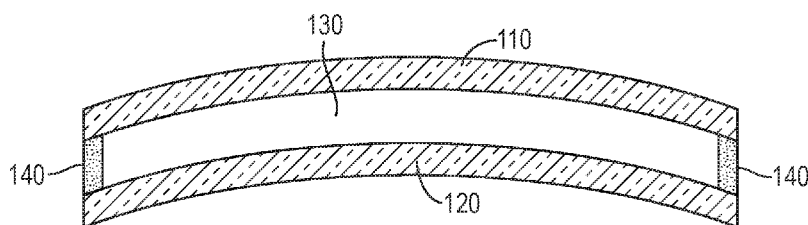


FIG. 2

(57) Abstract: Disclosed herein are methods for manufacturing curved liquid crystal display devices, the methods comprising determining the stress-retardance of a curved glass sheet in the liquid crystal display, determining a modified pre-tilt retardance for at least one layer of the liquid crystal layer, and adjusting the pre-tilt retardance of the liquid crystal layer. Methods for reducing light leakage in curved liquid crystal display devices are also disclosed herein as well as curved liquid crystal display devices manufactured according to these methods.



METHODS FOR MURA MITIGATION IN CURVED LIQUID CRYSTAL DISPLAYS

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application claims the benefit of priority under 35 U.S.C. § 119 of U.S. Provisional Application Serial No. 62/100,347 filed on January 6, 2015, the content of which is relied upon and incorporated herein by reference in its entirety.

FIELD OF THE DISCLOSURE

[0002] The present disclosure relates generally to curved liquid crystal displays, and more particularly to methods for mura mitigation in curved, vertically aligned liquid crystal displays.

BACKGROUND

[0003] High-performance display devices, such as liquid crystal displays (LCDs) and organic light-emitting diode (OLED) displays, are commonly used in various electronics, such as cell phones, laptops, electronic tablets, televisions, and computer monitors. Currently marketed display devices can employ one or more high-precision glass sheets, for example, as substrates for electronic circuit components or color filters, to name a few applications.

[0004] LCDs are one of the most common types of flat panel displays currently in use and typically include two substantially flat display panels provided with field generating electrodes such as a pixel electrode and a common electrode, and an intermediate liquid crystal layer. The LCD's sub-pixel circuitry supplies and delivers an electric field extending through the liquid crystal layer by applying a corresponding voltage across the field generating electrodes. This electric field determines the orientation direction of liquid crystal molecules in the liquid crystal layer and controls the phase delay (retardance) of the polarized incident light passing through the liquid crystal. Thus, other than the front and rear polarizers, the liquid crystal layer can be the only other polarization altering component in the LCD, although some LCDs may employ additional static compensation films laminated to

an interior surface of one or more of the polarizers to improve view angle performance.

[0005] During manufacture, the LCD glass substrates may be carefully controlled to limit or eliminate intrinsic stress (retardance) non-uniformities, for example, intrinsic stress-retardance may be limited to less than a small fraction of a wave of retardance. Extrinsic sources of stress-retardance in LCD glass substrates can include non-uniform temperature, for example, from the back light; external forces on the glass, for example, from mounting the LCD panel in its frame; and geometrical distortion of the panel from its naturally planar shape, for example, from curving the panel for special design. It can be important to manage such extrinsic sources of stress-retardance during the design and manufacture of the LCD to limit image distortion.

[0006] LCDs are often used as a display device in a television receiver, and market trends have led to an increased display size for a more cinema-like experience at home. A recent development in this trend is to provide a curved configuration to the LCD display rather than the convention flat panel design. Such a configuration can mitigate the difference in views that is experienced between a viewer disposed to watch head-on from the center of a display and a viewer disposed to watch from a left or right side of the display. A curved display device may be formed by curving the display panels in a concave or convex manner to compensate for the difference between views. The display device may be a portrait type where a vertical height is larger than a horizontal width and a monitor is bent about a vertical axis, or a landscape type where a vertical height is smaller than a horizontal width and a monitor is bent about a horizontal axis.

[0007] However, as previously discussed, when a display device panel is bent or curved, extrinsic stress-retardance can occur and, at appreciable levels, light leakage or “mura” may result in a visible artifact to the user. Such a bend or curve can cause stress-retardance in the LCD substrate glasses whose birefringence optically couples with the liquid crystal leading to light leakage in the display device. For example, defect-level objectionable light leakage regions in black (zero grayscale) and low grayscales may exist in curved LCDs, such as near the corners of the display. Accordingly, it would be advantageous to provide methods for mitigating or eliminating light leakage in bent or curved display surfaces. In various embodiments, the methods disclosed herein can minimize or prevent mura in

curved, multi-domain, vertically aligned (VA) LCDs. According to certain embodiments, a curved VA LCD made using the methods disclosed herein can exhibit superior performance in terms of contrast and low grayscale image quality and/or superior quality in terms of low grayscale uniformity.

SUMMARY

[0008] The disclosure relates to methods for manufacturing a curved liquid crystal display device, the methods comprising curving a display assembly around a predetermined axis to form a curved display assembly, wherein the display assembly comprises a first glass sheet, a second glass sheet, and an liquid crystal layer disposed between the first and second glass sheets; determining a stress-retardance of at least one region of the first or second glass sheet; determining a modified pre-tilt retardance for at least one corresponding region of the liquid crystal layer; and adjusting a pre-tilt retardance of the at least one corresponding region of the liquid crystal layer to the modified pre-tilt retardance.

[0009] The disclosure also relates to methods for manufacturing a curved liquid crystal display device, the methods comprising determining a stress-retardance of at least one region of a curved test glass sheet; determining a modified pre-tilt retardance for at least one corresponding region of a liquid crystal layer; adjusting a pre-tilt retardance of at least one region of the at least one corresponding liquid crystal layer region to the modified pre-tilt retardance; attaching the first surface of the first glass sheet to the second surface of the second glass sheet with the liquid crystal layer disposed between the first and second glass sheets to form a display assembly; and curving the display assembly about a predetermined axis to form a curved liquid crystal display device. In various embodiments, the test glass sheet has substantially the same properties (e.g., dimensions, radius and axis of curvature, and composition) as the first and second glass sheets.

[0010] Further disclosed herein are curved liquid crystal display devices manufactured according to these methods. Still further disclosed herein are methods for reducing light leakage in a curved liquid crystal display device comprising one or more of the steps disclosed herein, such as determining stress-retardance of at least one region of a glass sheet in a curved liquid crystal display or a test glass sheet, determining a modified pre-tilt retardance for the liquid crystal

layer, and adjusting a pre-tilt retardance of at least one region of the liquid crystal layer to the modified pre-tilt retardance.

[0011] Additional features and advantages of the disclosure will be set forth in the detailed description which follows, and in part will be readily apparent to those skilled in the art from that description or recognized by practicing the methods as described herein, including the detailed description which follows, the claims, as well as the appended drawings.

[0012] It is to be understood that both the foregoing general description and the following detailed description present various embodiments of the disclosure, and are intended to provide an overview or framework for understanding the nature and character of the claims. The accompanying drawings are included to provide a further understanding of the disclosure, and are incorporated into and constitute a part of this specification. The drawings illustrate various embodiments of the disclosure and together with the description serve to explain the principles and operations of the disclosure.

BRIEF DESCRIPTION OF THE DRAWINGS

[0013] The following detailed description can be best understood when read in conjunction with the following drawings, where like structures are indicated with like reference numerals where possible and in which:

[0014] **FIG. 1** is a perspective view of a curved display device according to an exemplary embodiment;

[0015] **FIG. 2** is a cross-sectional view of the curved display device of FIG. 1;

[0016] **FIGS. 3A and 3B** are schematic illustrations showing the operation principles of a VA LCD;

[0017] **FIG. 4** is a schematic illustration of the retardance orientation of a curved piece of glass with a radius of curvature along a horizontal axis;

[0018] **FIG. 5** is a schematic illustration of a pre-tilt orientation for an exemplary liquid crystal layer;

[0019] **FIG. 6** is an illustration of transmission with measured curved glass and +45° VA liquid crystal pre-tilt orientation;

[0020] FIG. 7 is an illustration of transmission with measured curved glass and -45° VA liquid crystal pre-tilt orientation; and

[0021] FIG. 8 is an illustration of transmission with measured curved glass and locally equal amounts of $+45^\circ$ and -45° VA liquid crystal pre-tilt orientation.

DETAILED DESCRIPTION

[0022] Disclosed herein are methods for manufacturing a curved liquid crystal display device and methods for reducing light leakage in curved liquid crystal display devices. By measuring or calculating (e.g., using the finite element method) the stress-retardance and/or orientation in one or more regions of a curved glass sheet in the liquid crystal display device, it is possible, using the methods disclosed herein to calculate a modified pre-tilt angle and/or orientation for a corresponding region of the liquid crystal layer in the device which can, in some embodiments, reduce or eliminate light leakage (mura) in the curved display device. In various embodiments, the modified pre-tilt retardance of the liquid crystal layer can be chosen so as counteract stress-retardance caused by glass curvature in one or more regions of the display device, thereby reducing or eliminating light leakage in these regions. For example, by varying the liquid crystal pre-tilt angle and orientation, the residual retardance of the liquid crystal at low grayscales can substantially cancel the stress-retardance from the curved glass substrates in those regions where, without such modifications, there would be unacceptable light leakage. LCDs produced according to these methods are also disclosed herein, such as multi-domain vertically-aligned (MVA) LCDs.

[0023] Retardance has both a direction (orientation) and a magnitude. Thus, as used herein, “stress-retardance” is intended to encompass both the magnitude and/or orientation of the glass sheet retardance. Likewise, “pre-tilt retardance” is intended to encompass both the magnitude and orientation of the liquid crystal retardance. Pre-tilt angle can be calculated from the pre-tilt retardance magnitude using the following formula:

$$\text{PreTiltRetMag} = \Delta n \times \sin(\text{PreTiltAngle})$$

where $\Delta n = n_e - n_o$, with n_e being the extraordinary and n_o being the ordinary refractive indices of the liquid crystal.

[0024] It should be noted that the terms “panel,” “sheet,” “substrate,” “device,” and variations of these terms can be used interchangeably in this disclosure and such use should not limit the scope of the claims appended herewith. It should further be noted that the terms “bent,” “curved,” and variations thereof are used interchangeably in this disclosure and such use should not limit the scope of the claims appended herewith.

[0025] Embodiments of the disclosure will be discussed with reference to **FIGS. 1-2**, which depict views of an exemplary curved display device. **FIG. 1** is a perspective view of a curved display device and **FIG. 2** is a cross-sectional view of the curved display device of **FIG. 1** taken along line **A-A**. With reference to **FIGS. 1-2**, a curved display device according to some embodiments can include a display unit **100** including a first substrate **110** and a spaced apart second substrate **120** facing the first substrate **110** and a liquid crystal layer **130** positioned between the first and second substrates **110, 120**.

[0026] An edge ringing sealant **140** can be provided along the edges of the first and second substrates **110, 120** to seal the liquid crystal material in the interior of the display unit **100**. The first and second substrates **110, 120** can be bonded to each other by the sealant **140** thereby forming a cavity containing the liquid crystal layer **130** between the substrates **110, 120**. An exemplary curved display device may also include one or more fixing members (not shown) configured to fix the shapes of the substrates **110, 120** to have a predetermined curvature relative to a predetermined axis of curvature. In some embodiments the width of the cross section of the sealant **140** may be about 2 mm or less.

[0027] As shown in **FIGS. 1-2**, the first and second substrates **110, 120** of the curved display device **100** can be bent or curved to have a predetermined curvature relative to a common central vertical or horizontal axis. This curvature may be either a single, simple radius, or a more complex shape with multiple radii. In some embodiments, a user of the display can face the portion concavely curving in a horizontal direction (left and right directions of the observer). More specifically, the user faces the display device from the side of the second substrate **120**. The first substrate **110** and second substrate **120** can also be bent to have respective predetermined radii of curvature sharing a common center point or central axis. In the illustrated, non-limiting embodiment, the center of the curvature radius in the

horizontal direction is positioned below the second substrate **120** in **FIG. 2**, that is, at the side at which the user is positioned to observe the image on the display.

[0028] An exemplary liquid crystal layer **130** injected between the first substrate **110** and the second substrate **120** may include any one of or all types of liquid crystal materials known in the art, such as a TN (twisted nematic) mode, a VA (vertically aligned) mode, an IPS (in plane switching) mode, a BP (blue phase) mode, a FFS (Fringe Field Switching) mode, and an ADS (AdvancedSuper Dimension Switch) mode, to name a few. According to various embodiments, the liquid crystal layer **130** may be a vertically aligned (VA) liquid crystal material. Additionally, although not shown in the figures, an initial liquid crystal alignment layer may be included on at least one of the first substrate **110** and second substrate **120**. Further, the alignment layer may be rubbed in a predetermined direction or optically aligned so that the liquid crystal molecules possess an initial alignment (e.g., tilt and orientation) when an electric field is not present. Alternatively, at least one of the liquid crystal layer **130** and the alignment layer may include a photopolymerizable material.

[0029] As noted above, when display devices panels are bent or curved light leakage from a display device may result in a visible artifact to a user. The curvature of the glass can cause stress retardation in the LCD substrate glasses whose birefringence optically couples with the liquid crystal, resulting in light leakage in many embodiments, such as VA modes. **FIG. 3** is a schematic illustration showing the operation principles of a VA LCD with flat substrates. With reference to **FIG. 3**, rear and front polarizers **150**, **160** have their axes of transmission in orthogonal directions. The liquid crystal molecules **170** in the liquid crystal layer **130** between the first and second substrates **110**, **120** can be aligned at a right angle relative to the substrates (homeotropic alignment) when there is no applied electric field (OFF position).

[0030] For VA or MVA, when no voltage is applied, light **L** from the backlight unit **180** passes through the rear polarizer **150** and then passes through the liquid crystal layer without a change in polarization and is thus blocked by the front polarizer **160**, which is oriented at 90° relative to the rear polarizer **150**. When voltage is applied (ON position), electrodes on the first and second substrates **110**, **120** generate an electric field parallel to the substrates. Depending on the strength of the electric field, the liquid crystal molecules **170**, which can be oriented at 45°

relative to the polarizers, can rotate to a tilted position and change the polarization of the light **L**, thereby allowing light to pass through the front polarizer **160**. **FIG. 3** illustrates the liquid crystal molecules **170** in a fully horizontal position in the ON position, but it is to be understood that various tilt angles are possible and are intended to fall within the scope of the disclosure.

[0031] As illustrated in **FIG. 3**, in traditional (flat) VA LCD configurations, in the OFF position, light is blocked by the front polarizer and the LCD theoretically displays a black image. However, when curved substrates are used, regions of the glass with curvature may be susceptible to light leakage, which can be perceived by the user as a cloudiness or color distortion. For example, curved glass substrates may have significant $\pm 45^\circ$ orientation stress-retardance (phase delay), e.g., in regions near the corners. **FIG. 4** illustrates the measured retardance orientation of a 0.5 mm thick test glass sheet (~ 160 mm x 200 mm) with a radius of curvature approximately equal to 1300 mm. The circled regions **A-D** generally refer to areas in which $\pm 45^\circ$ stress-retardance may be present in the glass sheet. Whereas $0^\circ/90^\circ$ stress-retardance can be eliminated by the $0^\circ/90^\circ$ crossed front and rear polarizers, $\pm 45^\circ$ stress-retardance may result in light leakage (mura) at the corners.

[0032] In conventional VA LCDs, each sub-pixel can have a number of different domains with various pre-tilt orientations to provide directional averaging of the liquid crystal with view direction. Pre-tilt alignment of the liquid crystal molecules can be achieved, for example, by treating the inner surfaces of the first and second substrates with an alignment layer to align the bordering liquid crystal molecules at a desired angle. For example, **FIG. 5** depicts a general schematic showing pre-tilt orientation for an exemplary liquid crystal layer. An internal surface of a substrate **S** (e.g., the first and/or second substrate) can be coated with a polymer **P** and rubbed in a desired direction **R** such that when the liquid crystal molecules **LC** fill the cell, the molecules align themselves along the rubbing direction. The resulting tilt of the liquid crystal molecules, Θ_P , is referred to as the pre-tilt angle. Suitable alignment layers may include, for example, polymers such as polyimides.

[0033] Applicants have discovered that the stress-retardance (or phase delay) of the curved glass can combine with the pre-tilt retardance of the liquid crystal in an additive and/or subtractive way depending on their relative orientations and magnitudes. Applicants thus propose that light leakage or mura in curved VA LCDs can be mitigated or eliminated by orienting the pre-tilt orientation of the liquid

crystal to be approximately 90° from that of the retardance orientation of the curved glass and/or adjusting the liquid crystal pre-tilt angle to give a retardance magnitude that approximately matches that of the curved glass. In practice, VA and MVA LCDs with horizontal and vertical polarizers can experience objectionable light leakage in areas where the curved glass stress-retardance is approximately ±45°. Without wishing to be bound by theory, it is believed that the pre-tilt orientation and magnitude can be varied in such a way that the liquid crystal pre-tilt retardance cancels the retardance caused by stress in the curved glass regions.

[0034] Whereas the stress-retardance orientation of the curved glass can vary on the order of centimeters, the pre-tilt orientation of the liquid crystal panel can vary on the order of tens of microns. In the usual case, what is observed may be the composite effect of the local ±45° curved glass stress-retardance orientation averaged over the ±45° pre-tilt orientation domains of each subpixel. This effect can be separated out into three different case studies.

Case 1: +45° pre-tilt LC orientation with ±45° orientation of corner stress-retardance

[0035] Solving the transmission equation for +45° orientation pre-tilt retardance (radians) that gives contrast 5000 black state for an ideal VA LC with no glass retardance yields a pre-tilt retardance magnitude of 1.621°. The Mueller matrix black state VA LC for +45° pre-tilt is thus:

$$\begin{bmatrix} 1. & 0. & 0. & 0. \\ 0. & 0.9996000000 & 0. & -0.02828144268 \\ 0. & 0. & 1. & 0. \\ 0. & 0.02828144268 & 0. & 0.9996000000 \end{bmatrix}$$

[0036] A transmission mura image was created with the Mueller matrix transmission equation below using measured retardance data for 0.5 mm thick curved glass with the black state VA LC for +45° pre-tilt to generate the image in **FIG. 6**.

$$\text{Transmission} = \left[\begin{bmatrix} \text{horizontal} \\ \text{analyzer} \end{bmatrix} \begin{bmatrix} \text{CF} \\ \text{glass} \end{bmatrix} [\text{LC}] \begin{bmatrix} \text{TFT} \\ \text{glass} \end{bmatrix} \begin{bmatrix} \text{vertical} \\ \text{polarizer} \end{bmatrix} \begin{bmatrix} 1 \\ -1 \\ 0 \\ 0 \end{bmatrix} \right] [1]$$

[0037] As can be seen in **FIG. 6**, there is little or no mura in the corners corresponding to a -45° orientation of curved glass stress-retardance, whereas there is mura in the corners with $+45^\circ$ orientation of curved glass stress-retardance (generally indicated by circled regions **B**, **C**). By simplifying the transmission model for $+45^\circ$ pre-tilt orientation and -45° curved glass stress-retardance orientation, the following formula can be obtained:

$$Transmission = \frac{CurvedGlassRetNm^2}{10000} - \frac{CurvedGlassRetNm\pi VApretiltDeg}{18000} + \frac{\pi^2 VApretiltDeg^2}{129600}$$

For this case, the interaction term is negative, e.g., indicating reduced light leakage from glass and pre-tilt retardance. By solving for a zero mura condition, the following formula can be obtained:

$$CurvedGlassRetNm = (5/18)*\pi*VApretiltDeg$$

[0038] Similarly, by simplifying the transmission model for $+45^\circ$ pre-tilt orientation and $+45^\circ$ curved glass stress-retardance orientation, the following formula can be obtained:

$$Transmission = \frac{CurvedGlassRetNm^2}{10000} + \frac{CurvedGlassRetNm\pi VApretiltDeg}{18000} + \frac{\pi^2 VApretiltDeg^2}{129600}$$

For this case, the interaction term is positive, e.g., indicating that light leakage from glass and pre-tilt retardance is additive (combined light leakage is larger than either component separately).

Case 2: -45° pre-tilt LC orientation with $\pm 45^\circ$ orientation of corner stress-retardance

[0039] Similar to Case 1 above, the transmission equation was solved for -45° orientation (LC pre-tilt orientation $\frac{\pi}{4} \rightarrow -\frac{\pi}{4}$ radians). Again, contrast 5000 black state for an ideal VA LC with no glass retardance yields a pre-tilt retardance magnitude of 1.621° . The Mueller matrix black state VA LC for -45° pre-tilt is thus:

$$\begin{bmatrix} 1. & 0. & 0. & 0. \\ 0. & 0.9996000000 & 0. & 0.02828144268 \\ 0. & 0. & 1. & 0. \\ 0. & -0.02828144268 & 0. & 0.9996000000 \end{bmatrix}$$

[0040] A transmission mura image was created with the Mueller matrix transmission equation using measured retardance data for 0.5 mm thick curved glass with the black state VA LC for -45° pre-tilt to generate the image in **FIG. 7**. As can be seen in **FIG. 7**, there is little or no mura in the corners corresponding to a $+45^\circ$ orientation of curved glass stress-retardance, whereas there is mura in the corners with -45° orientation of curved glass stress-retardance (generally indicated by circled regions **A**, **D**). By simplifying the transmission model for -45° pre-tilt orientation and $+45^\circ$ curved glass stress-retardance orientation, the following formula can be obtained:

$$Transmission = \frac{CurvedGlassRetNm^2}{10000} - \frac{CurvedGlassRetNm\pi VApretiltDeg}{18000} + \frac{\pi^2 VApretiltDeg^2}{129600}$$

For this case, the interaction term is negative, e.g., indicating reduced light leakage from glass and pre-tilt retardance. Similarly, by simplifying the transmission model for -45° pre-tilt orientation and -45° curved glass stress-retardance orientation, the following formula can be obtained:

$$Transmission = \frac{CurvedGlassRetNm^2}{10000} + \frac{CurvedGlassRetNm\pi VApretiltDeg}{18000} + \frac{\pi^2 VApretiltDeg^2}{129600}$$

For this case, the interaction term is positive, e.g., indicating that light leakage from glass and pre-tilt retardance is additive (combined light leakage is larger than either component separately).

Case 3: $\pm 45^\circ$ pre-tilt LC orientation with $\pm 45^\circ$ orientation of corner stress-retardance

[0041] In “real,” e.g., commercial, VA LCDs, each pixel has an equal number of LC domains of both pre-tilt orientations. Thus, an image is generated based on a local average of both $+45^\circ$ and -45° LC pre-tilt domains acting on the same local curved glass stress-retardance orientation.

[0042] A transmission mura image was created with the Mueller matrix transmission equation using measured retardance data for 0.5 mm thick curved glass with the black state VA LC for $+45^\circ$ and -45° pre-tilt orientation (weighted average assuming 50% contribution by each) to generate the image in **FIG. 8**. As can be seen in **FIG. 8**, there is mura in all four corners (generally indicated by circled regions **A-D**). By simplifying the transmission model for $\pm 45^\circ$ pre-tilt orientation and

+45° or -45° curved glass stress-retardance orientation, the following formula can be obtained:

$$Transmission = \frac{CurvedGlassRetNm^2}{10000} + \frac{\pi^2 V A pretiltDeg^2}{129600}$$

The interaction term cancels out in both cases, thus yielding the same outcome regardless of curved glass stress-retardance orientation.

[0043] In light of the above, Applicants have developed methods for reducing or eliminating mura in curved LCDs by controlling the degree and magnitude of LC pre-tilt orientation in domains corresponding to curved glass stress-retardance. As shown above, the resultant transmission (light leakage) may be either amplified (positive interaction term), mitigated (negative interaction term), or may be the independent sum of the individual light leakage from each component (LC and glass). In certain embodiments, the LC pre-tilt orientation may be modified to counteract or balance the curved glass stress-retardation such that unwanted light leakage is mitigated or eliminated.

[0044] By way of a non-limiting example, a modified pre-tilt retardance magnitude (and, hence, a modified pre-tilt angle) can be calculated to counterbalance light leakage due to stress-retardation in curved regions of the glass. The modified pre-tilt angle can be calculated based on stress-retardation measurements taken for a glass sheet in the curved LCD or a test curved glass sheet. For instance, a test glass sheet having substantially similar or identical properties to the glass sheets to be used in the curved LCD can be shaped to obtain a curvature substantially similar or identical to the desired curvature of the curved LCD (see, e.g., **FIG. 4**). Stress-retardance can be measured in one or more regions of the curved LCD or test glass sheet, for example, in corner regions, although other regions such as central and peripheral regions can also be measured.

[0045] Using the formulas and methods disclosed herein, a modified pre-tilt retardance for a corresponding region of the liquid crystal layer can be calculated. Thus at least one region of the liquid crystal layer, e.g., at least one domain of the liquid crystal layer can be adjusted to achieve the calculated modified pre-tilt retardance. In non-limiting embodiments, the relationships and models disclosed herein may be applied during the design, processing, and/or manufacture of curved

LCDs to produce displays with reduced mura and/or superior contrast, low grayscale image quality and/or low grayscale uniformity.

[0046] While embodiments disclosed herein have described methods for mitigating or elimination light leakage from VA LCDs, the claims should not be so limited. For example, additional methods may include using one or more sheets or panels of glass in LCDs operating with different modes, or a different display unit having different properties, alone or in combination with embodiments disclosed herein.

[0047] The glass panels, sheets or substrates described herein may comprise any glass known in the art for use in a backlit display, such as an LCD, including, but not limited to, soda-lime silicate, aluminosilicate, alkali-aluminosilicate, borosilicate, alkaliborosilicate, aluminoborosilicate, alkali-aluminoborosilicate, and other suitable glasses. The glass substrate may, in various embodiments, be chemically strengthened and/or thermally tempered. Non-limiting examples of suitable commercially available substrates include EAGLE XG®, Lotus™, Willow®, and Gorilla® glasses from Corning Incorporated, to name a few. Such chemically strengthened glass, for example, may be provided in accordance with U.S. Patent Nos. 7,666,511, 4,483,700, and 5,674,790, which are incorporated herein by reference in their entireties.

[0048] In non-limiting embodiments, the glass sheets, panels or substrates can have a thickness of less than or equal to about 3 mm, for example, ranging from about 0.1 mm to about 2 mm, from about 0.3 mm to about 1.5 mm, from about 0.5 mm to about 1.1 mm, or from about 0.7 mm to about 1 mm, including all ranges and subranges therebetween. According to various embodiments, the glass substrate can have a thickness of less than or equal to 0.3 mm, such as 0.2 mm, or 0.1 mm, including all ranges and subranges therebetween. In certain non-limiting embodiments, the glass substrate can have a thickness ranging from about 0.3 mm to about 1.5 mm, such as from about 0.5 to about 1 mm, including all ranges and subranges therebetween.

[0049] The glass sheets, panels or substrates can have any shape and/or size suitable for use in an LCD. For example, the glass substrate can be a glass sheet in the shape of a rectangle, square, circle, or any other suitable shape. The glass substrate can, in various embodiments, be transparent or substantially transparent. As used herein, the term “transparent” is intended to denote that the

glass substrate, at a thickness of approximately 1mm, has a transmission of greater than about 80% in the visible region of the spectrum (420-700nm). For instance, an exemplary transparent glass substrate may have greater than about 85% transmittance in the visible light range, such as greater than about 90%, or greater than about 95%, including all ranges and subranges therebetween. In certain embodiments, an exemplary glass substrate may have a transmittance of greater than about 50% in the ultraviolet (UV) region (200-410nm), such as greater than about 55%, greater than about 60%, greater than about 65%, greater than about 70%, greater than about 75%, greater than about 80%, greater than about 85%, greater than about 90%, greater than about 95%, or greater than about 99% transmittance, including all ranges and subranges therebetween.

[0050] It will be appreciated that the various disclosed embodiments may involve particular features, elements or steps that are described in connection with that particular embodiment. It will also be appreciated that a particular feature, element or step, although described in relation to one particular embodiment, may be interchanged or combined with alternate embodiments in various non-illustrated combinations or permutations.

[0051] It is also to be understood that, as used herein the terms “the,” “a,” or “an,” mean “at least one,” and should not be limited to “only one” unless explicitly indicated to the contrary. Thus, for example, reference to “a component” includes examples having two or more such components unless the context clearly indicates otherwise.

[0052] Ranges can be expressed herein as from “about” one particular value, and/or to “about” another particular value. When such a range is expressed, examples include from the one particular value and/or to the other particular value. Similarly, when values are expressed as approximations, by use of the antecedent “about,” it will be understood that the particular value forms another aspect. It will be further understood that the endpoints of each of the ranges are significant both in relation to the other endpoint, and independently of the other endpoint.

[0053] The terms “substantial,” “substantially,” and variations thereof as used herein are intended to note that a described feature is equal or approximately equal to a value or description. Moreover, “substantially similar” is intended to denote that two values are equal or approximately equal. In some embodiments,

“substantially similar” may denote values within about 10% of each other, such as within about 5% of each other, or within about 2% of each other.

[0054] Unless otherwise expressly stated, it is in no way intended that any method set forth herein be construed as requiring that its steps be performed in a specific order. Accordingly, where a method claim does not actually recite an order to be followed by its steps or it is not otherwise specifically stated in the claims or descriptions that the steps are to be limited to a specific order, it is no way intended that any particular order be inferred.

[0055] While various features, elements or steps of particular embodiments may be disclosed using the transitional phrase “comprising,” it is to be understood that alternative embodiments, including those that may be described using the transitional phrases “consisting” or “consisting essentially of,” are implied. Thus, for example, implied alternative embodiments to a method that comprises A+B+C include embodiments where a method consists of A+B+C and embodiments where a method consists essentially of A+B+C.

[0056] It will be apparent to those skilled in the art that various modifications and variations can be made to the present disclosure without departing from the spirit and scope of the disclosure. Since modifications combinations, sub-combinations and variations of the disclosed embodiments incorporating the spirit and substance of the disclosure may occur to persons skilled in the art, the disclosure should be construed to include everything within the scope of the appended claims and their equivalents.

WHAT IS CLAIMED IS:

1. A method for manufacturing a curved liquid crystal display device, comprising:
 - (a) curving a display assembly around a predetermined axis to form a curved display assembly, wherein the display assembly comprises a first glass sheet, a second glass sheet, and a liquid crystal layer disposed between the first and second glass sheets;
 - (b) determining a stress-retardance of at least one region of the first or second glass sheet;
 - (c) determining a modified pre-tilt retardance for at least one region of the liquid crystal layer corresponding to the first or second glass sheet regions; and
 - (d) adjusting a pre-tilt retardance of the at least one region of the liquid crystal layer to the modified pre-tilt retardance.
2. The method of claim 1, wherein the first glass sheet comprises a thin film transistor array and the second glass sheet comprises a color filter array.
3. The method of claim 1, wherein the predetermined axis is a central longitudinal axis, a central horizontal axis, or both a central longitudinal and a central horizontal axis.
4. The method of claim 1, wherein the stress-retardance is determined for one or more corner regions of the first glass sheet, second glass sheet, or first and second glass sheets.
5. The method of claim 4, wherein the determined stress-retardance has an orientation of $\pm 45^\circ$.
6. The method of claim 1, wherein the modified pre-tilt retardance is determined using the following formula:

$$\text{CurvedGlassRetNm} = (5/18) * \text{Pi} * \text{VApretiltDeg}.$$

7. The method of claim 1, wherein the pre-tilt retardance of at least one domain in at least one corner region of the liquid crystal layer is adjusted.
8. The method of claim 1, wherein adjusting the pre-tilt retardance comprises adjusting the orientation, pre-tilt angle, or orientation and pre-tilt angle of the liquid crystal layer region.
9. A curved liquid crystal display device manufactured according to any of claims 1-8.
10. The curved liquid crystal display device of claim 9, wherein the curved liquid crystal display device is in a vertically aligned mode.
11. A method for manufacturing a curved liquid crystal display device, comprising:
 - (a) determining a stress-retardance of at least one region of a curved test glass sheet;
 - (b) determining a modified pre-tilt angle for at least one corresponding region of a liquid crystal layer;
 - (c) adjusting a pre-tilt retardance of the at least one corresponding liquid crystal layer region to the modified pre-tilt retardance;
 - (d) attaching the first surface of the glass sheet to the second surface of the second glass sheet with the liquid crystal layer disposed between the first and second glass sheets to form a display assembly; and
 - (e) curving the display assembly about a predetermined axis to form a curved liquid crystal display device,wherein the dimensions, axis and radius of curvature, and composition of the test glass sheet are substantially identical to the dimensions, axis and radius of curvature, and composition of the first and second glass sheets.
12. The method of claim 11, wherein the stress-retardance is determined for at least one corner of the curved test glass sheet.
13. The method of claim 11, wherein the modified pre-tilt retardance is determined using the following formula:

$$\text{CurvedGlassRetNm} = (5/18) * \text{Pi} * \text{VApretiltDeg}.$$

14. The method of claim 11, wherein adjusting the pre-tilt retardance of the at least one corresponding liquid crystal layer region comprises applying an alignment layer to the first or second surface and optionally rubbing the alignment layer in a predetermined direction to align the liquid crystal layer at a modified pre-tilt angle.
15. The method of claim 14, wherein the alignment layer comprises a polyimide.
16. The method of claim 11, wherein the curved liquid crystal display device is in a vertically aligned mode.
17. A method for mitigating light leakage in a curved liquid crystal display device, comprising:
- (a) determining a stress-retardance of at least one region of a glass sheet in the curved display device;
 - (b) calculating a modified pre-tilt retardance for at least one corresponding region of a liquid crystal layer in the curved display device; and
 - (c) adjusting a pre-tilt retardance of the at least one corresponding region of the liquid crystal layer to the modified pre-tilt retardance.
18. The method of claim 17, wherein adjusting the pre-tilt retardance comprises adjusting the orientation, pre-tilt angle, or orientation and pre-tilt angle of the liquid crystal layer region.
19. The method of claim 18, further comprising manufacturing a display assembly by attaching a first surface of a glass sheet to a second surface of a second glass sheet with a liquid crystal layer disposed therebetween.
20. The method of claim 19, further comprising curving the display assembly about a predetermined axis to form a curved liquid crystal display device.

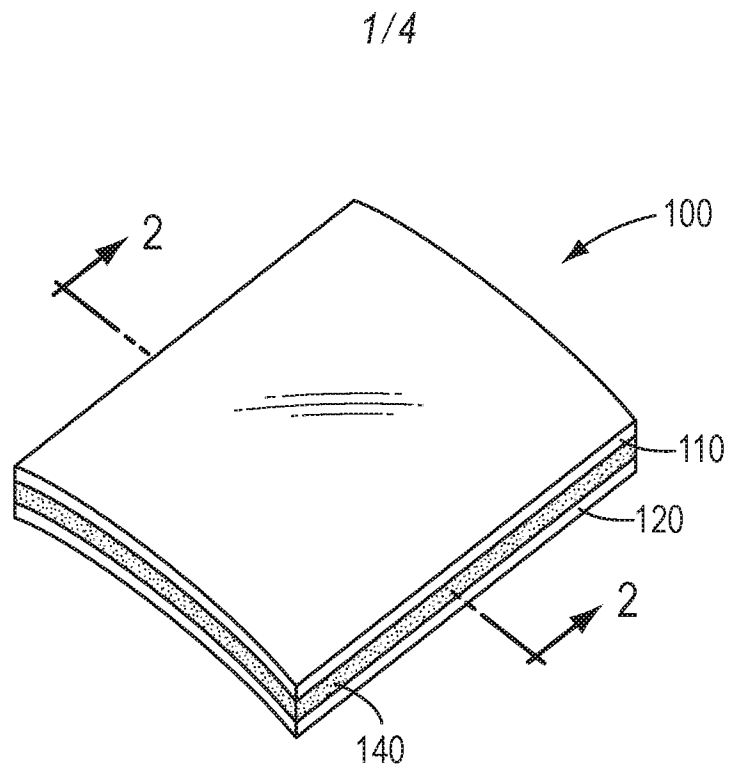


FIG. 1

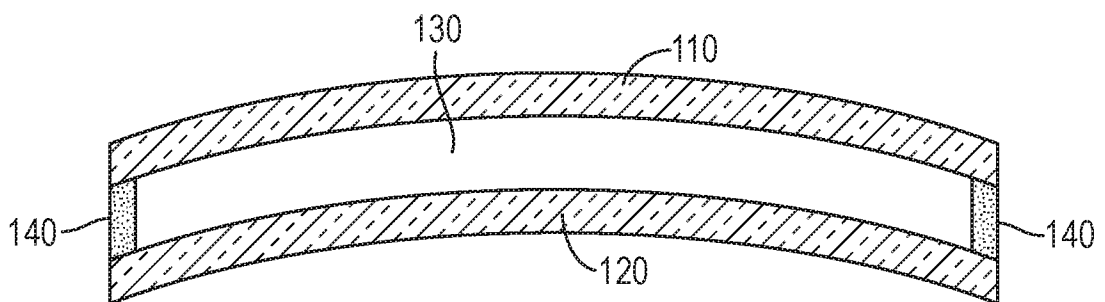
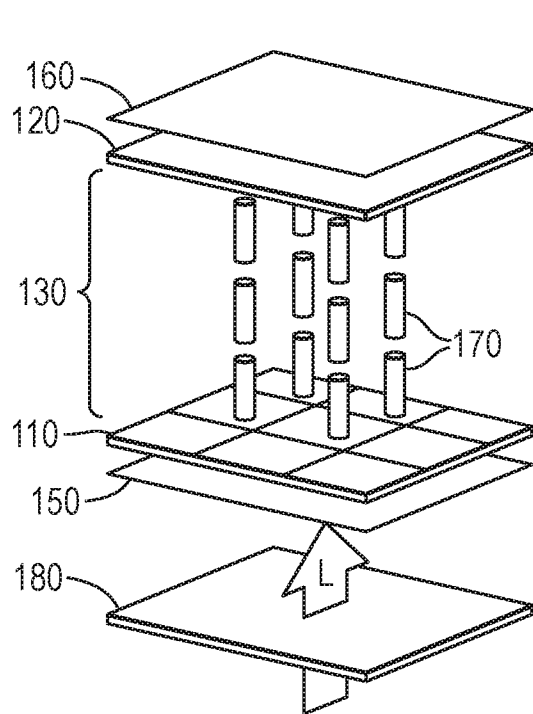


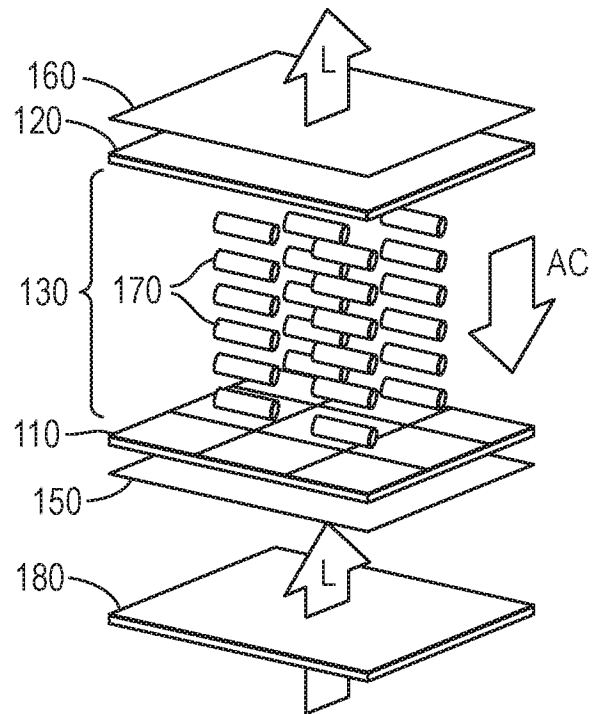
FIG. 2

2/4



VOLTAGE: OFF

FIG. 3A



VOLTAGE: ON

FIG. 3B

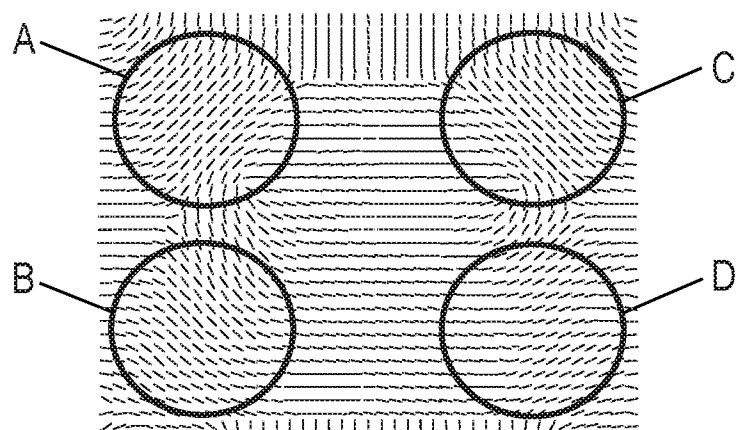


FIG. 4

3/4

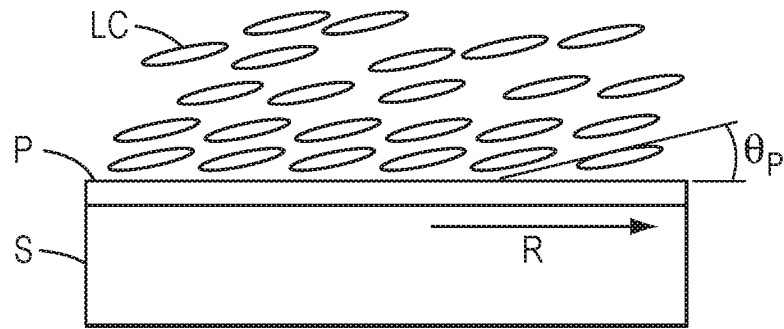


FIG. 5

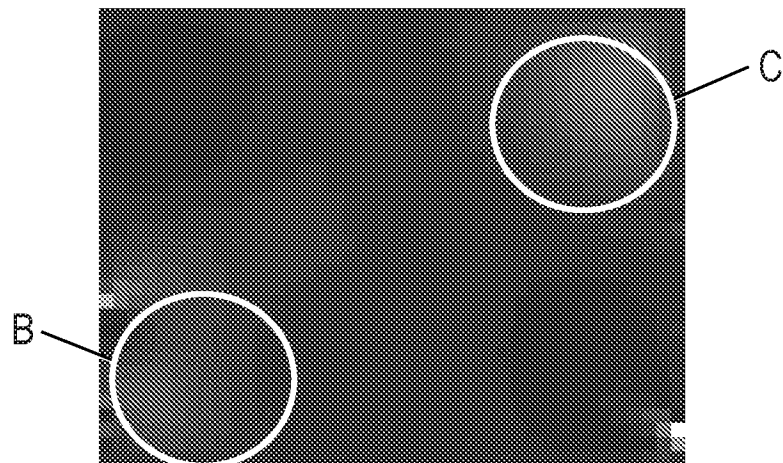


FIG. 6

4/4

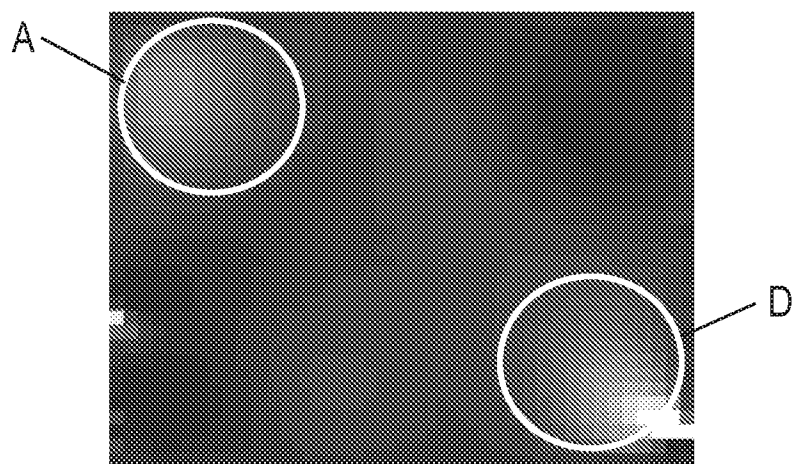


FIG. 7

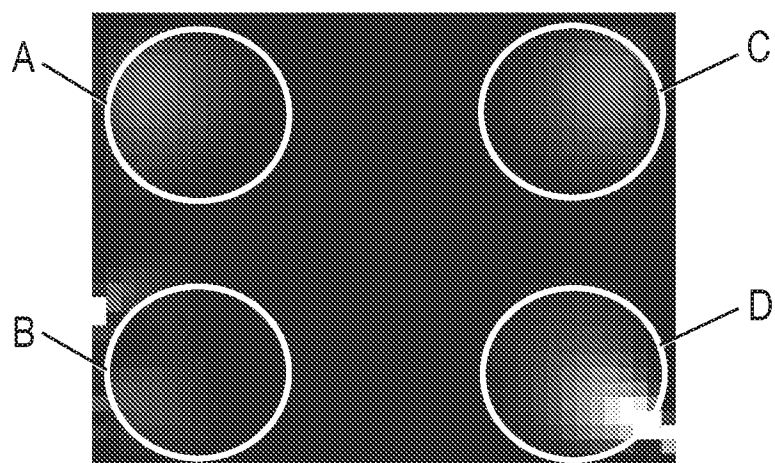


FIG. 8

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US2016/012333**A. CLASSIFICATION OF SUBJECT MATTER****G02F 1/1337(2006.01)i**

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

G02F 1/1337; G02F 1/13363; G01N 33/38; G02F 1/1335

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Korean utility models and applications for utility models

Japanese utility models and applications for utility models

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

eKOMPASS(KIPO internal) & keywords: curved liquid crystal display device, stress-retardance, pre-tilt retardance, glass sheets

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	US 2014-0078450 A1 (APPLE INC.) 20 March 2014 See paragraphs [0006]-[0009], [0072]-[0094]; and figures 8-13B.	1-20
Y	US 2014-0176856 A1 (SAMSUNG DISPLAY CO., LTD.) 26 June 2014 See paragraphs [0062]-[0096]; and figures 1-2.	1-20
A	US 2007-0058118 A1 (PETER CIRKEL et al.) 15 March 2007 See paragraphs [0039]-[0043]; claim 1; and figures 1-7.	1-20
A	US 2014-0098328 A1 (SHENZHEN CHINA STAR OPTOELECTRONICS TECHNOLOGY CO., LTD.) 10 April 2014 See paragraphs [0046]-[0058]; and figures 4-8.	1-20
A	US 2013-0319047 A1 (CYNTHIA C. CONTRERAS et al.) 05 December 2013 See paragraphs [0044]-[0045]; claim 1; and figure 3.	1-20



Further documents are listed in the continuation of Box C.



See patent family annex.

* Special categories of cited documents:

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier application or patent but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search

25 April 2016 (25.04.2016)

Date of mailing of the international search report

26 April 2016 (26.04.2016)

Name and mailing address of the ISA/KR

International Application Division

Korean Intellectual Property Office

189 Cheongsa-ro, Seo-gu, Daejeon, 35208, Republic of Korea

Facsimile No. +82-42-481-8578

Authorized officer

LEE, Dong Yun

Telephone No. +82-42-481-8734



INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No.

PCT/US2016/012333

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
US 2014-0078450 A1	20/03/2014	CN 103676291 A KR 10-2014-0037754 A TW 201415131 A US 2014-0078448 A1 US 9128327 B2 WO 2014-046771 A1	26/03/2014 27/03/2014 16/04/2014 20/03/2014 08/09/2015 27/03/2014
US 2014-0176856 A1	26/06/2014	CN 103901677 A EP 2749931 A1 JP 2014-126870 A KR 10-2014-0091100 A	02/07/2014 02/07/2014 07/07/2014 21/07/2014
US 2007-0058118 A1	15/03/2007	CN 100795411 A EP 1631858 A1 JP 2007-500879 A KR 10-2006-0020642 A TW M267469 U WO 2004-107028 A1	28/06/2006 08/03/2006 18/01/2007 06/03/2006 11/06/2005 09/12/2004
US 2014-0098328 A1	10/04/2014	CN 102879954 A CN 102879954 B WO 2014-056246 A1	16/01/2013 04/11/2015 17/04/2014
US 2013-0319047 A1	05/12/2013	CN 104471467 A JP 2015-519288 A KR 10-2015-0022817 A TW 201404728 A US 9010148 B2 WO 2013-181513 A1	25/03/2015 09/07/2015 04/03/2015 01/02/2014 21/04/2015 05/12/2013