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Privacy displays

Abstract

A switchable privacy display device comprises a spatial light modulator comprising an in-plane display polariser, an out-of-plane polariser and a polarisation switch arranged between the in-plane display polariser and the out-of-plane polariser. The display achieves high image visibility to an off-axis user in a wide-angle mode and high image security to an off-axis snooper in privacy mode of operation.

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Background/Summary

TECHNICAL FIELD

(1) This disclosure generally relates to optical stacks for use in privacy display and low stray light displays.

BACKGROUND

(2) Privacy displays provide image visibility to a primary user that is typically in an on-axis

position and reduced visibility of image content to a snooper, that is typically in an off-axis position.
(3) Switchable privacy displays may be provided by control of the off-axis optical output.
(4) Control of off-axis privacy may be provided by means of contrast reduction, for example by adjusting the liquid crystal bias tilt in an In-Plane-Switching LCD.
(5) Control may be further provided by means of off-axis luminance reduction. Luminance reduction may be achieved by means of switchable backlights for a liquid crystal display (LCD) spatial light modulator. Off-axis luminance reduction may also be provided by switchable liquid crystal retarders and compensation retarders arranged to modulate the input and/or output directional luminance profile of a spatial light modulator.
(6) Control may be further provided by means of off-axis reflectivity increase. Reflectivity increase may be achieved by means of switchable liquid crystal retarders, compensation retarders that are arranged to control the polarisation of ambient light that falls onto a reflective polariser.
BRIEF SUMMARY
(7) According to a first aspect of the present disclosure there is provided a polar angle control display device comprising: a spatial light modulator arranged to output light; an in-plane polariser having an absorption axis in a plane of the in-plane polariser arranged on a side of the spatial light modulator; and an out-of-plane polariser having an absorption axis in a direction having a component out of a plane of the out-of-plane polariser arranged on the same side of the spatial light modulator as the in-plane polariser.
(8) A privacy display may be provided with high luminance in desirable viewing directions and reduced luminance in non-viewing directions. A low thickness and cost display may be provided.
(9) The polar angle control display device may further comprise a polarisation switch provided between the in-plane polariser and the out-of-plane polariser, the polarisation switch being switchable between a first mode in which it may be arranged to change a polarisation state of the light passing therethrough and a second mode in which it may be arranged to affect the polarisation state of the light passing therethrough differently from the first mode. The privacy display may be switchable between a landscape privacy operating mode, a portrait privacy operating mode and a share mode of operation.
(10) In the first mode, the polarisation switch may be arranged to change the polarisation state of the light passing therethrough from a first linear polarisation state to a second linear polarisation state that may be orthogonal to the first linear polarisation state. In the second mode, the polarisation switch may be arranged not to change the polarisation state of the light passing therethrough. The change of polarisation state may be provided with a wide field of view to achieve desirable off-axis luminance reduction.
(11) The polarisation switch may comprise a switchable layer of liquid crystal material and at least one electrode arranged to switch the state of the liquid crystal material. A polarisation switch may be provided with low thickness and cost.
(12) The polarisation switch may further comprise two surface alignment layers disposed adjacent to the liquid crystal material on opposite sides thereof and each arranged to provide alignment at the adjacent liquid crystal material. Advantageously a switchable layer of liquid crystal material may be provided.
(13) One or both of the surface alignment layers may be arranged to provide homogeneous alignment in the adjacent liquid crystal material. Improved resilience to applied pressure may be achieved. One or both of the surface alignment layers may be arranged to provide homeotropic alignment in the adjacent liquid crystal material. Reduced colouration in at least one mode of operation may be achieved. One of the surface alignment layers may be arranged to provide homogeneous alignment in the adjacent liquid crystal material and the other of the surface alignment layers may be arranged to provide homeotropic alignment in the adjacent liquid crystal material. Increased size of polar region for desirable image security may be achieved.

(14) Each of the surface alignment layers may have a pretilt having a pretilt direction with a component in the plane of the layer of liquid crystal material that may be parallel or anti-parallel or orthogonal to the electric vector transmission direction of the in-plane polariser. The luminance in the elevation direction may be substantially preserved in both wide-angle mode and privacy modes of operation. Luminance profiles that are symmetric about the lateral direction may be provided.
(15) Each alignment layer may have a pretilt having a pretilt direction with a component in the plane of the layer of liquid crystal material and the components may be orthogonal. Colour variations with viewing angle in at least one mode of operation may be reduced.
(16) The polarisation switch may further comprise at least one passive retarder. Advantageously increased reduction of transmission may be provided over an increased polar region.
(17) The display device may further comprise a biaxial retarder arrangement arranged between the out-of-plane polariser and the in-plane polariser. The size of the angular region in privacy mode for which reduced transmission and increased security factor is achieved may be increased.
(18) The biaxial retarder arrangement may comprise a B-plate. The B-plate may have principal components of refractive index nx, ny, nz and a thickness d, and wherein for light at a wavelength of 550 nm: the value of (nx−ny) d is in a range between −130 nm and −170 nm, the value of (nx−nz) d is in a range between +270 nm and +330 nm, and the value of a parameter Rth is in a range between +340 nm and +400 nm, wherein Rth=((nx+ny)/2−nz)d. A low thickness component may be provided that may be formed with low cost, for example by double stretching.
(19) The biaxial retarder arrangement may comprise a C-plate arranged to receive the light output from an A-plate. For light at a wavelength of 550 nm the A-plate has a retardance in a range between +85 nm and +115 nm, and the C-plate may be a negative C-plate with a retardance in a range between −190 nm and −250 nm. The complexity of manufacture of the A-plate and negative C-plate retarders may be reduced, achieving reduced cost.
(20) For light at a wavelength of 550 nm the A-plate has a retardance in a range between +85 nm and +115 nm, and the C-plate may be a positive C-plate with a retardance in a range between +220 nm and +280 nm. The thickness of the positive C-plate may be reduced.
(21) Such ranges represent particularly beneficial or advantageous embodiments because the luminance in the viewing quadrants of the display device may be reduced in comparison to alternative combinations of values. In operation, the angular variation of output polarisation state of the out-of-plane polariser may be modified by the means of the biaxial retarder arrangement with said combination of values. The angular variation of output polarisation state of the biaxial retarder arrangement may achieve said reduction of luminance in viewing quadrants in narrow-angle or privacy mode. Image security factor in non-viewing directions may be increased.
(22) The direction of the absorption axis of the out-of-plane polariser may be normal to the plane of the out-of-plane polariser. Advantageously a symmetric reduction about a plane of transmission profile may be achieved.
(23) The direction of the absorption axis of the out-of-plane polariser may be inclined at an acute angle to the normal orthogonal to the plane of the out-of-plane polariser. Advantageously an asymmetric reduction about a plane of transmission profile may be achieved. A display suitable for use as a passenger infotainment display in a vehicle may be provided.
(24) The direction of the absorption axis of the out-of-plane polariser may change monotonically along a predetermined axis across the display device. The display device may be curved with a concave curvature as viewed from an output side of the display device. Luminance uniformity to a user in a viewing direction and security factor uniformity in a non-viewing direction may be improved across the area of the display device. Aesthetic appearance may be improved.
(25) Said side of the spatial light modulator may be an output side of the spatial light modulator and the spatial light modulator may comprise an output polariser. The output polariser may be the in-plane polariser. Advantageously thickness and cost may be reduced. The in-plane polariser may be a different component from the output polariser. Advantageously improved performance may be

achieved.
(26) The polar angle control display device may further comprise: an additional polariser arranged on the output side of the output polariser; and at least one polar control retarder arranged between the output polariser and the additional polariser. Advantageously increased security factor may be achieved in non-viewing directions. The additional polariser may be the in-plane polariser. Advantageously thickness and cost may be reduced. The polar angle control display device may further comprise a reflective polariser arranged on the output side of the output polariser, wherein the reflective polariser is the in-plane polariser. Advantageously improved image security may be achieved for a device illuminated by ambient light.
(27) Said side of the spatial light modulator may be an input side of the spatial light modulator and the spatial light modulator may comprise an input polariser. Advantageously image blur may be reduced and image contrast may be increased.
(28) The input polariser may be the in-plane polariser. Advantageously thickness and cost may be reduced. The in-plane polariser may be a different component from the input polariser. The polar angle control display device may further comprise: an additional polariser arranged on the input side of the input polariser; and at least one polar control retarder arranged between the input polariser and the additional polariser. The additional polariser may be the in-plane polariser. Advantageously increased security factor may be achieved in non-viewing directions.
(29) The spatial light modulator may be a transmissive spatial light modulator. A backlight may be provided with directional output to achieve reduced off-axis luminance and improved security factor in non-viewing directions of the privacy mode of operation. Further polar control retarder optical elements and out-of-plane polarisers may be provided. Improved security factor may be achieved in non-viewing directions.
(30) The spatial light modulator may be an emissive spatial light modulator and said side of the spatial light modulator may be an output side of the spatial light modulator. In comparison to a transmissive spatial light modulator, display thickness may be reduced.
(31) The polar angle control display device may further comprise at least one polar control retarder arranged between the additional polariser and the display polariser, the at least one polar control retarder including a switchable liquid crystal retarder comprising a layer of liquid crystal material; and a transmissive electrode arrangement arranged to drive the layer of liquid crystal material, wherein the transmissive electrode arrangement is patterned to be capable of driving the layer of liquid crystal material into a structure of orientations providing relative phase shifts that vary spatially across an area of the layer of liquid crystal material so that the layer of liquid crystal material provides a diffractive effect.
(32) In at least one mode of operation of a display device, wide-angle mode may be provided. The display device may provide a directional light cone and advantageously achieve high efficiency of operation. Light may be distributed from the directional light cone to a larger size light cone so that the display may be viewed with high image visibility from a wider range of viewing directions than provided by the directional light cone. Multiple viewers may advantageously see the displayed image simultaneously and comfortably. A thin, light-weight and low-cost display device may be provided.
(33) The transmissive electrode arrangement may also be capable of driving the layer of liquid crystal material into a structure of orientations providing uniform phase shifts across the area of the layer of liquid crystal material so that the layer of liquid crystal material may provide no diffractive effect. A display device capable of switching between wide-angle and narrow-angle modes of operation may be provided. In at least one narrow-angle mode the display may be a privacy display that is arranged to provide a desirably high luminance and high image visibility to a primary display user along a viewing direction, and may advantageously be arranged to provide desirable security factor along a non-viewing direction such that image data on the display is not visible to image snoopers. In another narrow-angle mode, the display may provide high luminance with low

power consumption to a primary user with reduced image visibility along the non-viewing direction. Advantageously image uniformity to the primary user may be improved.
(34) The transmissive electrode arrangement may be patterned to be capable of driving the layer of liquid crystal material into a structure of orientations providing relative phase shifts that vary spatially in one direction across the area of the layer of liquid crystal material so that the layer of liquid crystal material may provide a diffractive effect in the one direction. The one direction may be in the lateral direction that may be a horizontal axis to enable horizontally spaced locations of viewers. The efficiency of operation in the wide-angle mode may advantageously be increased.
(35) The transmissive electrode arrangement may comprise an array of separated electrodes. The separated electrodes may be manufactured by known manufacturing processes at low cost and complexity.
(36) The array of separated electrodes may be arrayed in the one direction and the separated electrodes may extend across the area of the layer of liquid crystal material in the direction orthogonal to the one direction. The separated electrodes may have a common connection. The common connection may be formed by a bar located outside an area of the spatial light modulator. Electrical connections to the separated electrodes may be conveniently provided at low cost and complexity.
(37) The array of separated electrodes may comprise two interdigitated sets of separated electrodes. Each set of separated electrodes may have a common connection. The common connection for each set of separated electrodes may be formed by a respective bar, the bars being located outside an area of the spatial light modulator on opposite sides of the layer of liquid crystal material. Further control of the structure of orientations of the layer of liquid crystal material may be provided to achieve alternative profiles of diffracted light. Asymmetric diffraction patterns may be provided to achieve improved control of light output to the non-viewing direction that is primarily to one side of the optical axis of the display device. Increased display functionality may be provided. Passenger infotainment displays that provide higher luminance to a driver in wide-angle mode may be provided.
(38) The transmissive electrode arrangement may further comprise a control electrode extending across the entirety of the spatial light modulator, the control electrode being arranged on the same side of the layer of liquid crystal material as the array of separated electrodes, outside the array of separated electrodes. The profile of electric field within the layer of liquid crystal material may be modified and diffraction angles may be increased for a given pitch of separated electrodes.
(39) The transmissive electrode arrangement may further comprise a reference electrode extending across the entirety of the spatial light modulator, the reference electrode being arranged on the opposite side of the layer of liquid crystal material from the array of separated electrodes. The layer of liquid crystal material may be switched between different structures of orientations to achieve desirable wide-angle and narrow-angle modes of operation.
(40) The display device may further comprise a control system arranged to supply voltages to the transmissive electrode arrangement for driving the layer of liquid crystal material. The control system may be arranged: in a narrow-angle mode, to supply voltages to the transmissive electrode arrangement that may be selected to drive the layer of liquid crystal material into a structure of orientations providing relative phase shifts that may be uniform across the area of the layer of liquid crystal material; and in a wide-angle mode, to supply voltages to the transmissive electrode arrangement that may be selected to drive the layer of liquid crystal material into the structure of orientations providing relative phase shifts that vary spatially across the area of the layer of liquid crystal material so that the layer of liquid crystal material may provide a diffractive effect. The liquid crystal layer of the display device may be controlled to provide output light cones for wide-angle or narrow-angle modes of operation. The size of the display device output light cones in each mode may be adjusted to achieve desirable viewing properties.
(41) The switchable liquid crystal retarder may comprise two surface alignment layers disposed

adjacent to the layer of liquid crystal material and on opposite sides thereof. The alignment layer on the side of the layer of liquid crystal material adjacent the array of separated electrodes may have a component of alignment in the plane of the layer of liquid crystal material in the direction that may be orthogonal to the one direction. Advantageously the direction of diffracted light dispersion in the wide-angle mode is in the one direction; and the direction of luminance reduction in the narrow-angle privacy mode is also in the one direction. For display devices wherein the one direction is the horizontal direction, viewing freedom in the vertical direction may be increased.
(42) According to a second aspect of the present disclosure there is provided a polar angle control component for assembly with a display device comprising a spatial light modulator, the polar angle control component comprising an out-of-plane polariser having an absorption axis in a direction having a component out of the plane of the out-of-plane polariser. The polar angle control component may further comprise a polarisation switch, the polarisation switch being switchable between a first mode in which it may be arranged to change a polarisation state of the light passing therethrough and a second mode in which it may be arranged to affect the polarisation state of the light passing therethrough differently from the first mode. The polar angle control component may further comprise an in-plane polariser having an absorption axis in a plane of the in-plane polariser, the polarisation switch being provided between the in-plane polariser and the out-of-plane polariser. The polar angle control component may further comprise an in-plane polariser having an absorption axis in a plane of the in-plane polariser. Components may be provided for attachment to spatial light modulators during manufacture of a display apparatus, or may be added by a user.
(43) Embodiments of the present disclosure may be used in a variety of optical systems. The embodiments may include or work with a variety of projectors, projection systems, optical components, displays, microdisplays, computer systems, processors, self-contained projector systems, visual and/or audio-visual systems and electrical and/or optical devices. Aspects of the present disclosure may be used with practically any apparatus related to optical and electrical devices, optical systems, presentation systems or any apparatus that may contain any type of optical system. Accordingly, embodiments of the present disclosure may be employed in optical systems, devices used in visual and/or optical presentations, visual peripherals and so on and in a number of computing environments.
(44) Before proceeding to the disclosed embodiments in detail, it should be understood that the disclosure is not limited in its application or creation to the details of the particular arrangements shown, because the disclosure is capable of other embodiments. Moreover, aspects of the disclosure may be set forth in different combinations and arrangements to define embodiments unique in their own right. Also, the terminology used herein is for the purpose of description and not of limitation.
(45) Directional backlights offer control over the illumination emanating from substantially the entire output surface controlled typically through modulation of independent LED light sources arranged at the input aperture side of an optical waveguide. Controlling the emitted light directional distribution can achieve single-person viewing for a security function, where the display can only be seen by a single viewer from a limited range of angles; high electrical efficiency, where illumination is primarily provided over a small angular directional distribution; alternating left-eye and right-eye viewing for time sequential stereoscopic and autostereoscopic display; and low cost.
(46) These and other advantages and features of the present disclosure will become apparent to those of ordinary skill in the art upon reading this disclosure in its entirety.

Description

BRIEF DESCRIPTION OF THE DRAWINGS
(1) Embodiments are illustrated by way of example in the accompanying FIGURES, in which like

reference numbers indicate similar parts, and in which:
(2) FIG. **1**A is a schematic diagram illustrating in perspective side view a switchable privacy display comprising: a polar angle control display device comprising a backlight comprising a light source array, a waveguide, a rear reflector and a light-turning component; a polar transmission control arrangement comprising an out-of-plane polariser, a polarisation switch and an in-plane polariser that is the input polariser of a spatial light modulator;
(3) FIG. **1**B is a schematic diagram illustrating in perspective front view components of the optical stack of the display device of FIG. **1**A;
(4) FIG. **2**A is a schematic diagram illustrating in perspective side view an in-plane polariser;
(5) FIG. **2**B is a schematic diagram illustrating in perspective side view an out-of-plane polariser comprising an absorption axis with no in-plane component;
(6) FIG. **2**C is a schematic diagram illustrating in perspective side view an out-of-plane polariser comprising an absorption axis with an in-plane component;
(7) FIG. **3**A is a schematic diagram illustrating in perspective side view operation of an out-of-plane polariser, a switchable layer of liquid crystal material and an in-plane polariser for light rays, inclined in lateral and elevation directions for a first mode of operation;
(8) FIG. **3**B is a schematic diagram illustrating in perspective side view operation of an out-of-plane polariser, a switchable layer of liquid crystal material and an in-plane polariser for light rays inclined in lateral and elevation directions for a second mode of operation;
(9) FIG. **4**A is a schematic diagram illustrating in side view an out-of-plane polariser, a twisted nematic liquid crystal polarisation switch and an in-plane polariser in a first mode for an on-axis ray;
(10) FIG. **4**B is a schematic diagram illustrating the arrangement of FIG. **4**A in edge view;
(11) FIG. **4**C is a schematic diagram illustrating in side view an out-of-plane polariser, a twisted nematic liquid crystal polarisation switch and an in-plane polariser in a second mode for an on-axis ray;
(12) FIG. **4**D is a schematic diagram illustrating the arrangement of FIG. **4**C in edge view;
(13) FIG. **5**A is a schematic diagram illustrating in side view an out-of-plane polariser, a twisted nematic liquid crystal polarisation switch and an in-plane polariser in the first mode for an off-axis ray;
(14) FIG. **5**B is a schematic graph illustrating the polar variation of transmission output for the arrangement of FIG. **3**A, FIGS. **4**A-B, and FIG. **5**A for the illustrative embodiment of TABLE 1;
(15) FIG. **5**C is a schematic diagram illustrating in side view an out-of-plane polariser, a twisted nematic liquid crystal polarisation switch and an in-plane polariser in the second mode for an off-axis ray;
(16) FIG. **5**D is a schematic graph illustrating the polar variation of transmission output for the arrangement of FIG. **3**B, FIGS. **4**C-D, and FIG. **5**C for the illustrative embodiment of TABLE 1;
(17) FIG. **6**A is a schematic diagram illustrating in side view an out-of-plane polariser, a twisted nematic liquid crystal polarisation switch and an in-plane polariser in an alternative second mode for an off-axis ray;
(18) FIG. **6**B is a schematic graph illustrating the polar variation of transmission output for the arrangement of FIG. **6**A;
(19) FIG. **7**A is a schematic graph illustrating the polar variation of luminance output for a collimated backlight of the type illustrated in FIG. **1**A;
(20) FIG. **7**B is a schematic graph illustrating the polar variation of security factor, S for a collimated backlight of the type illustrated in FIG. **1**A modified by the transmission profile of FIG. **6**B for typical illumination conditions;
(21) FIG. **7**C is a schematic graph illustrating the polar variation of security factor, S for a collimated backlight of the type illustrated in FIG. **1**A modified by the transmission profile of FIG. **5**B for typical illumination conditions;

(22) FIG. **7**D is a schematic graph illustrating the polar variation of security factor, S for a collimated backlight of the type illustrated in FIG. **1**A modified by the transmission profile of FIG. **5**D for typical illumination conditions;
(23) FIG. **7**E is a schematic graph illustrating the polar variation of transmission output for the illustrative embodiment of TABLE 2 in a first driven state;
(24) FIG. **7**F is a schematic graph illustrating the polar variation of transmission output for the illustrative embodiment of TABLE 2 in a second driven state;
(25) FIG. **7**G is a schematic graph illustrating the polar variation of transmission output for the illustrative embodiment of TABLE 2 in a third driven state;
(26) FIG. **8**A is a schematic diagram illustrating in perspective side view a polarisation switch comprising a passive retarder operating in a first mode;
(27) FIG. **8**B is a schematic diagram illustrating in perspective side view a polarisation switch comprising a passive retarder operating in a second mode;
(28) FIG. **8**C is a schematic graph illustrating the polar variation of luminance transmission for the arrangement of FIG. **8**A provided between an out-of-plane polariser and an in-plane polariser operating in the first mode and as described in TABLE 3;
(29) FIG. **8**D is a schematic graph illustrating the polar variation of luminance transmission for the arrangement of FIG. **8**B provided between an out-of-plane polariser and an in-plane polariser operating in the first mode and as described in TABLE 3;
(30) FIG. **9**A is a schematic diagram illustrating in perspective side view a polar transmission control arrangement comprising an out-of-plane polariser, a polarisation switch, a biaxial retarder arrangement and an in-plane polariser;
(31) FIG. **9**B is a schematic diagram illustrating in perspective front view a biaxial retarder arrangement comprising an A-plate retarder and a negative C-plate retarder arranged between an out-of-plane polariser and an in-plane polariser;
(32) FIG. **9**C is a schematic diagram illustrating in perspective front view a biaxial retarder arrangement comprising an A-plate retarder and a positive C-plate retarder arranged between an out-of-plane polariser and an in-plane polariser;
(33) FIG. **9**D is a schematic diagram illustrating in perspective top view an out-of-plane polariser;
(34) FIG. **9**E is a schematic diagram illustrating in perspective left side view an out-of-plane polariser;
(35) FIG. **9**F is a schematic diagram illustrating in perspective upper left quadrant view an out-of-plane polariser;
(36) FIG. **9**G is a schematic graph illustrating a polar variation of output polarisation state from an out-of-plane polariser without a biaxial retarder arrangement;
(37) FIG. **9**H is a schematic graph illustrating a polar variation of output polarisation state from an out-of-plane polariser arranged with a desirable biaxial retarder arrangement;
(38) FIG. **9**I is a schematic diagram illustrating in perspective top view propagation of a polarisation state through an out-of-plane polariser and a biaxial retarder arrangement;
(39) FIG. **9**J is a schematic diagram illustrating in perspective left side view propagation of a polarisation state through an out-of-plane polariser and a biaxial retarder arrangement;
(40) FIG. **9**K is a schematic diagram illustrating in perspective upper left quadrant view propagation of a polarisation state through an out-of-plane polariser and a biaxial retarder arrangement;
(41) FIG. **10**A is a schematic graph illustrating a polar variation of transmission for the arrangement of FIG. **9**A comprising the arrangement of TABLE 4 for operation in the privacy mode;
(42) FIG. **10**B is a schematic graph illustrating a polar variation of transmission for a share mode of operation comprising the polarisation switch of TABLE 6;
(43) FIG. **10**C is a schematic diagram illustrating in perspective front view a polarisation switch

comprising a vertically aligned polarisation switch layer with privacy and share mode regions;
(44) FIG. **10**D is a schematic graph illustrating a polar variation of transmission for the out-of-plane polariser and the biaxial retarder of TABLE 4, and the polarisation switch of FIG. **10**C and TABLE 7 in a share region of the display device;
(45) FIG. **11**A, FIG. **11**B, FIG. **11**C, FIG. **11**D, and FIG. **11**E are schematic diagrams illustrating in top view various alternative structures of display device optical stacks comprising biaxial retarders;
(46) FIG. **12**A is a schematic diagram illustrating in side view an out-of-plane polariser of the type illustrated in FIG. **2**C, a liquid crystal polarisation switch and an in-plane polariser in an alternative second mode for two off-axis rays;
(47) FIG. **12**B is a schematic graph illustrating the polar variation of transmission for the structure illustrated in FIG. **12**A wherein the absorption axis is tilted in the elevation direction and TABLE 8;
(48) FIG. **12**C is a schematic graph illustrating the polar variation of transmission for the structure FIG. **12**A wherein the absorption axis is tilted in the lateral direction and TABLE 9 in a first mode;
(49) FIG. **12**D is a schematic graph illustrating the polar variation of transmission for the arrangement of FIG. **12**C in a second mode;
(50) FIG. **12**E is a schematic graph illustrating the polar variation of transmission for the arrangement of FIG. **12**C in a third, mixed mode of operation;
(51) FIG. **12**F is a schematic graph illustrating the polar variation of transmission for a collimated backlight of the type illustrated in FIG. **12**A wherein the absorption axis is tilted and rotated on an axis inclined to the lateral and elevation directions;
(52) FIG. **13** is a schematic diagram illustrating in top view a vehicle comprising a passenger infotainment display;
(53) FIG. **14**A is a schematic diagram illustrating in top view a polar angle control display device wherein the direction k.sub.e of the absorption axis tilt ϕ to surface normal is the same across the display device;
(54) FIG. **14**B is a schematic diagram illustrating in top view an out-of-plane polariser wherein the direction k.sub.e of the absorption axis tilt ϕ to surface normal changes monotonically along a predetermined axis across the out-of-plane polariser;
(55) FIG. **14**C is a schematic diagram illustrating in top view a polar angle control display device wherein the direction k.sub.e of the absorption axis tilt ϕ to surface normal changes monotonically along a predetermined axis across the display device for an off-axis viewing direction;
(56) FIG. **15**A is a schematic diagram illustrating in perspective side view a polar angle control display device comprising a backlight, a transmissive spatial light modulator, an in-plane polariser that is the output polariser of the spatial light modulator, a polarisation switch and an out-of-plane polariser;
(57) FIG. **15**B is a schematic diagram illustrating in perspective side view a polar angle control display device comprising a backlight, an out-of-plane polariser, a polarisation switch, an in-plane polariser that is the input polariser of a spatial light modulator, a further in-plane polariser that is the output polariser of the spatial light modulator, a further polarisation switch and a further out-of-plane polariser;
(58) FIG. **15**C is a schematic graph illustrating the polar variation of transmission for a collimated backlight of the type illustrated in FIG. **15**B and comprising the arrangement of TABLE 11;
(59) FIG. **16**A is a schematic diagram illustrating in perspective side view a polar angle control display device comprising a backlight, an additional polariser, a polar control retarder comprising a layer of liquid crystal material and a passive compensation retarder, an input polariser of a transmissive spatial light modulator, an output polariser of a spatial light modulator, a reflective polariser that is an in-plane polariser, a polarisation switch and an out-of-plane polariser;
(60) FIG. **16**B is a schematic diagram illustrating in perspective side view a polar angle control display device comprising a backlight, a spatial light modulator comprising an input polariser and an output polariser, a polar control retarder comprising a layer of liquid crystal material and a

passive compensation retarder, an additional polariser that is an in-plane polariser, a polarisation switch and an out-of-plane polariser;

(61) FIG. **16**C is a schematic diagram illustrating in perspective side view a polar angle control display device comprising a backlight, an out-of-plane polariser, a polarisation switch, an in-plane polariser that is the input polariser of a spatial light modulator, a display polariser that is the input polariser of the spatial light modulator, an output polariser, a reflective polariser, a polar control retarder comprising a layer of liquid crystal material and a passive compensation retarder and an additional polariser;

(62) FIG. **16**D is a schematic diagram illustrating in perspective side view a polar angle control display device comprising a backlight, an out-of-plane polariser, a polarisation switch, an in-plane polariser that is an additional polariser, a polar control retarder comprising a layer of liquid crystal material and a passive compensation retarder, an input display polariser, and a spatial light modulator comprising an output display polariser;

(63) FIG. **17**A is a schematic diagram illustrating in perspective side view a polar angle control display device comprising a backlight, an out-of-plane polariser, an in-plane polariser that is the input polariser of a spatial light modulator, an output polariser of the spatial light modulator, a reflective polariser, a polar control retarder comprising a layer of liquid crystal material and a passive compensation retarder, and an additional polariser;

(64) FIG. **17**B is a schematic diagram illustrating in perspective side view a polar angle control display device comprising a backlight, a spatial light modulator, an in-plane polariser that is the output polariser of the spatial light modulator, an out-of-plane polariser, a reflective polariser that is a further in-plane polariser, a polar control retarder comprising a layer of liquid crystal material and a passive compensation retarder, and an additional polariser;

(65) FIG. **18** is a schematic diagram illustrating in perspective side view a polar angle control display device comprising a backlight, an out-of-plane polariser, an in-plane polariser that is the input polariser of a spatial light modulator, a further in-plane polariser that is the output polariser of the spatial light modulator, and a further out-of-plane polariser;

(66) FIG. **19**A is a schematic diagram illustrating in perspective side view a polar angle control display device comprising an emissive spatial light modulator, an in-plane polariser that is the output polariser of the spatial light modulator, a polarisation switch and an out-of-plane polariser;

(67) FIG. **19**B is a schematic diagram illustrating in perspective side view a polar angle control display device comprising an emissive spatial light modulator, a display polariser that is an in-plane polariser that is the output polariser of the spatial light modulator, a polar control retarder comprising a layer of liquid crystal material and a passive compensation retarder, an additional polariser that is an in-plane polariser, a polarisation switch and an out-of-plane polariser;

(68) FIG. **19**C is a schematic diagram illustrating in perspective side view a polar angle control display device comprising an emissive spatial light modulator, an in-plane polariser that is the output polariser of the spatial light modulator, an out-of-plane polariser, a reflective polariser, a polar control retarder comprising a layer of liquid crystal material and a passive compensation retarder, and an additional polariser that is an in-plane polariser;

(69) FIG. **19**D is a schematic diagram illustrating in perspective side view a polar angle control display device comprising an emissive spatial light modulator, an in-plane polariser that is the output polariser of the spatial light modulator, an out-of-plane polariser, a polar control retarder comprising a twisted nematic layer of liquid crystal material, an additional polariser that is an in-plane polariser and a further out-of-plane polariser;

(70) FIG. **19**E is a schematic diagram illustrating in perspective side view a polar angle control display device comprising an emissive spatial light modulator, an in-plane polariser that is the output polariser of the spatial light modulator, a reflective polariser, an out-of-plane polariser, a passive compensation retarder, a polar control retarder comprising a layer of liquid crystal material, and an additional polariser that is an in-plane polariser;

(71) FIG. **19**F is a schematic diagram illustrating in top view the transmission and reflection of light through the reflective polariser, out-of-plane polariser, polar control retarder and in-plane additional polariser of FIG. **19**E in a privacy mode;
(72) FIG. **19**G is a schematic diagram illustrating in top view the transmission and reflection of light through the reflective polariser, out-of-plane polariser, polar control retarder and in-plane additional polariser of FIG. **19**E in a share mode;
(73) FIG. **20**A is a schematic diagram illustrating in perspective side view a polar angle control display device comprising an emissive spatial light modulator, an in-plane polariser that is the output polariser of the spatial light modulator, and an out-of-plane polariser;
(74) FIG. **20**B is a schematic diagram illustrating in perspective side view a polar angle control display device comprising an emissive spatial light modulator, an out-of-plane polariser, and an in-plane polariser that is the output polariser of the spatial light modulator;
(75) FIG. **20**C is a schematic diagram illustrating in perspective side view a polar angle control display device comprising an emissive spatial light modulator, an out-of-plane polariser, and an in-plane polariser that is the output polariser of the spatial light modulator, a further out-of-plane polariser and a further in-plane polariser;
(76) FIG. **20**D is a schematic diagram illustrating in perspective side view operation of an out-of-plane polariser comprising discotic dichroic molecules, and an in-plane polariser for light rays inclined in lateral and elevation directions;
(77) FIG. **21** is a schematic diagram illustrating in perspective side view a polar angle control component comprising an out-of-plane polariser;
(78) FIG. **22** is a schematic diagram illustrating in perspective side view a polar angle control component comprising an out-of-plane polariser and a polarisation switch;
(79) FIG. **23** is a schematic diagram illustrating in perspective side view a polar angle control component comprising an out-of-plane polariser and an in-plane polariser;
(80) FIG. **24** is a schematic diagram illustrating in perspective side view a polar angle control component comprising a polarisation switch arranged between an out-of-plane polariser and an in-plane polariser;
(81) FIG. **25**A is a schematic diagram illustrating in perspective side view an alternative backlight comprising addressable first and second arrays of light sources;
(82) FIG. **25**B is a schematic diagram illustrating in perspective side view an alternative backlight comprising first and second waveguides and respective aligned first and second arrays of light sources;
(83) FIG. **26**A is a schematic diagram illustrating in top view operation of the backlight of FIG. **25**B;
(84) FIG. **26**B is a schematic diagram illustrating in perspective rear view a light-turning component;
(85) FIG. **26**C is a schematic diagram illustrating in top view a light-turning component;
(86) FIG. **27** is a schematic diagram illustrating in perspective side view an alternative backlight comprising an array of light sources and an array of light-deflecting wells;
(87) FIG. **28**A is a schematic diagram illustrating in perspective side view an alternative backlight comprising a light-scattering waveguide, a rear reflector, crossed prismatic films and a light control film;
(88) FIG. **28**B is a schematic diagram illustrating in side view operation of the backlight of FIG. **26**;
(89) FIG. **29**A is a schematic diagram illustrating in top view propagation of transmitted light through a polar control retarder arranged between a reflective polariser and an additional polariser in privacy mode;
(90) FIG. **29**B is a schematic diagram illustrating in top view propagation of ambient light through a polar control retarder arranged between a reflective polariser and an additional polariser in

privacy mode;
(91) FIG. **30**A is a schematic diagram illustrating in side view propagation of output light from a spatial light modulator through the optical stack of FIG. **29**A in a wide-angle mode;
(92) FIG. **30**B is a schematic graph illustrating the polar variation of output luminance with polar direction for the transmitted light rays in FIG. **30**A;
(93) FIG. **30**C is a schematic diagram illustrating in top view propagation of ambient illumination light through the optical stack of FIG. **29**A in a wide-angle mode;
(94) FIG. **30**D is a schematic graph illustrating the polar variation of reflectivity with polar direction for the reflected light rays in FIG. **30**C;
(95) FIG. **31**A is a schematic diagram illustrating in perspective front view a polar transmission control arrangement comprising an in-plane polariser, a polarisation switch comprising a homeotropic alignment layer and a homogeneous alignment layer and an out-of-plane polariser;
(96) FIG. **31**B is a schematic diagram illustrating in perspective side view the arrangement of FIG. **31**A;
(97) FIG. **31**C is a schematic diagram illustrating in top view the arrangement of FIG. **31**A;
(98) FIG. **32**A is a schematic graph illustrating the polar variation of luminance transmission for the arrangement of FIG. **31**A operating in the first mode and as described in TABLE 12;
(99) FIG. **32**B is a schematic graph illustrating the polar variation of luminance transmission for the arrangement of FIG. **31**A operating in the second mode and as described in TABLE 12;
(100) FIG. **33**A is a schematic diagram illustrating in perspective side view a polar transmission control arrangement comprising an in-plane polariser, a splayed discotic passive compensation retarder, a polarisation switch comprising a homeotropic alignment layer and a homogeneous alignment layer and an out-of-plane polariser;
(101) FIG. **33**B is a schematic diagram illustrating in perspective side view the arrangement of FIG. **31**B operating in a first mode;
(102) FIG. **33**C is a schematic diagram illustrating in perspective side view the arrangement of FIG. **31**B operating in a second mode;
(103) FIG. **34**A is a schematic diagram illustrating in perspective side view a polar transmission control arrangement comprising an in-plane polariser, a polarisation switch comprising two homogeneous alignment layers and an out-of-plane polariser arranged in a first mode;
(104) FIG. **34**B is a schematic diagram illustrating in perspective side view the arrangement of FIG. **34**A arranged in a second mode;
(105) FIG. **35**A is a schematic graph illustrating the polar variation of luminance transmission for the arrangement of FIG. **34**A operating in the first mode and as described in TABLE 13;
(106) FIG. **35**B is a schematic graph illustrating the polar variation of luminance transmission for the arrangement of FIG. **34**B operating in the second mode and as described in TABLE 13;
(107) FIG. **36**A is a schematic diagram illustrating in perspective side view a polar transmission control arrangement comprising an in-plane polariser, a polarisation switch comprising two homogeneous alignment layers and an out-of-plane polariser arranged in a first mode;
(108) FIG. **36**B is a schematic diagram illustrating in perspective side view the arrangement of FIG. **34**A arranged in a second mode;
(109) FIG. **37**A is a schematic graph illustrating the polar variation of luminance transmission for the arrangement of FIG. **36**A operating in the first mode and as described in TABLE 14;
(110) FIG. **37**B is a schematic graph illustrating the polar variation of luminance transmission for the arrangement of FIG. **36**B operating in the second mode and as described in TABLE 14;
(111) FIG. **38**A is a schematic diagram illustrating in perspective side view a switchable privacy display device comprising a backlight comprising an array of light sources, a waveguide, a rear reflector and a light turning component; an out-of-plane polariser; a switchable diffractive polar control retarder; and a transmissive spatial light modulator;
(112) FIG. **38**B is a schematic diagram illustrating in perspective side view a switchable diffractive

polar control retarder component;
(113) FIG. **38**C is a schematic diagram illustrating in perspective front view alignment orientations for an optical stack for use in the embodiment of FIG. **38**A;
(114) FIG. **38**D is a schematic diagram illustrating in perspective side view a transmissive electrode arrangement for the switchable diffractive polar control retarder of FIG. **38**A;
(115) FIG. **38**E is a schematic diagram illustrating in front view a transmissive electrode for the transmissive electrode arrangement of FIG. **38**D;
(116) FIG. **39**A is a schematic diagram illustrating in top view the structure and operation of the optical stack comprising a switchable diffractive polar control retarder for wide-angle mode;
(117) FIG. **39**B is a schematic diagram illustrating in perspective front view an electrode and liquid crystal molecular arrangement for the switchable diffractive polar control retarder in wide-angle mode;
(118) FIG. **39**C is a schematic diagram illustrating in top view an electrode and liquid crystal molecular arrangement for the switchable diffractive polar control retarder in wide-angle mode;
(119) FIG. **39**D is a schematic graph illustrating a profile of diffracted luminance into diffractive orders for the embodiment of FIG. **39**C in wide-angle mode for a first drive voltage;
(120) FIG. **39**E is a schematic graph illustrating a profile of diffracted luminance into diffractive orders for the embodiment of FIG. **39**C in wide-angle mode for different drive voltages;
(121) FIG. **39**F is a schematic diagram illustrating in top view the structure and operation of the display device comprising a switchable diffractive polar control retarder for wide-angle mode;
(122) FIG. **39**G is a schematic diagram illustrating in top view the propagation of a first linear polarisation state through a layer comprising a switchable diffractive polar control retarder arranged in wide-angle mode;
(123) FIG. **39**H is a schematic diagram illustrating in perspective front view the propagation of the first polarisation state through a layer comprising a switchable diffractive polar control retarder arranged in wide-angle mode;
(124) FIG. **40**A is a schematic diagram illustrating in top view the structure and operation of the optical stack comprising a switchable diffractive polar control retarder for privacy mode;
(125) FIG. **40**B is a schematic diagram illustrating in perspective front view an electrode and liquid crystal molecular arrangement for a switchable diffractive polar control retarder in privacy mode;
(126) FIG. **40**C is a schematic diagram illustrating in top view an electrode and liquid crystal molecular arrangement for a switchable diffractive polar control retarder in privacy mode;
(127) FIG. **40**D is a schematic diagram illustrating in top view the structure and operation of the display device comprising a switchable diffractive polar control retarder for wide-angle mode;
(128) FIG. **41**A and FIG. **41**B are schematic diagrams illustrating in perspective side views alternative electrode arrangements comprising interdigitated electrodes; and
(129) FIG. **41**C and FIG. **41**D are schematic diagrams illustrating in perspective side views alternative electrode arrangements comprising interdigitated electrodes arranged on a single substrate and further control and reference electrodes.

DETAILED DESCRIPTION

(130) Terms related to optical retarders for the purposes of the present disclosure will now be described.
(131) In a layer comprising a uniaxial birefringent material there is a direction governing the optical anisotropy whereas all directions perpendicular to it (or at a given angle to it) have equivalent birefringence.
(132) The optical axis of an optical retarder refers to the direction of propagation of a light ray in the uniaxial birefringent material in which no birefringence is experienced. This is different from the optical axis of an optical system which may for example be parallel to a line of symmetry or normal to a display surface along which a principal ray propagates.
(133) For light propagating in a direction orthogonal to the optical axis, the optical axis is the slow

axis when linearly polarized light with an electric vector direction parallel to the slow axis travels at the slowest speed. The slow axis direction is the direction with the highest refractive index at the design wavelength. Similarly the fast axis direction is the direction with the lowest refractive index at the design wavelength.
(134) For positive dielectric anisotropy uniaxial birefringent materials the slow axis direction is the extraordinary axis of the birefringent material. For negative dielectric anisotropy uniaxial birefringent materials the fast axis direction is the extraordinary axis of the birefringent material.
(135) The terms half a wavelength and quarter a wavelength refer to the operation of a retarder for a design wavelength λ.sub.0 that may typically be between 500 nm and 570 nm. In the present illustrative embodiments exemplary retardance values are provided for a wavelength of 550 nm unless otherwise specified.
(136) The retarder provides a phase shift between two perpendicular polarization components of the light wave incident thereon and is characterized by the amount of relative phase, Γ, that it imparts on the two polarization components: which is related to the birefringence Δn and the thickness d of the retarder by
(137) $= 2 \text{ .Math. } \text{ .Math. } n \text{ .Math. } d / {}_0$ eqn . 1
(138) In eqn. 1, Δn is defined as the difference between the extraordinary and the ordinary index of refraction, i.e.
(139) $n = n_e - n_o$ eqn . 2
(140) For a half-wave retarder, the relationship between d, Δn, and λ.sub.0 is chosen so that the phase shift between polarization components is Γ=π. For a quarter-wave retarder, the relationship between d, Δn, and λ.sub.0 is chosen so that the phase shift between polarization components is Γ=π/2. The term half-wave retarder herein typically refers to light propagating normal to the retarder and normal to the spatial light modulator.
(141) An absorption-type polariser transmits light waves of a specific polarisation state and absorbs light (in a spectral waveband) of different polarisation states which may be orthogonal polarisation states to the specific polarisation state. For a given wavefront, an absorptive linear polariser absorbs light waves of a specific linear polarisation state and transmits light waves of the orthogonal polarisation state of the wavefront. The absorptive linear polariser comprises an absorption axis with unit vector direction k.sub.e which may alternatively be termed the optical axis or the director of the absorption material. Orthogonal directions k.sub.o to the absorption axis direction may be termed transmission axes.
(142) A dichroic material has different absorption coefficients α.sub.e, α.sub.o for light polarized in different directions, where the complex extraordinary refractive index is:
(143) $\overset{\text{.fwdarw.}}{n_e} = n_e + i \text{ .Math. } {}_e$ eqn . 3A
and the complex ordinary refractive index is:
(144) $\overset{\text{.fwdarw.}}{n_o} = n_o + i \text{ .Math. } {}_o$ eqn . 3B
(145) Absorptive linear polarisers may comprise a dichroic material such as a dye or iodine. During manufacture a polyvinyl alcohol (PVA) layer is stretched so that the PVA chains align in one particular direction. The PVA layer is doped with iodine molecules, from which valence electrons are able to move linearly along the polymer chains, but not transversely. An incident polarisation state parallel to the chains is, at least in part, absorbed and the perpendicular polarisation state is substantially transmitted. Such a polariser may conveniently provide an in-plane polariser.
(146) Another type of absorptive linear polariser is a liquid crystal dye-type dichroic linear polariser. A thermotropic liquid crystal material is doped with a dye, and the liquid crystal material is aligned during manufacture, or by an electric field. The liquid crystal layers may be untwisted, or may incorporate a twist from one side of the device to the other. Alternatively, alignment may be provided by lyotropic liquid crystal molecules that self-align onto a surface by provision of

amphiphilic compounds (with hydrophilic and hydrophobic molecular groups) during manufacture. The alignment may be aided by mechanical movement of the liquid by for example a Meyer rod in a coating machine. The liquid crystal material may be a curable liquid crystal material. The dye may comprise an organic material that is aligned by the liquid crystal material or is provided in the liquid crystal molecules or may comprise silver nano-particles. Such polarisers may provide in-plane polarisers or may provide out-of-plane polarisers, wherein the optical axis direction k.sub.e or the absorption axis is out of the plane of the polariser. The directions k.sub.o of the transmission axes may be in the plane of the out-of-plane polariser. The direction k.sub.e may alternatively be referred to as the extraordinary axis direction and the directions k.sub.o may be referred to as the ordinary axis directions of the dichroic molecules.

(147) If the absorbing dye molecules are rod-shaped then the polariser absorbs along a single axis and transmits on orthogonal axes. If the absorbing dye molecules are disc-shaped rather than rod-shaped, then the polariser can absorb two orthogonal axes and transmit the third.

(148) Some aspects of the propagation of light rays through a transparent retarder between a pair of polarisers will now be described.

(149) The state of polarisation (SOP) of a light ray is described by the relative amplitude and phase shift between any two orthogonal polarization components. Transparent retarders do not alter the relative amplitudes of these orthogonal polarisation components but act only on their relative phase. Providing a net phase shift between the orthogonal polarisation components alters the SOP whereas maintaining net relative phase preserves the SOP. In the current disclosure, the SOP may be termed the polarisation state.

(150) A linear SOP has a polarisation component with a non-zero amplitude and an orthogonal polarisation component which has zero amplitude.

(151) A linear polariser transmits a unique linear SOP that has a linear polarisation component parallel to the electric vector transmission direction of the linear polariser and attenuates light with a different SOP. The term “electric vector transmission direction” refers to a non-directional axis of the polariser parallel to which the electric vector of incident light is transmitted, even though the transmitted “electric vector” always has an instantaneous direction. The term “direction” is commonly used to describe this axis.

(152) Absorbing polarisers are polarisers that absorb one polarisation component of incident light and transmit a second orthogonal polarisation component. Examples of absorbing linear polarisers are dichroic polarisers.

(153) Reflective polarisers are polarisers that reflect one polarisation component of incident light and transmit a second orthogonal polarisation component. Examples of reflective polarisers that are linear polarisers are multilayer polymeric film stacks such as DBEF™ or APF™ from 3M Corporation, or wire grid polarisers such as ProFlux™ from Moxtek. Reflective linear polarisers may further comprise cholesteric reflective materials and a quarter waveplate arranged in series.

(154) A retarder arranged between a linear polariser and a parallel linear analysing polariser that introduces no relative net phase shift provides full transmission of the light other than residual absorption within the linear polariser.

(155) A retarder that provides a relative net phase shift between orthogonal polarisation components changes the SOP and provides attenuation at the analysing polariser.

(156) In the present disclosure an ‘A-plate’ refers to an optical retarder utilizing a layer of birefringent material with its optical axis parallel to the plane of the layer.

(157) A ‘positive A-plate’ refers to positively birefringent A-plates, i.e. A-plates with a positive Δn.

(158) In the present disclosure a ‘C-plate’ refers to an optical retarder utilizing a layer of birefringent material with its optical axis perpendicular to the plane of the layer. A ‘positive C-plate’ refers to positively birefringent C-plates, i.e. C-plates with a positive Δn. A ‘negative C-plate’ refers to negatively birefringent C-plates, i.e. C-plates with a negative Δn.

(159) ‘O-plate’ refers to an optical retarder utilizing a layer of birefringent material with its optical

axis having a component parallel to the plane of the layer and a component perpendicular to the plane of the layer. A ‘positive O-plate’ refers to positively birefringent O-plates, i.e. O-plates with a positive Δn.
(160) A biaxial-plate or ‘B-plate’ is a non-chiral retarder that has three different principal refractive indices nx, ny, nz wherein:
(161) $nx \neq ny \neq nz \quad \text{eqn}.4A$
(162) The out-of-plane retardation of a B-plate is described by the parameter Rth wherein
(163) $Rth = ((nx + ny) / 2 - nz)d \quad \text{eqn}.4B$
(164) A B-plate is typically fabricated by stretching organic polymer films along two orthogonal in-plane directions that become two of the three principal axes; the third being orthogonal to both and out-of-plane. The direction that is stretched the most induces the largest principal refractive index along that same direction. A smaller refractive index results along the orthogonal in-plane stretch direction leaving the smallest third principal refractive index out-of-plane.
(165) The angular dependence of birefringence is different between uniaxial A-plates, uniaxial C-plates and biaxial B-plates. In particular A-plates and C-plates have only one propagation direction with no birefringence whereas B-plates can achieve increased control of modification of output polarisation states with respect to transmission angle.
(166) Achromatic retarders may be provided wherein the material of the retarder is provided with a retardance Δn.Math.d that varies with wavelength λ as
(167) n .Math. d / = eqn . 5
(168) where σ is substantially a constant.
(169) Examples of suitable materials include modified polycarbonates from Teijin Films. Achromatic retarders may be provided in the present embodiments to advantageously minimise colour changes between polar angular viewing directions which have low luminance reduction and polar angular viewing directions which have increased luminance reductions as will be described below.
(170) Various other terms used in the present disclosure related to retarders and to liquid crystals will now be described.
(171) A liquid crystal cell has a retardance given by Δn.Math.d where Δn is the birefringence of the liquid crystal material in the liquid crystal cell and d is the thickness of the liquid crystal cell, independent of the alignment of the liquid crystal material in the liquid crystal cell.
(172) Homogeneous alignment refers to the alignment of liquid crystals in liquid crystal displays where molecules align substantially parallel to a substrate. Homogeneous alignment is sometimes referred to as planar alignment. Homogeneous alignment may typically be provided with a small pre-tilt such as 2 degrees, so that the molecules at the surfaces of the alignment layers of the liquid crystal cell are slightly inclined as will be described below. Pretilt is arranged to minimise degeneracies in switching of cells or in alignment of curable liquid crystal layers before a curing step.
(173) In the present disclosure, homeotropic alignment is the state in which rod-like liquid crystalline molecules align substantially perpendicularly to the substrate. In discotic liquid crystals homeotropic alignment is defined as the state in which an axis of the column structure, which is formed by disc-like liquid crystalline molecules, aligns perpendicularly to a surface. In homeotropic alignment, pretilt is the tilt angle of the molecules that are close to the alignment layer and is typically close to 90 degrees and for example may be 88 degrees.
(174) In a twisted liquid crystal layer, a twisted configuration (also known as a helical structure or helix) of nematic liquid crystal molecules is provided. The twist may be achieved by means of a non-parallel alignment of alignment layers. Further, cholesteric dopants may be added to the liquid crystal material to break degeneracy of the twist direction (clockwise or anti-clockwise) and to further control the pitch of the twist in the relaxed (typically undriven) state. A supertwisted liquid

crystal layer has a twist of greater than 180 degrees. A twisted nematic layer used in spatial light modulators typically has a twist of 90 degrees.

(175) Liquid crystal molecules with positive dielectric anisotropy may be switched from a homogeneous alignment (such as an A-plate retarder orientation) to a homeotropic alignment (such as a C-plate or O-plate retarder orientation) by means of an applied electric field.

(176) Liquid crystal molecules with negative dielectric anisotropy may be switched from a homeotropic alignment (such as a C-plate or O-plate retarder orientation) to a homogeneous alignment (such as an A-plate retarder orientation) by means of an applied electric field.

(177) Rod-like molecules have a positive birefringence so that n.sub.e>n.sub.o as described in eqn. 2. Discotic molecules have negative birefringence so that n.sub.e<n.sub.o.

(178) Positive retarders such as A-plates, positive O-plates and positive C-plates may typically be provided by stretched films or rod-like liquid crystal molecules. Negative retarders such as negative C-plates may be provided by stretched films or discotic-like liquid crystal molecules.

(179) Parallel liquid crystal cell alignment refers to the alignment direction of homogeneous alignment layers being parallel or more typically antiparallel. In the case of pre-tilted homeotropic alignment, the alignment layers may have components that are substantially parallel or antiparallel. Hybrid aligned liquid crystal cells may have one homogeneous alignment layer and one homeotropic alignment layer. Twisted liquid crystal cells may be provided by alignment layers that do not have parallel alignment, for example oriented at 90 degrees to each other.

(180) Transmissive spatial light modulators may further comprise retarders between the input display polariser and the output display polariser for example as disclosed in U.S. Pat. No. 8,237,876, which is herein incorporated by reference in its entirety. Such retarders (not shown) are in a different place to the passive retarders of the present embodiments. Such retarders compensate for contrast degradations for off-axis viewing locations, which is a different effect to the luminance reduction for off-axis viewing positions of the present embodiments.

(181) A private mode of operation of a display is one in which a viewer sees a low contrast sensitivity such that an image is not clearly visible. Contrast sensitivity is a measure of the ability to discern between luminances of different levels in a static image. Inverse contrast sensitivity may be used as a measure of visual security, in that a high visual security level (VSL) corresponds to low image visibility.

(182) For a privacy display providing an image to a viewer, visual security may be given as:

(183) $V = (Y + R) / (Y - K)$ eqn. 6

(184) where V is the visual security level (VSL), Y is the luminance of the white state of the display at a snooper viewing angle (which may be termed a non-viewing direction), K is the luminance of the black state of the display at the snooper viewing angle and R is the luminance of reflected light from the display.

(185) Panel contrast ratio is given as:

(186) $C = Y / K$ eqn. 7

so the visual security level may be further given as:

(187) 0 $V = (P \text{ .Math. } Y_{max} + I \text{ .Math. } \quad / \quad) / (P \text{ .Math. } (Y_{max} - Y_{max} / C))$ eqn. 8

where: Y.sub.max is the maximum luminance of the display; P is the off-axis relative luminance typically defined as the ratio of luminance at the snooper angle to the maximum luminance Y.sub.max; C is the image contrast ratio; ρ is the surface reflectivity; π is a solid angle factor (with units steradians) and I is the illuminance. The units of Y.sub.max are the units of I divided by solid angle in units of steradian.

(188) The luminance of a display varies with angle and so the maximum luminance of the display Y.sub.max occurs at a particular angle that depends on the configuration of the display.

(189) In many displays, the maximum luminance Y.sub.max occurs head-on, i.e. normal to the display. Any display device disclosed herein may be arranged to have a maximum luminance

Y.sub.max that occurs head-on, in which case references to the maximum luminance of the display device Y.sub.max may be replaced by references to the luminance normal to the display device.
(190) Alternatively, any display described herein may be arranged to have a maximum luminance Y.sub.max that occurs at a polar angle to the normal to the display device that is greater than zero degrees. By way of example, the maximum luminance Y.sub.max may occur at a non-zero polar angle and at an azimuth angle that has for example zero lateral angle so that the maximum luminance is for an on-axis user that is looking down on to the display device. The polar angle may for example be 10 degrees and the azimuthal angle may be the northerly direction (90 degrees anti-clockwise from easterly direction). The viewer may therefore desirably see a high luminance at typical non-normal viewing angles.
(191) The off-axis relative luminance, P is sometimes referred to as the privacy level. However, such privacy level P describes relative luminance of a display at a given polar angle compared to head-on luminance, and in fact is not a measure of privacy appearance.
(192) The illuminance, I is the luminous flux per unit area that is incident on the display and reflected from the display towards the viewer location. For Lambertian illuminance, and for displays with a Lambertian front diffuser, illuminance I is invariant with polar and azimuthal angles. For arrangements with a display with non-Lambertian front diffusion arranged in an environment with directional (non-Lambertian) ambient light, illuminance I varies with polar and azimuthal angle of observation.
(193) Thus in a perfectly dark environment, a high contrast display has VSL of approximately 1.0. As ambient illuminance increases, the perceived image contrast degrades, VSL increases and a private image is perceived.
(194) For typical liquid crystal displays the panel contrast C is above 100:1 for almost all viewing angles, allowing the visual security level to be approximated to:
(195) $V = 1 + I \text{ .Math. } / (\text{ .Math. } P \text{ .Math. } Y_{max}) \quad \text{eqn. 9}$
(196) In the present embodiments, in addition to the exemplary definition of eqn. 6, other measurements of visual security level, V may be provided, for example to include the effect on image visibility to a snooper of snooper location, image contrast, image colour and white point and subtended image feature size. Thus the visual security level may be a measure of the degree of privacy of the display but may not be restricted to the parameter V.
(197) The perceptual image security may be determined from the logarithmic response of the eye, such that a Security Factor, S is given by
(198) $S = \log_{10}(V) \quad \text{eqn. 10} \quad S = \log_{10}(1 + \text{ .Math. } / (\text{ .Math. } P)) \quad \text{eqn. 11}$
where α is the ratio of illuminance I to maximum luminance Y.sub.max.
(199) Desirable limits for S were determined in the following manner. In a first step a privacy display device was provided. Measurements of the variation of privacy level, P(θ) of the display device with polar viewing angle and variation of reflectivity ρ(θ) of the display device with polar viewing angle were made using photopic measurement equipment. A light source such as a substantially uniform luminance light box was arranged to provide illumination from an illuminated region that was arranged to illuminate the privacy display device along an incident direction for reflection to viewer positions at a polar angle of greater than zero degrees to the normal to the display device. The variation I(θ) of illuminance of a substantially Lambertian emitting lightbox with polar viewing angle was determined by and measuring the variation of recorded reflective luminance with polar viewing angle taking into account the variation of reflectivity ρ(θ). The measurements of P(θ), ρ(θ) and I(θ) were used to determine the variation of Security Factor S(θ) with polar viewing angle along the zero elevation axis.
(200) In a second step a series of high contrast images were provided on the privacy display including (i) small text images with maximum font height 3 mm, (ii) large text images with maximum font height 30 mm and (iii) moving images.

(201) In a third step each viewer (with eyesight correction for viewing at 1000 mm where appropriate) viewed each of the images from a distance of 1000 mm, and adjusted their polar angle of viewing at zero elevation until image invisibility was achieved for one eye from a position near on the display at or close to the centre-line of the display. The polar location of the viewer's eye was recorded. From the relationship S(θ), the security factor at said polar location was determined. The measurement was repeated for the different images, for various display luminance Y.sub.max, different lightbox illuminance I(θ=0), for different background lighting conditions and for different viewers.
(202) From the above measurements S<1.0 provides low or no visual security, and S≥1 makes the image not visible. In the range 1.0≤S<1.5, even though the image is not visible for practical purposes, some features of the image may still be perceived dependent on the contrast, spatial frequency and temporal frequency of image content, whereas in the range 1.5≤S<1.8, the image is not visible for most images and most viewers and in the range S≥1.8 the image is not visible, independent of image content for all viewers.
(203) In practical display devices, this means that it is desirable to provide a value of S for an off-axis viewer who is a snooper that meets the relationship S≥S.sub.min, where: S.sub.min has a value of 1.0 or more to achieve the effect that in practical terms the displayed image is not visible to the off-axis viewer.
(204) At an observation angle θ in question, the security factor S.sub.n for a region of the display labelled by the index n is given from eqn. 10 and eqn. 11 by:
(205) $S_n(\ ) = \log_{10}[1 + \ _n(\ ) .Math. \ (\ ) / (\ .Math. P_n(\ ))]$ eqn . 12
where: α is the ratio of illuminance I(θ) onto the display that is reflected from the display to the angle in question and with units lux (lumen.Math.m.sup.−2), to maximum luminance Y.sub.max with units of nits (lumen.Math.m.sup.−2.Math.sr.sup.−1) where the units of α are steradians, π is a solid angle in units of steradians, ρ.sub.n(θ) is the reflectivity of the display device along the observation direction in the respective n.sup.th region, and P.sub.n(θ) is the ratio of the luminance of the display device along the observation direction in the respective n.sup.th region.
(206) In human factors measurement, it has been found that desirable privacy displays of the present embodiments described hereinbelow typically operate with security factor S.sub.n≥1.0 at the observation angle when the value of the ratio α of illuminance I to maximum luminance Y.sub.max is 4.0. For example, the illuminance I(θ=−45°) that illuminates the display and is directed towards the snooper at the observation direction (θ=+45°) after reflection from the display may be 1000 lux and the maximum display illuminance Y.sub.max that is provided for the user may be 250 nits. This provides an image that is not visible for a wide range of practical displays.
(207) More preferably, the display may have improved characteristics of reflectivity ρ.sub.n(θ=45°) and privacy P.sub.n(θ=45°) by operating with security factor S.sub.n≥1.0 at the observation angle when the ratio α is 2.0. Such an arrangement desirably improves the relative perceived brightness and contrast of the display to the primary user near to the direction of Y.sub.max while achieving desirable security factor, S.sub.n≥1.0. Most preferably, the display may have improved characteristics of reflectivity ρ.sub.n(θ=45°) and privacy P.sub.n(θ=45°) by operating with security factor S.sub.n≥1.0 at the observation angle when the ratio α is 1.0. Such an arrangement achieves desirably high perceived brightness and contrast of the display to the primary user near to the direction of Y.sub.max in comparison to the brightness of illuminated regions around the display, while achieving desirable security factor, S.sub.n≥1.0 for an off-axis viewer **47** at the observation direction.
(208) The above discussion focusses on reducing visibility of the displayed image to an off-axis viewer who is a snooper, but similar considerations apply to visibility of the displayed image to the intended user of the display device who is typically on-axis. In this case, decrease of the level of the visual security level (VSL) V corresponds to an increase in the visibility of the image to the

viewer. During observation S<0.2 may provide acceptable visibility (perceived contrast ratio) of the displayed image and more desirably S<0.1. In practical display devices, this means that it is desirable to provide a value of S for an on-axis viewer who is the intended user of the display device that meets the relationship S≤S.sub.max, where S.sub.max has a value of 0.2.
(209) In the present discussion the colour variation Δε of an output colour (u.sub.w′+Δu′, v.sub.w′+Δv′) from a desirable white point (u.sub.w′, v.sub.w′) may be determined by the CIELUV colour difference metric, assuming a typical display spectral illuminant and is given by:
(210) $$\Delta\varepsilon = (u'^2 + v'^2)^{1/2} \quad \text{eqn. 13}$$
(211) A diffractive effect of a liquid crystal layer relates to the interference or bending of waves around the corners of an obstacle or through an aperture into the region of the geometrical shadow of the obstacle/aperture. The diffractive effect arises from the interaction of plane waves incident onto the phase structure of the layer, rather than the propagation of rays through the layer.
(212) The structure and operation of various directional display devices will now be described. In this description, common elements have common reference numerals. It is noted that the disclosure relating to any element applies to each device in which the same or corresponding element is provided. Accordingly, for brevity such disclosure is not repeated.
(213) It may be desirable to provide high visual security levels for a display device in a privacy mode and to provide high luminance in off-axis viewing angles in the wide-angle mode of the display device. The structure of a switchable privacy display will now be described.
(214) FIG. **1**A is a schematic diagram illustrating in perspective side view a switchable privacy display comprising: a polar angle control display device **100** comprising a backlight **20** comprising a light source array **15**, a waveguide **1**, a rear reflector **3** and a light-turning component **50**; a polar transmission control arrangement **600** comprising an out-of-plane polariser **602**, a polarisation switch **601** and an in-plane polariser **610** that is the input polariser **210** of a spatial light modulator **48**; and FIG. **1**B is a schematic diagram illustrating in perspective front view alignment orientations for an optical stack for use in the display device **100** of FIG. **1**A.
(215) The embodiment of FIG. **1**A illustrates a display device **100** comprising a spatial light modulator **48** arranged to output spatially modulated light. The spatial light modulator **48** comprises a liquid crystal display device comprising transparent substrates **212**, **216**, and pixel layer **214** that may comprise a liquid crystal layer pixel having red, green and blue pixels **220**, **222**, **224**. The spatial light modulator **48** has an input display polariser **210** and an output display polariser **218** on opposite sides thereof. The display polarisers **210**, **218** are arranged to provide high extinction ratio for light from the pixels **220**R. **220**G, **220**B of the spatial light modulator **48**. Typical polarisers **210**, **218** may be absorptive linear in-plane polarisers, the operation of which will be described further hereinbelow. The transmissive spatial light modulator **48** thus comprises an input polariser **210** and an output polariser **218**, and the input polariser **210** is the in-plane polariser **610** and a said side of the spatial light modulator **48** is an input side of the spatial light modulator **48**.
(216) The display device **100** further comprises a backlight **20** arranged to output light, and the spatial light modulator **48** is a transmissive spatial light modulator **48** arranged to receive the output light from the backlight **20**. The backlight apparatus **20** comprises a rear reflector **3** and a waveguide arrangement comprising waveguide **1**, and light sources **15**, light-turning film **50** and light control components **5** that may comprise diffusers and arranged to receive light exiting from the waveguide **1** and directed through the spatial light modulator **48**. A reflective polariser **217** may be provided between the backlight **20** and the additional polariser **918** to improve the efficiency of output light from the backlight **20** to achieve improved luminance. The reflective polariser **217** may alternatively be omitted. The reflective polariser **217** is different in operation to the reflective polariser **302** to achieve increased security factor, S that will be described in alternative embodiments hereinbelow. The backlight **20** may be arranged to provide light with high luminance

in a preferred direction such as the on-axis direction, and to provide reduced luminance in other directions. Alternative backlight arrangements will be described further hereinbelow.

(217) The display device has a normal **199** to at least one region of the display device. The nominal display user **45** polar viewing direction **445** may be parallel to the normal **199**, for example in displays such as laptops where the user **45** desirably aligns centrally to the display device **100**. In applications such as automotive applications, the direction **445** may be different to the normal **199** direction. In privacy mode, the non-viewing direction **447**, that is the direction in which a display snooper is located, is inclined at a polar angle (ϕ,θ) to the viewing direction **445**.

(218) Polar transmission control arrangement **600** comprises in-plane polariser **610** that is the input polariser **210** of the spatial light modulator **48**. In-plane polariser **610** thus has an absorption axis **620** in a plane of the in-plane polariser **610** arranged on the input side of the spatial light modulator **48**.

(219) In the present description the term plane does not imply flat and could be a curved plane, for example for use in curved displays. The normal direction **199** is the normal direction to the plane at a given spatial location and may vary across the display device **100**.

(220) Polar transmission control arrangement **600** further comprises an out-of-plane polariser **602** having an absorption axis **622** in a direction k.sub.e having a component out of a plane of the out-of-plane polariser **602**. Out-of-plane polariser **602** is arranged on the same side of the spatial light modulator **48** as the in-plane polariser **610**.

(221) The polar angle control display device **100** further comprises a polarisation switch **601** provided between the in-plane polariser **610** and the out-of-plane polariser **602**. The polarisation switch **601** comprises a switchable layer **614** of liquid crystal material **615** and at least one electrode **613**A, **613**B arranged to switch the state of the liquid crystal material **615**. A transmissive electrode arrangement comprising electrodes **618**A. **618**B is arranged to drive the layer **614** of liquid crystal material **615** by means of applied voltages V from voltage drivers **650**. The display device **100** further comprises a control system **500** arranged to supply voltages by means of the drivers **650** to the transmissive electrode arrangement for driving the layer **614** of liquid crystal material **615**.

(222) The polarisation switch **601** further comprises alignment layers **617**A. **617**B with alignment directions with components **619**Ap, **627**Bp in the plane of the respective alignment layers **617**A, **617**B at angles η.sub.A, η.sub.B and arranged to provide alignment of the layer **614** of liquid crystal material **615**. In the present illustrative embodiments, the direction of various orientations of respective layers is measured anticlockwise from an easterly direction when viewing the front of the display device **100**.

(223) The two surface alignment layers **617**A, **617**B are disposed adjacent to the layer **914** of liquid crystal material **915** and on opposite sides thereof.

(224) In operation as will be described below, the polarisation switch **601** is switchable between a first mode in which it is arranged to change a polarisation state of the light passing therethrough and a second mode in which it is arranged to affect the polarisation state of the light passing therethrough differently from the first mode.

(225) The structure and operation of various layers of the optical stack of FIG. **1**A will now be described further with respect to FIG. **1**B. Backlight **20** provides output polarised light state **21** that may be an unpolarised or partially polarised light state and can be resolved into horizontal and vertical polarisation states **642**, **640**. Such polarisation state **21** is incident onto the out-of-plane polariser **602** comprising dichroic material **603** with absorption axis **622** direction k.sub.e, that has a component that is out of the plane of the out-of-plane polariser **602**. The out-of-plane polariser **602** modifies the polar polarisation state distribution of the input light polarisation state **21**, and output light is directed through the polarisation switch **601**. The light is output towards the in-plane polariser **610** comprising dichroic material **611** with absorption axis **620** direction j.sub.e that has no component that is out of the plane of the out-of-plane polariser **602**.

(226) Further, pretilt of the alignment directions **619**At, **619**Bt provides an out-of-plane component in the thickness direction {circumflex over (t)} through the layer **614** of liquid crystal material **615** that reduces degeneracy of the structure of liquid crystal material **615** orientation and advantageously improves uniformity across the area **103** of the layer **614** of liquid crystal material **615**.
(227) The electrodes **618**A, **618**B may further comprise electrode structures arranged to provide a mark as described in U.S. Pat. No. 11,892,717, which is herein incorporated by reference in its entirety. Advantageously a switchable mark **322** may be provided.
(228) Structures of polarisers will now be further described.
(229) FIG. **2**A is a schematic diagram illustrating in perspective side view an in-plane polariser **610**; FIG. **2**B is a schematic diagram illustrating in perspective side view an out-of-plane polariser **602** comprising an absorption axis **622** with no in-plane component; and FIG. **2**C is a schematic diagram illustrating in perspective side view an out-of-plane polariser **602** comprising an absorption axis **622** with an in-plane component. Features of the embodiments of FIGS. **2**A-C not discussed in further detail may be assumed to correspond to the features with equivalent reference numerals as discussed above, including any potential variations in the features.
(230) FIG. **2**A illustrates that an in-plane polariser **610** comprises a dichroic molecule **611** (such as iodine contained within a PVA layer) with an absorption axis **620** that has direction j.sub.e that is in the direction {circumflex over (t)} through the thickness of the layer of the in-plane polariser **610**, that is the direction j.sub.e is in the plane in which the in-plane polariser **610** extends. For an incident wavefront with a linear polarisation state, the electric vector transmission direction for an incident polarisation state is the in-plane direction j.sub.oa, **621***a* and is oriented at an angle θ to the easterly direction.
(231) By way of comparison with FIG. **2**A, the direction of the absorption axis **622** of the out-of-plane polariser **602** is normal to the plane of the out-of-plane polariser **602**. The out-of-plane polariser **602** of FIG. **2**B comprises molecules **603** that may be different material to the molecules **601** of the in-plane polariser **610** and have an orientation so that the absorption axis direction k.sub.e, **622** is normal to the plane of the out-of-plane polariser **602**, that is parallel to the direction {circumflex over (t)} through the thickness of the layer of the out-of-plane polariser **602**.
(232) By way of comparison with FIG. **2**B, in the out-of-plane polariser **602** of FIG. **2**C, the direction of the absorption axis **622** of the out-of-plane polariser **602** is inclined at an acute angle ϕ to the normal **199** orthogonal to the plane of the out-of-plane polariser **602**. The molecules **603** have an orientation so that the absorption axis **622** has a component **622***z* that is in a direction k.sub.ez inclined to the normal **199** to plane of the out-of-plane polariser **602**; and a component **622***p* that is in a direction k.sub.ep in the plane of the out-of-plane polariser **602** and with the orientation θ.
(233) The operation of out-of-plane polariser **602** will now be described.
(234) FIG. **3**A is a schematic diagram illustrating in perspective side view operation of an out-of-plane polariser **602**, a switchable layer **614** of liquid crystal material **615** and an in-plane polariser **610** for light rays **662***a*, **662***b*, **662***c* inclined in lateral and elevation directions for a first mode of operation; and FIG. **3**B is a schematic diagram illustrating in perspective side view operation of an out-of-plane polariser **602**, a switchable layer **614** of liquid crystal material **615** and an in-plane polariser **610** for light rays **662***a*, **662***b*, **662***c* inclined in lateral and elevation directions for a second mode of operation. Features of the embodiments of FIGS. **3**A-B not discussed in further detail may be assumed to correspond to the features with equivalent reference numerals as discussed above, including any potential variations in the features.
(235) FIG. **3**A illustrates light ray **662** propagation with polarisation state **642** from backlight **20** that is incident on a molecule **603** of the out-of-plane polariser **602** of the type illustrated in FIG. **2**B.
(236) Light ray **662***a* from location **660***a* along the normal **199** propagates along the absorption axis

k.sub.e direction **622** of the molecule **603**, and parallel to the transmission axis k.sub.oa, **623***a*, so that substantially no absorption takes place and the light ray **662***a* is transmitted with high luminous flux through the out-of-plane polariser **602**.
(237) The linear polarisation state **639** that is incident on the input of the polarisation switch **601** is the same as the polarisation state **642**.
(238) In the first mode, the polarisation switch **601** is arranged to change the polarisation state **639** of the light passing therethrough from the first linear polarisation state **642** to a second linear polarisation state **640** that is orthogonal to the first linear polarisation state **642**. A first voltage V**1** is applied to the layer **614** of liquid crystal material **603** so that the linear polarisation state **639**, **642** is modified through the layer **614** as will be described further hereinbelow.
(239) In-plane polariser **610** has electric vector transmission direction **611** arranged to transmit linear polarisation state **644**. Light ray **663***a* with modified polarisation state **640** and high luminous flux is transmitted by the in-plane polariser **610** with electric vector transmission direction **611** that has a direction orthogonal to the absorption axis **622** direction k.sub.e.
(240) Light ray **662***c* from location **660***c* is incident on the molecule **603** with polarisation state **642** aligned orthogonally to the absorption axis k.sub.e direction **622** so that substantially no absorption takes place by the molecules **603** of the out-of-plane polariser **602** and the light ray **663***c* is transmitted by the layer **614** of liquid crystal material **603**, polarisation switch **610** and in-plane polariser **610** with high luminous flux.
(241) By comparison with light rays **662***a*, **662***c*, for light ray **662***b* from location **660***b* the polarisation state **642** has a component along the ray **662***b* that is aligned with the absorption axis k.sub.e direction **622** of the molecule **603**. Such alignment provides some absorption at the molecule **603** so that the output ray **663***b* from the out-of-plane polariser **602** has reduced luminous flux. The amount of absorption is determined by the thickness, d, refractive indices n.sub.e, n.sub.o and absorption coefficients α.sub.e(ϕ,θ) α.sub.o(ϕ,θ) of the out-of-plane polariser **602** for polar angle (ϕ, θ), at the angle of incidence of the ray **662***b* for the polarisation state **640**.
(242) Considering the orthogonal polarisation state **640**, in the first mode, light rays **662***a*, **662***b*, **662***c* from the backlight **20** are absorbed by the in-plane polariser **610** from the locations **660***a*, **660***b*, **660***c* across the backlight **20** and so are not illustrated.
(243) By way of comparison with FIG. **3**A, in the second mode as illustrated in FIG. **3**B, the polarisation switch **601** is arranged not to change the polarisation state of the light passing therethrough. FIG. **3**B illustrates light ray **662** propagation with polarisation state **640** from backlight **20**.
(244) Light ray **662***a* from location **660***a* along the normal **199** propagates along the absorption axis k.sub.e direction **622** of the molecule **603**, and parallel to the transmission axis k.sub.oa, **623***a*, so that substantially no absorption takes place and the light ray **662***a* is transmitted with high luminous flux through the out-of-plane polariser **602**.
(245) In the second mode, the polarisation switch **601** is arranged to not change the polarisation state **639**, **640** of the incident light that passes therethrough. A second voltage V**2** is applied to the layer **614** of liquid crystal material **603** so that the linear polarisation state **640** is unmodified through the layer **614**.
(246) Light ray **663***a* with unmodified polarisation state **640** and high luminous flux is transmitted by the in-plane polariser **610**.
(247) Light ray **662***b* from location **660***b* is incident on the molecule **603** with polarisation state **640** aligned orthogonally to the absorption axis k.sub.e direction **622** so that substantially no absorption takes place by the molecules **603** of the out-of-plane polariser **602** and the light ray **663***b* is transmitted by the layer **614** of liquid crystal material **603**, polarisation switch **610** and in-plane polariser **610** with high luminous flux.
(248) By comparison with light rays **662***a*, **662***b*, for light ray **662***c* from location **660***c* the polarisation state **640** has a component along the ray **662***c* that is aligned with the absorption axis

k.sub.e direction **622** of the molecule **603** so that the output ray **663***c* from the out-of-plane polariser **602** has reduced luminous flux.
(249) Considering the orthogonal polarisation state **640**, in the second mode, light rays **662***a*, **662***b*, **662***c* from the backlight **20** are absorbed by the in-plane polariser **610** from the locations **660***a*, **660***b*, **660***c* across the backlight **20** and so are not illustrated.
(250) As will be described in FIGS. **9**A-K hereinbelow, output polarisation states **639** are modified in quadrants, that is in directions that are not along the directions with zero elevation or with zero lateral angle.
(251) The operation of an arrangement with an illustrative polarisation switch **601** will now be further described.
(252) FIG. **4**A is a schematic diagram illustrating in side view an out-of-plane polariser **602**, a twisted nematic liquid crystal polarisation switch **601** and an in-plane polariser **610** in a first mode of operation for an on-axis ray **663***a*; FIG. **4**B is a schematic diagram illustrating the arrangement of FIG. **4**A in edge view; FIG. **4**C is a schematic diagram illustrating in side view an out-of-plane polariser **602**, a twisted nematic liquid crystal polarisation switch **601** and an in-plane polariser **610** in a second mode of operation for an on-axis ray **663***a*; and FIG. **4**D is a schematic diagram illustrating the arrangement of FIG. **4**C in edge view. Features of the embodiments of FIGS. **4**A-D not discussed in further detail may be assumed to correspond to the features with equivalent reference numerals as discussed above, including any potential variations in the features.
(253) By way of comparison with FIG. **3**A, FIGS. **4**A-B illustrate that the polarisation switch **601** comprises a layer **614** of twisted nematic liquid crystal material **615** provided by alignment layers **617**A, **617**B and the first voltage V**1** may be zero volts for example to provide polarisation modification through the layer **614**.
(254) By way of comparison with FIG. **3**B, FIGS. **4**C-D illustrate that the polarisation switch **601** comprises a layer **614** of twisted nematic liquid crystal material **615** provided by alignment layers **617**A, **617**B and the second voltage V**2** may be 5V for example to provide substantially no polarisation modification through the layer **614**.
(255) FIG. **5**A is a schematic diagram illustrating in side view an out-of-plane polariser **602**, a twisted nematic liquid crystal polarisation switch **601** and an in-plane polariser **610** in the first mode of operation for an off-axis ray **663***b*; FIG. **5**B is a schematic graph illustrating a simulated polar variation of transmission output for the arrangement of FIG. **3**A, FIGS. **4**A-B and FIG. **5**A for the illustrative embodiment of TABLE 1; FIG. **5**C is a schematic diagram illustrating in side view an out-of-plane polariser **602**, a twisted nematic liquid crystal polarisation switch **601** and an in-plane polariser **610** in the second mode of operation for an off-axis ray **663***b*; and FIG. **5**D is a schematic graph illustrating a simulated polar variation of transmission output for the arrangement of FIG. **3**B, FIGS. **4**C-D and FIG. **5**C for the illustrative embodiment of TABLE 1. Features of the embodiments of FIGS. **5**A-D not discussed in further detail may be assumed to correspond to the features with equivalent reference numerals as discussed above, including any potential variations in the features.
(256) FIG. **5**A illustrates in top view the propagation of the ray **663***b* of FIG. **3**A, and FIG. **5**C illustrates in top view the propagation of the ray **663***c* of FIG. **3**B.
(257) In the current description, the lateral angle with zero elevation is the angle in a plane that is typically defined as the plane comprising the x-axis and z-axis of the respective figures and is most typically the angle across the horizontal with respect to the frame of reference of the observer **45**. Similarly the elevation angle with zero lateral angle is the angle in a plane that is typically defined as the plane comprising the y-axis and z-axis of the respective figures and is most typically the angle across the vertical with respect to the frame of reference of the observer **45**. Angles with both non-zero elevation and non-zero lateral angle may be referred to as being in the viewing quadrants in the frame of reference of the observer **45**.
(258) FIG. **5**B and FIG. **5**D illustrate the operation for an idealised twisted nematic liquid crystal

mode. In practice, the propagation of the input polarisation state **639** through the layer **614** of liquid crystal material **615** will be modified by non-ideal properties of the optical structure of the layer **614**.
(259) TABLE-US-00001 TABLE 1 Item Property Value Out-of-plane polariser Material 603 ordinary refractive index, {right arrow over (n.sub.o)} at 550 nm 1.506 + 0.00165i 602 Material 603 extraordinary refractive index, {right arrow over (n.sub.e)} at 550 nm 1.53 + 0.116i Thickness, d 5 μm Absorption axis 622 tilt ϕ to surface normal 199 0° Polarisation switch 601 Twist through layer 614 of liquid crystal material 615 90° first mode Polarisation state 639, 642 angle in plane of polarisation switch 0° 601 Polarisation switch 601 Twist through layer 614 of liquid crystal material 615 0° second mode Polarisation state 639, 640 angle in plane of polarisation switch 90° 601 In-plane polariser 610 Absorption axis 620 in-plane angle 0°
(260) FIG. **5**B and FIG. **5**C illustrate the polar locations and transmission of rays **663***a*, **663***b*, **663***c* for the illustrative embodiment of TABLE 1. Considering polar angle of ray **663***a*, the luminance is the same for the first and second modes, that is the luminance is maximised. By comparison, in the arrangement of FIG. **5**B the ray **663***b* has a reduced transmission while the ray **663***c* has substantially unmodified transmission; and in the arrangement of FIG. **5**C the ray **663***c* has a reduced transmission while the ray **663***b* has substantially unmodified transmission.
(261) When arranged with the spatial light modulator **48** of FIG. **1**A for example, the arrangement of FIG. **5**B and FIG. **6**B provide transmission profiles that may achieve switching between landscape and portrait privacy modes of operation, for example in a mobile display device.
(262) FIG. **5**B further illustrates that some regions **761** such as in the viewing quadrants for directions **663***d*, undesirable increased transmission may be provided. As will be described further hereinbelow, additional biaxial retarders **730** may be provided to achieve increased transmission in the region **761**.
(263) It may be desirable to provide improved rotational symmetry of the transmission profile in comparison to the arrangements of FIG. **5**B and FIG. **6**B.
(264) FIG. **6**A is a schematic diagram illustrating in side view an out-of-plane polariser **602**, a twisted nematic liquid crystal polarisation switch **601** and an in-plane polariser **610** in an alternative second mode of operation for an off-axis ray **663***b*; and FIG. **6**B is a schematic graph illustrating a simulated polar variation of transmission output for the arrangement of FIG. **6**A. Features of the embodiments of FIGS. **6**A-B not discussed in further detail may be assumed to correspond to the features with equivalent reference numerals as discussed above, including any potential variations in the features.
(265) In the alternative embodiment illustrated in FIGS. **6**A-B, in the second mode, the polarisation switch **601** is arranged to change the polarisation state **21** of the light passing therethrough differently from the first mode.
(266) For ray **663***b*A, the input polarisation state **639**, **640** is partially absorbed by the out-of-plane polariser **602**. Such polarisation state **640** is converted by the polarisation switch **601** into an elliptical polarisation state **645**A that can be considered a superposition of polarisation state **642**, **640** by the polarisation switch **601** and residual light with polarisation state **644** transmitted by the in-plane polariser **610**.
(267) Further for ray **663***b*B, the polarisation state **642** from the backlight **20** is transmitted by the out-of-plane polariser **602**. Such polarisation state **642** is converted by the polarisation switch **601** into an elliptical polarisation state **645**B that can be considered a superposition of polarisation state **642**, **640** and light with polarisation state **644** transmitted by the in-plane polariser **610**. Such an arrangement may achieve an output similar to that of FIG. **6**B. Advantageously improved rotation symmetry is achieved in the second mode of operation. A share mode of operation may be achieved.
(268) The illustrative embodiments of FIG. **5**B, FIG. **5**D and FIG. **6**B are provided assuming that the polarisation rotation of the polarisation switch **601** is independent of the polar angle. In

practice, some mixed polarisation state **642**, **640** will be provided that vary with viewing angle for a single input polarisation state **642** or **640**. Such polarisation mixing may modify the transmission profiles. The arrangement of the layer **614** of liquid crystal material **615** may be adjusted to optimise the uniformity of polarisation modification with polar angle. Additional passive compensation retarders may further be provided as described elsewhere hereinbelow.

(269) The operation of a switchable privacy display device **100** of FIG. **1**A will now be further described.

(270) FIG. **7**A is a schematic graph illustrating the polar variation of luminance output for a collimated backlight of the type illustrated in FIG. **1**A; FIG. **7**B is a schematic graph illustrating the polar variation of security factor. S for a collimated backlight of the type illustrated in FIG. **1**A modified by the transmission profile of FIG. **6**B for typical illumination conditions; FIG. **7**C is a schematic graph illustrating the polar variation of security factor, S for a collimated backlight of the type illustrated in FIG. **1**A modified by the transmission profile of FIG. **5**B for typical illumination conditions; and FIG. **7**D is a schematic graph illustrating the polar variation of security factor, S for a collimated backlight of the type illustrated in FIG. **1**A modified by the transmission profile of FIG. **5**D for typical illumination conditions, wherein the thickness of the out-of-plane polariser **602** is 10 μm for the material **603** of TABLE 1. Features of the embodiments of FIGS. **7**A-D not discussed in further detail may be assumed to correspond to the features with equivalent reference numerals as discussed above, including any potential variations in the features.

(271) FIG. **7**B illustrates a share mode of operation and provides a display device **100** with images that are visible (security factor $S<1$) over a wide polar region.

(272) FIG. **7**C illustrates a privacy mode of operation of the display of FIG. **1**A, wherein the display is not visible to viewers to the left and right of the nominal on-axis user direction **445**; while FIG. **7**D illustrates a privacy mode of operation of the display of FIG. **1**A, wherein the display is not visible to viewers above or below the nominal on-axis user direction **445** for the same display orientation as in FIG. **7**C. Alternatively, the arrangement of FIG. **7**D may be provided when the display of FIG. **7**C is rotated through 90 degrees. For example, a cell phone may operate with the security factor profile of FIG. **7**C when held in portrait mode and may operate with the security factor profile of FIG. **7**D when held in landscape mode. Advantageously landscape and portrait privacy operation may be achieved.

(273) Alternative simulations of a twisted nematic polarisation switch will now be described.

(274) FIG. **7**E is a schematic graph illustrating the polar variation of transmission output for the illustrative embodiment of TABLE 2 in a first driven state; FIG. **7**F is a schematic graph illustrating the polar variation of transmission output for the illustrative embodiment of TABLE 2 in a second driven state; and FIG. **7**G is a schematic graph illustrating the polar variation of transmission output for the illustrative embodiment of TABLE 2 in a third driven state.

(275) By way of comparison with the simulations of FIG. **5**B, FIG. **6**B and FIG. **5**D, the simulated results of FIG. **7**E, FIG. **7**F and FIG. **7**G are provided with a more complete description of the alignment of molecules **615** in the liquid crystal layer **614** through the thickness of the layer **614**, including pretilt and residual retardance near to the alignment layers **619**A, **619**B and splay in intermediate twisted states. As can be seen in FIG. **7**F, such non-ideal alignments provide asymmetry in output particularly in share mode operation.

(276) TABLE-US-00002 TABLE 2 Item Value Out-of-plane polariser Material 603 ordinary refractive index, {right arrow over (n.sub.o)} at 550 nm 1.506 + 0.00165i 602 Material 603 extraordinary refractive index, {right arrow over (n.sub.e)} at 550 nm 1.53 + 0.116i Thickness, d 6 μm Absorption axis 622 tilt ϕ to surface normal 199 0° Polarisation switch 601 Layer 614 of liquid crystal material 615 retardance 1500 nm Layer 614 of liquid crystal material 615 in-plane alignment 90° direction, 619Ap angle θ Layer 614 of liquid crystal material 615 in-plane alignment 0° direction, 619Bp angle θ Privacy mode voltage 15 V, FIG. 7E Share mode voltage 3 V, FIG. 7F Rotated privacy mode voltage 0 V, FIG. 7G In-plane polariser 610 Absorption axis 620

in-plane angle 90°
(277) Alternative arrangements of polarisation switch **601** will now be described.
(278) FIG. **8**A is a schematic diagram illustrating in perspective side view a polarisation switch comprising a passive retarder operating in a first mode; FIG. **8**B is a schematic diagram illustrating in perspective side view a polarisation switch comprising a passive retarder operating in a second mode. Features of the embodiments of FIGS. **8**A-B not discussed in further detail may be assumed to correspond to the features with equivalent reference numerals as discussed above, including any potential variations in the features.
(279) The alignment layers **617**A, **617**B of the layer **614** of liquid crystal material **615** provide alignment directions **619**A, **619**B with in-plane components **619**Ap, **619**Bp and out-of-plane components **619**At, **619**Bt respectively.
(280) By way of comparison with the twisted nematic embodiments hereinabove, the polarisation switch **601** of FIG. **8**A may provide a quarter waveplate in one of the modes of operation. Said quarter waveplate provides a circular output polarisation state **22** from the linear input polarisation state **21**. Such an arrangement conveniently provides output equivalent to comprising some light with the profile similar to FIG. **5**B and some light with the output of FIG. **5**D.
(281) In the second mode of operation, the polarisation switch **601** may provide no modification of the polarisation state **21**.
(282) It may be desirable to improve the switching properties of the polarisation switch **601**. In an alternative embodiment, the polarisation switch **601** may further comprise at least one passive retarder **630** that is arranged to provide improved control of the switched polarisation states **21**, **22**. The passive retarder **630** and layer **614** of liquid crystal material **615** may for example comprise a Pancharatnam stack to advantageously achieve improved chromaticity of the switched polarisation state **22**.
(283) FIG. **8**C is a schematic graph illustrating the polar variation of luminance transmission for the arrangement of FIG. **8**A provided between an out-of-plane polariser and an in-plane polariser operating in the first mode and as described in TABLE 3; and FIG. **8**D is a schematic graph illustrating the polar variation of luminance transmission for the arrangement of FIG. **8**B provided between an out-of-plane polariser and an in-plane polariser operating in the first mode and as described in TABLE 3. Features of the embodiments of FIGS. **8**C-D not discussed in further detail may be assumed to correspond to the features with equivalent reference numerals as discussed above, including any potential variations in the features.
(284) TABLE-US-00003 TABLE 3 Item Value Out-of-plane polariser Material 603 ordinary refractive index, {right arrow over (n.sub.o)} at 550 nm 1.506 + 0.00165i 602 Material 603 extraordinary refractive index, {right arrow over (n.sub.e)} at 550 nm 1.53 + 0.116i   Thickness, d 6 μm Absorption axis 622 tilt ϕ to surface normal 199 0° Polarisation switch 601 Layer 614 of liquid crystal material 615 retardance 140 nm Layer 614 of liquid crystal material 615 in-plane alignment 135°   direction, 619Ap angle θ Layer 614 of liquid crystal material 615 in-plane alignment 315°   direction, 619Bp angle θ Privacy mode voltage 0 V Share mode voltage 8 V Passive retarder 630 Not used In-plane polariser 610 Absorption axis 620 in-plane angle 0°
(285) By way of comparison with FIG. **6**B, improved rotational symmetry is achieved in share mode as illustrated in FIG. **8**C. Further in privacy mode as illustrated in FIG. **8**D, the luminance in look-down directions **663***c* is also reduced to achieve improved privacy.
(286) It may be desirable to reduce luminance in the quadrant regions **761** in privacy mode of operation.
(287) FIG. **9**A is a schematic diagram illustrating in perspective side view a polarisation switch **601** arranged between an in-plane polariser that is in-plane polariser **610**, a biaxial retarder arrangement **730** comprising biaxial material **731** and an out-of-plane polariser **602**. Features of the embodiment of FIG. **9**A not discussed in further detail may be assumed to correspond to the features with equivalent reference numerals as discussed above, including any potential variations in the features.

(288) By way of comparison with FIG. **5**A, the optical stack comprising biaxial retarder arrangement **730** of FIG. **9**A comprises a B-plate with biaxial molecules **731** that provide off-axis retardation properties for input polarisation state **639** of FIGS. **3**A-B in the viewing quadrants.
(289) Alternative embodiments of biaxial retarder arrangement **730** will now be described.
(290) FIG. **9**B is a schematic diagram illustrating in perspective front view, an alternative biaxial retarder arrangement **730** comprising an A-plate and a negative C-plate; and FIG. **9**C is a schematic diagram illustrating in perspective front view, an alternative biaxial retarder arrangement comprising an A-plate and a positive C-plate. Features of the embodiments of FIGS. **9**B-C not discussed in further detail may be assumed to correspond to the features with equivalent reference numerals as discussed above, including any potential variations in the features.
(291) By way of comparison with FIG. **9**A, in the alternative embodiment of FIG. **9**B, the biaxial retarder arrangement **730** comprises a negative C-plate **736** comprising birefringent material **737** arranged to receive the light from an A-plate **734** comprising birefringent material **735** with optical axis direction aligned to the vertical direction or y-axis; that is the extraordinary index n.sub.e is the same as the index ny. Negative C-plates may be more conveniently manufactured at low cost than positive C-plates.
(292) By way of comparison with FIG. **9**B, in the alternative embodiment of FIG. **9**C, the biaxial retarder arrangement **730** comprises a positive C-plate **738** comprising birefringent material **739** arranged to receive the light from an A-plate **734** comprising birefringent material **735** with optical axis direction aligned to the horizontal direction or x-axis; that is the extraordinary index n.sub.e is the same as the index ny. Positive C-plate **738** may be provided by a coating manufacturing method, achieving reduced thickness.
(293) The complexity of manufacture of the A-plate **735** and C-plates **736**, **738** may be reduced compared to the B-plate **732** of FIG. **9**A, advantageously achieving reduced cost.
(294) The operation of the biaxial retarder arrangement **730** will now be described further.
(295) FIG. **9**D is a schematic diagram illustrating in perspective top view an out-of-plane polariser; FIG. **9**E is a schematic diagram illustrating in perspective left side view an out-of-plane polariser; and FIG. **9**F is a schematic diagram illustrating in perspective upper left quadrant view an out-of-plane polariser. Features of the embodiments of FIGS. **9**D-F not discussed in further detail may be assumed to correspond to the features with equivalent reference numerals as discussed above, including any potential variations in the features.
(296) In operation, the out-of-plane polariser **602** with absorption axis k.sub.e **622** provides absorption of the incident unpolarised transmitted polarisation state without output polarisation state **639** that varies with viewing direction **663**, such as polarisation states **639**(T) for the top look-down direction **663***c*, **639**(L) for the left side viewing direction **663***b* and **639**(TL) for the left side top quadrant viewing direction **663***d*.
(297) FIG. **9**G is a schematic graph illustrating a polar variation of output polarisation state **639** from an out-of-plane polariser **602** without a biaxial retarder arrangement **730**; and FIG. **9**H is a schematic graph illustrating a polar variation of output polarisation state **639** from an out-of-plane polariser **602** arranged with a desirable biaxial retarder arrangement **730**, for example as illustrated in FIG. **9**A. Features of the embodiments of FIGS. **9**G-H not discussed in further detail may be assumed to correspond to the features with equivalent reference numerals as discussed above, including any potential variations in the features.
(298) FIG. **9**G illustrates that in the region **761**, the polarisation state **639**(TL) is rotated with respect to the polarisation state **639**(L), providing the increased transmission of FIG. **7**B.
(299) It would be desirable to reduce the transmission in the region **761** by modifying the polarisation state **639**(TL) and not substantially modifying the polarisation states **639**(L) and **639**(T) such as is illustrated in FIG. **9**H.
(300) FIG. **9**I is a schematic diagram illustrating in perspective top view propagation of a polarisation state **639** (*t*) through an out-of-plane polariser **602** and a biaxial retarder arrangement

730; FIG. **9**J is a schematic diagram illustrating in perspective left side view propagation of a polarisation state **639**(L) through an out-of-plane polariser **602** and a biaxial retarder arrangement **730**; and FIG. **9**K is a schematic diagram illustrating in perspective upper left quadrant view propagation of a polarisation state **639**(TL) through an out-of-plane polariser **602** and a biaxial retarder arrangement **730**. Features of the embodiments of FIGS. **9**I-K not discussed in further detail may be assumed to correspond to the features with equivalent reference numerals as discussed above, including any potential variations in the features.

(301) FIGS. **9**B-C illustrate that the biaxial retarder arrangement **730** may be formed as a C-plate arranged to receive the light from an A-plate. Principal axes nx, ny, nz components of the A-plate and C-plate are aligned with the orthogonal x, y and z system axes and preserve polarization in the lateral viewing direction (for zero elevation angle) and elevation viewing directions (for zero lateral angle) so that no modification of polarisation states **639**(T) and **639**(L) is achieved, as illustrated in FIGS. **9**I-K for the directions **663***c*, **663***b* respectively where the polarisation states **639**(T) A, **639**(T) B and **639**(T) C are the same and the polarisation states **639**(L) A, **639**(L) B and **639**(L) C are the same.

(302) By comparison, in the viewing quadrant direction **663***d* as illustrated in FIG. **9**I, the biaxial retarder **730** may be provided to provide rotation of polarisation state **639**A at a desirable angle, such as illustrated by direction **663***d* in FIG. **10**A hereinbelow. Such embodiments of biaxial retarder arrangement may achieve the desirable polarisation state **639** profiles of FIG. **9**H.

(303) Illustrative embodiments of transmission profile for the arrangement of FIG. **9**A will now be described.

(304) FIG. **10**A is a schematic graph illustrating a polar variation of transmission for the arrangement of FIG. **9**A comprising the arrangement of TABLE 4 and the polarisation switch of TABLE 6 for operation in the privacy mode; and FIG. **10**B is a schematic graph illustrating a polar variation of transmission for the arrangement of FIG. **9**A comprising the arrangement of TABLE 4 and the polarisation switch of TABLE 6 in the share mode. Features of the embodiments of FIGS. **10**A-B not discussed in further detail may be assumed to correspond to the features with equivalent reference numerals as discussed above, including any potential variations in the features.

(305) TABLE 4 illustrates a biaxial retarder arrangement **730** comprising a B-plate arranged between an out-of-plane polariser **602** and an in-plane polariser **610**.

(306) TABLE-US-00004 TABLE 4 Item Property Value (Range) Out-of-plane polariser 602 Material 751 ordinary refractive index, {right arrow over (n.sub.o)} 1.506 + 0.00165i Material 751 extraordinary refractive index, {right arrow over (n.sub.e)} 1.53 + 0.116i Thickness, d 5 μm Absorption axis 622 tilt ϕ to surface normal 199 0° Biaxial retarder Refractive index profile ny > nx > nz arrangement 730 (nx − ny)d −150 nm comprising B-plate 732 (−130 nm to −170 nm) (nx − nz)d +300 nm (+270 nm to +330 nm) Rth +370 nm (+340 nm to +400 nm) nx alignment 0° in plane ny alignment 90° in plane nz alignment 90° out of plane In-plane polariser 610 Absorption axis 620 in-plane angle 0°

(307) In other words, the biaxial retarder arrangement **730** may comprise a B-plate **732**. The B-plate **732** may comprise material **731** with principal components of refractive index nx, ny, nz and a thickness d, and wherein for light at a wavelength of 550 nm: the value of (nx−ny)d is in a range between −130 nm and −170 nm, the value of (nx−nz)d is in a range between +270 nm and +330 nm, and the value of a parameter Rth is in a range between +340 nm and +400 nm, wherein Rth=(nx+ny)/2−nz)d. A low thickness component may be provided that may be formed with low cost, for example by double stretching.

(308) By way of comparison with FIG. **5**B, the alternative embodiment of FIG. **10**A illustrates that luminance is reduced in the quadrant regions such as regions **761** of FIG. **10**A by means of the biaxial retarder arrangement **730**. Advantageously the size of the region for which security factor, S≥1 may be increased.

(309) Alternative biaxial retarder arrangements **730** will now be further described. In an alternative

arrangement of B-plate, a negative Rth may be provided, and the B-plate is rotated by 90 degrees so that the values of nx and ny are reversed compared to the embodiment of TABLE 4. The embodiment of TABLE 4 is more conveniently provided by double stretching, in comparison to said alternative arrangement.

(310) TABLE 5A provides illustrative arrangements for the embodiment of FIG. **9**B to achieve the equivalent transmission profile of FIG. **10**A.

(311) TABLE-US-00005 TABLE 5A Item Property Value (Range) Biaxial retarder A-plate 734 (ne − no)d +100 nm arrangement 730 (+85 nm to +115 nm) ne alignment 90° in plane Negative (ne − no)d −220 nm C-plate 737 (−190 nm to −250 nm) ne alignment 90° out of plane

(312) The biaxial retarder arrangement **730** may comprise a C-plate **736** arranged to receive the light output from an A-plate **734**. For light at a wavelength of 550 nm the A-plate **734** has a retardance in a range between +85 nm and +115 nm, and the C-plate **736** is a negative C-plate with a retardance in a range between −190 nm and −250 nm. The complexity of manufacture of the retarders **734**, **736** may be reduced, achieving reduced cost.

(313) TABLE 5B provides illustrative arrangements for the embodiment of FIG. **9**C to achieve the equivalent transmission profile of FIG. **10**A.

(314) TABLE-US-00006 TABLE 5B Item Property Value (Range) Biaxial retarder A-plate 734 (ne − no)d +100 nm arrangement 730 (+85 nm to +115 nm) ne alignment 0° in plane Positive (ne − no)d +250 nm C-plate 738 (+220 nm to +280 nm) ne alignment 90° out of plane

(315) For light at a wavelength of 550 nm the A-plate **734** has a retardance in a range between +85 nm and +115 nm, and the positive C-plate **738** has a retardance in a range between +220 nm and +280 nm. The thickness of the positive C-plate **738** may be reduced compared to the thickness of the negative C-plate **736**, for example by providing cured reactive mesogen layers on the A-plate **734**.

(316) It will be appreciated that the combination of values provided in TABLE 4 and TABLES 5A-B represent particularly beneficial or advantageous embodiments because in privacy mode the luminance in the viewing quadrants such as region **761** of the display device **100** may be reduced as shown in FIG. **10**A in comparison to alternative combinations of values and advantageously image security improved.

(317) In operation, the angular variation of output polarisation state of the out-of-plane polariser **750** of FIG. **9**G may be modified by the means of the biaxial retarder arrangement **730** with said combination of values to achieve the angular variation of output polarisation state of FIG. **9**H, which provides said reduction of luminance in region **761**.

(318) An illustrative embodiment for the liquid crystal polarisation switch layer **614** driven by driver **650** is given in TABLE 6 for a third minimum cell design to advantageously achieve low chromatic variation of polarisation state switching.

(319) TABLE-US-00007 TABLE 6 LC polarisation switch layer 614 Alignment layers Alignment Pretilt/ Δn .Math. d/ Voltage/ Mode 617A, 617B direction deg nm Twist Δε V Share Homogeneous 90° 2 168 90° +13.2 V.sub.614S: 5.0 Privacy Homogeneous 180° 2 V.sub.614P: 0.0

(320) FIG. **10**C is a schematic diagram illustrating in perspective front view a polarisation switch comprising a vertically aligned polarisation switch layer with privacy and share mode regions; and FIG. **10**D is a schematic graph illustrating a polar variation of transmission for the out-of-plane polariser **602** and the biaxial retarder **730** of TABLE 4, and the polarisation switch **601** of FIG. **10**C and TABLE 7 in the share region of the display device that in FIG. **10**C is the region **626***b*. Features of the embodiments of FIGS. **10**C-D not discussed in further detail may be assumed to correspond to the features with equivalent reference numerals as discussed above, including any potential variations in the features.

(321) By way of comparison with TABLE 6, the polarisation switch layer **601** of FIG. **10**C and TABLE 7 may provide a switchable half waveplate to provide polarisation state **902** rotation to output polarisation state **904**. The regions **626***a*, **626***b* may be provided by patterning of the

electrode **619***a* or alternatively by patterning of electrode **619***b*.
(322) TABLE-US-00008 TABLE 7 LC polarisation switch layer 614 Alignment layers Alignment Pretilt/ Δn .Math. d/ Voltage/ Mode 617A, 617B direction deg nm Twist Δε V Share Homeotropic 45° 88 312 0° +10.3 V.sub.614S: 7.0 Privacy Homeotropic 225° 88 V.sub.614P: 0
(323) Patterning of share and privacy mode regions is provided by a gap between electrodes **619**Aa and **619**Ab. The profile of transmission in privacy mode in region **626***a* is substantially the same as for FIG. **10**A wherein in each case, the incident polarisation state **639** is substantially unmodified by the polarisation switch **601**. By way of comparison with FIG. **10**B, FIG. **10**D illustrates that improved transmission may be achieved in the lateral direction in share mode operation.
(324) Alternative arrangements of optical stacks will now be described.
(325) FIGS. **11**A-E are schematic diagrams illustrating in top view various alternative structures of optical stacks for display device **100** comprising at least one biaxial retarder **730**. Features of the embodiments of FIGS. **11**A-E not discussed in further detail may be assumed to correspond to the features with equivalent reference numerals as discussed above, including any potential variations in the features.
(326) In the non-exhaustive optical stack embodiments of FIGS. **11**A-E, at least one of the biaxial retarders **732** may be provided by the alternative embodiments illustrated in FIGS. **9**B-C.
(327) By way of comparison with FIG. **9**A, the alternative embodiment of FIG. **11**A illustrates that the biaxial retarder arrangement **730** may comprise first and second biaxial retarders **732**A, **732**B.
(328) By way of comparison with FIG. **11**A the alternative embodiment of FIG. **11**B illustrates that the biaxial retarders **732**AA, **732**B may be arranged on opposite sides of the polarisation switch **601**. Improved correction of chromaticity with viewing direction **663***d* may be achieved.
(329) By comparison with the embodiments hereinabove, the alternative embodiments of FIGS. **11**C-E comprise a further out-of-plane polariser **745** arranged between the polarisation switch **600** and the in-plane polariser **610**. The transmission profile of the display device may have a non-switchable additional transmission profile of FIG. **10**A. Off-axis luminance in privacy mode may be further reduced in comparison to the illustrative embodiments described hereinabove. Advantageously security factor may be further improved.
(330) FIG. **12**A is a schematic diagram illustrating in a cross sectional view across the z-W plane an out-of-plane polariser **602** of the type illustrated in FIG. **2**C, a liquid crystal polarisation switch and a display polariser in an alternative second mode of operation for two off-axis rays; and FIG. **12**B is a schematic graph illustrating the polar variation of luminance output for the structure illustrated in FIG. **12**A and TABLE 8 where the W-axis is the y-axis, that is the arrangement of FIG. **12**A is the side view of the out-of-plane polariser **602**. Features of the embodiments of FIGS. **12**A-B not discussed in further detail may be assumed to correspond to the features with equivalent reference numerals as discussed above, including any potential variations in the features.
(331) TABLE-US-00009 TABLE 8 Item Property Value Out-of-plane Material 603 ordinary refractive index, 1.506 + 0.00165i polariser 602 {right arrow over (n.sub.o)} at 550 nm Material 603 extraordinary refractive 1.53 + 0.116i index, {right arrow over (n.sub.e)} at 550 nm Thickness, d 10 μm Absorption axis 622 tilt ϕ to surface 20° normal 199 Absorption axis 622 azimuthal angle θ 90° In-plane Absorption axis 620 in-plane angle 0° polariser 610
(332) In comparison to FIG. **5**A, FIG. **12**A illustrates in operation, for lateral angles different to the on-axis direction, the ray **664***a* has higher transmission than the ray **664***b*, and asymmetric transmission profile is achieved. In the display of FIG. **1**A, advantageously reduced luminance may be achieved for desirable look-down directions.
(333) It may be desirable to provide off-axis operation in the lateral direction.
(334) FIG. **12**C is a schematic graph illustrating the polar variation of transmission for the structure illustrated in FIG. **12**A wherein the absorption axis **322** is tilted in the lateral direction and TABLE 9 in a first mode of operation; FIG. **12**D is a schematic graph illustrating the polar variation of transmission for the arrangement of FIG. **12**C in the second mode of operation; and FIG. **12**E is a

schematic graph illustrating the polar variation of transmission for the arrangement of FIG. **12**C in the third, mixed mode of operation and as illustrated in TABLE 9. Features of the embodiments of FIGS. **12**C-E not discussed in further detail may be assumed to correspond to the features with equivalent reference numerals as discussed above, including any potential variations in the features.
(335) Considering the arrangement of FIG. **12**A, in the alternative embodiments of FIGS. **12**C-E, the W-axis is the x-axis and FIG. **12**A is a top view of the out-of-plane polariser **602**. By way of comparison with FIG. **12**B, FIG. **12**C illustrates that the direction of the maximum luminance is offset from the normal to the out-of-plane polariser **602**. Further, FIG. **12**E has a share mode maximum luminance that is similarly offset from the normal direction.
(336) TABLE-US-00010 TABLE 9 Item Property Value Out-of-plane Material 603 ordinary refractive index, 1.506 + 0.00165i polariser 602 {right arrow over (n.sub.o)} at 550 nm Material 603 extraordinary refractive 1.53 + 0.116i index, {right arrow over (n.sub.e)} at 550 nm Thickness, d 7 μm Absorption axis 622 tilt ϕ to surface 10° normal 199 Absorption axis 622 azimuthal angle θ 0° In-plane Absorption axis 620 in-plane angle 0° polariser 610
(337) FIG. **12**F is a schematic graph illustrating the polar variation of transmission for a collimated backlight of the type illustrated in FIG. **12**A wherein the absorption axis **322** is tilted and rotated on an axis inclined to the lateral and elevation directions and TABLE 10 in a first mode of operation. Features of the embodiment of FIG. **12**F not discussed in further detail may be assumed to correspond to the features with equivalent reference numerals as discussed above, including any potential variations in the features.
(338) Considering the arrangement of FIG. **12**A, in the alternative embodiments of FIG. **12**F, the W-axis is a bisector of the x-axis and y-axis and FIG. **12**A is an inclined top-side view of the out-of-plane polariser **602**.
(339) TABLE-US-00011 TABLE 10 Item Property Value Out-of-plane Material 603 ordinary refractive index, 1.506 + 0.00165i polariser 602 {right arrow over (n.sub.o)} at 550 nm Material 603 extraordinary refractive 1.53 + 0.116i index, {right arrow over (n.sub.e)} at 550 nm Thickness, d 7 μm Absorption axis 622 tilt ϕ to surface 15° normal 199 Absorption axis 622 azimuthal angle θ 45° In-plane Absorption axis 620 in-plane angle 0° polariser 610
(340) Embodiments comprising the off-axis profiles of FIGS. **12**B-F will now be further described.
(341) FIG. **13** is a schematic diagram illustrating in top view a vehicle **950** comprising a passenger infotainment display device **100**. Features of the embodiment of FIG. **13** not discussed in further detail may be assumed to correspond to the features with equivalent reference numerals as discussed above, including any potential variations in the features.
(342) Polar control display device **100** is arranged to provide images to passenger **45** in nominal viewing direction **445**, while preventing driver **47** in nominal direction **447**, but with viewing freedom between angles t and v from the normal **199**. It is desirable to provide passenger **45** with high image visibility and driver **47** with high image security, by means of luminance reduction to the driver **47**. It is desirable to provide reduced luminance in the direction **447** to maximise security factor. FIG. **12**C illustrates that the off-axis distribution of light transmission may be advantageously provided to improve the security factor S to the driver **47**.
(343) It may be desirable to improve the luminance uniformity of a privacy display device.
(344) FIG. **14**A is a schematic diagram illustrating in top view a polar angle control display device **100** wherein the direction k.sub.e of the absorption axis **622** tilt ϕ to surface normal **199** is the same across the display device **100**. Features of the embodiment of FIG. **14**A not discussed in further detail may be assumed to correspond to the features with equivalent reference numerals as discussed above, including any potential variations in the features.
(345) The embodiment of FIG. **14**A illustrates that the display may provide the same direction of light cones **461**R, **461**C, **461**L from the backlight and the same transmission profiles **465**R, **465**C, **465**L across the area **613** of the polar control display device **100**. The out-of-plane polariser **602** may be provided with uniform alignment, advantageously reducing manufacturing cost and

complexity.
(346) In operation, the user or passenger **45** sees an image with different luminances from different locations across the area **613** of the display device **100**. Undesirably image uniformity is degraded. Further, for a snooper or driver **47** then the uniformity of security factor is reduced so that some parts of the display device **100** may become undesirably visible.
(347) FIG. **14**B is a schematic diagram illustrating in top view a display device **100** comprising an out-of-plane polariser **602** wherein the direction k.sub.e of the absorption axis **622** tilt ø to surface normal **199** changes monotonically along a predetermined axis across the out-of-plane polariser **602**. Features of the embodiment of FIG. **14**B not discussed in further detail may be assumed to correspond to the features with equivalent reference numerals as discussed above, including any potential variations in the features.
(348) The direction of the absorption axis **622** of the out-of-plane polariser **602** changes monotonically along a predetermined axis across the display device **100**.
(349) Further, as illustrated in FIG. **12**F, the direction of the absorption axis **622** of the out-of-plane polariser **602** may change across more than one predetermined axis so that the tilt and rotation angles [$\phi(x, y)$, $\theta(x, y)$] vary with location across the area **613** of the display device **100**.
(350) In operation, the direction of maximum luminance also varies across the are **613** of the display device **100**. Light rays **664***a*L, **664***a*C, **664***a*R are directed towards the user **45** with high luminance, while light rays **664***b*L, **664***b*C, **664***b*R with reduced luminance. Advantageously in comparison to the embodiment of FIG. **14**A, luminance uniformity is improved for the user **45** and uniformity of security factor is improved for the snooper **47**.
(351) FIG. **14**C is a schematic diagram illustrating in top view a polar angle control display device **100** wherein the direction k.sub.e of the absorption axis **622** tilt ø to surface normal **199** changes monotonically along a predetermined axis across the display device **100** for an off-axis viewing direction. Features of the embodiment of FIG. **14**C not discussed in further detail may be assumed to correspond to the features with equivalent reference numerals as discussed above, including any potential variations in the features.
(352) By way of comparison with FIG. **14**A, the display device **100** is curved with a concave curvature as viewed from an output side of the display device **100**. The curvature provides a variation in the direction **199** with location across the display and may provide that the rays **664***a*R. **664***a*C, **664***a*L may be directed towards the observer **45** with high transmission to advantageously achieve improved image uniformity; and the rays **664***b*R, **664***b*C, **664***b*L may be directed towards the snooper **47** with low transmission to advantageously achieve improved uniformity of security factor.
(353) Further the direction of the absorption axis **622** of the out-of-plane polariser **602** changes monotonically along a predetermined axis which may be the lateral axis across the display device **100** to further improve the display uniformity.
(354) Alternative arrangements of polar angle control display device **100** will now be described.
(355) FIG. **15**A is a schematic diagram illustrating in perspective side view a polar angle control display device **100** comprising a backlight **20**, a transmissive spatial light modulator **48**, an in-plane polariser **610** that is the output polariser **218** of the spatial light modulator **48**, a polarisation switch **601** and an out-of-plane polariser **602**. Features of the embodiment of FIG. **15**A not discussed in further detail may be assumed to correspond to the features with equivalent reference numerals as discussed above, including any potential variations in the features.
(356) By way of comparison with FIG. **1**A, in the alternative embodiment of FIG. **15**A, the transmissive spatial light modulator **48** comprises an input polariser **210** and an output polariser **218**, and the output polariser **218** is the in-plane polariser **610** and said side of the spatial light modulator **48** is an output side of the spatial light modulator **48**. In other words, the spatial light modulator **48** comprises an output polariser **218**, and the output polariser **218** is the in-plane polariser **610**.

(357) The polarisation switch **601** and out-of-plane polariser **602** may be provided as a separate component and may be conveniently added to the front of an existing spatial light modulator **48** to provide a user mounted switchable privacy display function. Alternatively or additionally, a touch screen control arrangement may be provided on or in the polarisation switch **601** such as described in U.S. Pat. No. 10,802,356, which is herein incorporated by reference in its entirety. Advantageously cost may be reduced.
(358) FIG. **15**B is a schematic diagram illustrating in perspective side view a polar angle control display device **100** comprising a backlight **20**, an out-of-plane polariser **602**, a polarisation switch **601**, an in-plane polariser **610** that is the input polariser of a spatial light modulator **48**, a further in-plane polariser **610** that is the output polariser **218** of the spatial light modulator **48**, a further polarisation switch **601** and a further out-of-plane polariser **602**; and FIG. **15**C is a schematic graph illustrating the polar variation of transmission for a collimated backlight of the type illustrated in FIG. **15**B and comprising the arrangement of TABLE 11, in which the polarisation switch **601**A and polarisation switch **601**B are provided as for TABLE 1. Features of the embodiment of FIGS. **15**B-C not discussed in further detail may be assumed to correspond to the features with equivalent reference numerals as discussed above, including any potential variations in the features.
(359) By way of comparison with FIG. **1**A, the alternative embodiment of FIG. **15**B illustrates that the transmissive spatial light modulator **48** comprises an out-of-plane polariser **602**A and a polarisation switch **601**A with driver **650**A arranged on the input side of the in-plane polariser **610** that is the input polariser **210**, and further comprises a further in-plane polariser **610**B that is the output polariser **218**, a further polarisation switch **601**B with driver **650**B (that may alternatively be the same driver as the driver **650**A) and a further out-of-plane polariser **602**B on the output side of the further polarisation switch **601**B. By way of comparison with FIG. **1**A or FIG. **15**A, additional functionality may be provided, for example as illustrated in FIG. **15**C wherein the first and second in-plane polarisers are crossed.
(360) TABLE-US-00012 TABLE 11 Item Value Out-of-plane polariser Material 603 ordinary refractive index, {right arrow over (n.sub.o)} at 550 nm 1.506 + 0.00165i 602A Material 603 extraordinary refractive index, {right arrow over (n.sub.e)} at 550 nm 1.53 + 0.116i Thickness, d 7 μm Absorption axis 622 tilt ϕ to surface normal 199 0° In-plane polariser 610A Absorption axis 620 in-plane angle 0° Out-of-plane polariser Material 603 ordinary refractive index, {right arrow over (n.sub.o)} at 550 nm 1.506 + 0.00165i 602B Material 603 extraordinary refractive index, {right arrow over (n.sub.e)} at 550 nm 1.53 + 0.116i Thickness, d 7 μm Absorption axis 622 tilt ϕ to surface normal 199 0° In-plane polariser 610B Absorption axis 620 in-plane angle 90°
(361) Advantageously improved privacy performance may be achieved in landscape and portrait modes of operation.
(362) It may be desirable to provide alternative profiles of light suppression in privacy mode of operation.
(363) FIG. **16**A is a schematic diagram illustrating in perspective side view a polar angle control display device **100** comprising a backlight **20**, an additional polariser, a polar control retarder **300** comprising a layer **314** of liquid crystal material **315** and a passive compensation retarder **330**, an input polariser **210** of the transmissive spatial light modulator **48**, an in-plane polariser **610** that is the output polariser **218** of a spatial light modulator **48**, a polarisation switch **601** and an out-of-plane polariser **602**. Features of the embodiment of FIG. **16**A not discussed in further detail may be assumed to correspond to the features with equivalent reference numerals as discussed above, including any potential variations in the features.
(364) In other words, the out-of-plane polariser **602** is arranged on a side of the spatial light modulator **48** that is the output side of the spatial light modulator **48** and the spatial light modulator **48** comprises an output polariser **218**. The output polariser **218** is the in-plane polariser **610**.
(365) By way of comparison with FIG. **15**A, in the alternative embodiment of FIG. **16**A the polar control retarder **300** and additional polariser **318** are arranged between the backlight **20** and in-

plane polariser **310** that is the input polariser **210** of the spatial light modulator **48**. The in-plane polariser **310** illustrated herein provides a different operation of the display to the display polariser **610** described hereinabove. Polar control retarder **300** is arranged to provide variation of transmission with polar angle when provided between in-plane polariser **310** and additional polariser **318**, that is also an in-plane polariser and as illustrated in FIGS. **29**A-B and FIGS. **30**A-D hereinbelow.
(366) Polar control retarders **300** are described in U.S. Pat. No. 11,092,851, 10,976,578, 10,802,356, 11,099,448, 11,340,482, 11,892,717, and U.S. patent application Ser. No. 18/609,272, all of which are herein incorporated by reference in their entireties. Polar control retarders **300** are further described in FIG. **29**A and FIGS. **30**A-B hereinbelow.
(367) By way of comparison with FIG. **15**A, advantageously improved control of light suppression may be achieved in privacy mode and alternative polar regions may be provided with improved security factor.
(368) FIG. **16**B is a schematic diagram illustrating in perspective side view a polar angle control display device **100** comprising a backlight **20**, a spatial light modulator **48** comprising an input polariser **210** and an output polariser **218**, a polar control retarder **300** comprising a layer **314** of liquid crystal material **315** and a passive compensation retarder **330**, an additional polariser **318** that is an in-plane polariser **610**, a polarisation switch **601** and an out-of-plane polariser **602**. Features of the embodiment of FIG. **16**B not discussed in further detail may be assumed to correspond to the features with equivalent reference numerals as discussed above, including any potential variations in the features.
(369) The alternative embodiment of FIG. **16**B illustrates that the in-plane polariser **610** is a different component from the output polariser **218**. The polar angle control display device **100** further comprises: an additional polariser **318** arranged on the output side of the output polariser **218**; and at least one polar control retarder **300** arranged between the output polariser **218** and the additional polariser **318** wherein the additional polariser **318** is the in-plane polariser **610**.
(370) By way of comparison with FIG. **16**A, the alternative embodiment of FIG. **16**B comprises components polar control retarder **300** and polar transmission control arrangement **600** that are provided on the output side of the spatial light modulator **48**. A polar angle control display device **100** may be conveniently provided with switchable privacy after manufacture of the spatial light modulator **48**, for example by user fitting.
(371) FIG. **16**C is a schematic diagram illustrating in perspective side view a polar angle control display device **100** comprising a backlight **20**, an out-of-plane polariser **602**, a polarisation switch **601**, an in-plane polariser **610** that is the input polariser **210** of spatial light modulator **48**, an output polariser **218**, a reflective polariser **302**, a polar control retarder **300** comprising a layer **314** of liquid crystal material **315** and a passive compensation retarder **330**, and an additional polariser **318**. Features of the embodiment of FIG. **16**C not discussed in further detail may be assumed to correspond to the features with equivalent reference numerals as discussed above, including any potential variations in the features.
(372) In other words, the out-of-plane polariser **602** is arranged on the side of the spatial light modulator **48** that is an input side of the spatial light modulator **48** and the spatial light modulator **48** comprises an input polariser **210** and the input polariser **210** is the in-plane polariser **610**.
(373) By way of comparison with FIG. **1**A, in the alternative embodiment of FIG. **16**C the polar control retarder **300** is arranged between the in-plane polariser **310** that is the output polariser **218** of the spatial light modulator **48** and a reflective polariser **302** that is provided between the polariser **310** and the polar control retarder **300**.
(374) By way of comparison with FIG. **16**B, the reflective polariser **302** may be arranged to achieve increased reflectivity in non-viewing directions in the privacy mode of operation. Advantageously image security factor may be improved.
(375) The operation of the reflective polariser **302**, polar control retarder **300** and additional

polariser **318** is described in FIG. **29**B and FIGS. **30**C-D hereinbelow. Advantageously improved image security may be achieved in privacy mode of operation and improved share mode performance may be achieved.

(376) FIG. **16**D is a schematic diagram illustrating in perspective side view a polar angle control display device **100** comprising a backlight **20**, an out-of-plane polariser **602**, a polarisation switch **601**, an in-plane polariser **610** that is an additional polariser **318**, a polar control retarder **300** comprising a layer **314** of liquid crystal material **315** and a passive compensation retarder **330**, a polariser **310** that is the input polariser **210** of a spatial light modulator **48** further comprising an output display polariser **218**. Features of the embodiment of FIG. **16**D not discussed in further detail may be assumed to correspond to the features with equivalent reference numerals as discussed above, including any potential variations in the features.

(377) By way of comparison with FIG. **1**A, in the alternative embodiment of FIG. **16**D, the spatial light modulator **48** comprises an input polariser **210** and an output polariser **218**, and the in-plane polariser **610** is a different component from the input polariser **210** and the output polariser **218**. The display polariser **610** is the in-plane additional polariser **318**.

(378) In other words, the out-of-plane polariser **602** is arranged on the side of the spatial light modulator **48** that is an input side of the spatial light modulator **48** and the spatial light modulator **48** comprises an input polariser **210**. The in-plane polariser **610** is a different component from the input polariser **210**. The polar angle control display device **100** further comprises: an additional polariser **318** arranged on the input side of the input polariser **210**; and at least one polar control retarder **300** arranged between the input polariser **210** and the additional polariser **318**. The additional polariser **318** is the in-plane polariser **610**.

(379) In comparison to the embodiments of FIGS. **16**A-C, each of the out-of-plane polariser **602**, polarisation switch **601** and polar control retarder **300** are arranged between the backlight **20** and the input polariser **210** of the spatial light modulator **48**. Advantageously front-of-screen contrast is improved. In-cell touch sensing may be provided near the layer **314** of liquid crystal material **315** so that cost of the touch screen control is reduced and improved image contrast provided.

(380) It may be desirable to reduce the cost and thickness of the optical stack while providing desirable image security.

(381) FIG. **17**A is a schematic diagram illustrating in perspective side view a polar angle control display device **100** comprising a backlight **20**, an out-of-plane polariser **602**, an in-plane polariser **610** that is the input polariser of a spatial light modulator **48**, a polariser **310** that is the output polariser **218** of the spatial light modulator **48**, a reflective polariser **302**, a polar control retarder **300** comprising a layer **314** of liquid crystal material **315** and a passive compensation retarder **330**, and an additional polariser **318**. Features of the embodiment of FIG. **17**A not discussed in further detail may be assumed to correspond to the features with equivalent reference numerals as discussed above, including any potential variations in the features.

(382) Such an arrangement may provide a suppression of backlight **20** luminance profile at high angles, and improve image security. Device thickness may be reduced. Advantageously off-axis image security may be improved. In comparison to a micro-louver privacy film, Moiré patterning may be eliminated.

(383) FIG. **17**B is a schematic diagram illustrating in perspective side view a polar angle control display device **100** comprising a backlight **20**, a spatial light modulator **48**, an in-plane polariser **610**A that is the output polariser **218** of the spatial light modulator **48**, an out-of-plane polariser **602**, a reflective polariser **302** that is a further in-plane polariser **610**B and the in-plane polariser **310** for polar control retarder **300**, a polar control retarder **300** comprising a layer **314** of liquid crystal material **315** and a passive compensation retarder **330**, and an additional polariser **318**. Features of the embodiment of FIG. **17**B not discussed in further detail may be assumed to correspond to the features with equivalent reference numerals as discussed above, including any potential variations in the features.

(384) The polar angle control display device **100** may further comprise a reflective polariser **302** arranged on the output side of the output polariser **218**, wherein the reflective polariser **302** is the in-plane polariser **610**B.

(385) By way of comparison with FIG. **17**A, in the alternative embodiment of FIG. **17**B, the out-of-plane polariser **602** is arranged between the output polariser **218** of the spatial light modulator **48** that is the in-plane polariser **610** and in-plane polariser **310**; and the polar control retarder **300**. Further reflective polariser **302** may be arranged between the out-of-plane polariser **602** and the polar control retarder **300** to advantageously achieve improved security factor in a thin and reduced cost optical stack.

(386) FIG. **18** is a schematic diagram illustrating in perspective side view a polar angle control display device **100** comprising a backlight **20**, an out-of-plane polariser **602**A, an in-plane polariser **610**A that is the input polariser **210** of a spatial light modulator **48**, a further in-plane polariser **610**B that is the output polariser **218** of the spatial light modulator **48**, and a further out-of-plane polariser **602**B. Features of the embodiment of FIG. **18** not discussed in further detail may be assumed to correspond to the features with equivalent reference numerals as discussed above, including any potential variations in the features.

(387) By way of comparison with FIG. **15**B, in the alternative embodiment of FIG. **18** both of the polarisation switches **601**A, **601**B are omitted. Advantageously thickness, cost and complexity are reduced and increased security factor may be achieved, including with the transmission profile of FIG. **15**C. Such a display device may be suitable for use as a non-switchable privacy display device or may be a component for use with polar control retarders **300** and additional polarisers **318** as described elsewhere herein.

(388) It may be desirable to provide improved image security from emissive spatial light modulator **48**.

(389) FIG. **19**A is a schematic diagram illustrating in perspective side view a polar angle control display device **100** comprising an emissive spatial light modulator **48**, an in-plane polariser **610** that is the output polariser **218** of the spatial light modulator **48**, a polarisation switch **601** and an out-of-plane polariser **602**. Features of the embodiment of FIG. **19**A not discussed in further detail may be assumed to correspond to the features with equivalent reference numerals as discussed above, including any potential variations in the features.

(390) By way of comparison with the embodiments hereinabove, the spatial light modulator **48** is an emissive spatial light modulator **48** and said side of the spatial light modulator **48** is an output side of the spatial light modulator **48**. By way of comparison with FIG. **1**A, the pixel layer **214** may comprise emissive pixels for example pixels **220**R, **220**G, **220**B.

(391) The spatial light modulator **48** comprises an output polariser **218**, and the output polariser **218** is the in-plane polariser **610**. Retarder **272** that may be a quarter waveplate is arranged to provide reduced reflections from the pixel layer **214**, increasing image contrast.

(392) The spatial light modulator **48** may comprise pixels **220** that are organic LED (OLED) emitters or inorganic LED (microLED) emitters for example. The pixels **220** of the present embodiments may output red, green or blue light or may output in other spectral bands such as yellow or white; or may provide illumination output in non-visible wavelengths such as infra-red. The display device **100** may alternatively be arranged as an illumination apparatus.

(393) The polar control transmission element **600** of FIG. **19**A may further be provided by the polar control transmission elements **600** of the embodiments hereinabove when arranged on the output side of the spatial light modulator **48**, including but not limited to the twisted nematic polarisation switch **601** of FIGS. **4**A-D, FIGS. **5**A-D, FIGS. **6**A-B; the non-twisted nematic polarisation switch **601** of FIGS. **8**A-B, the off-axis out-of-plane polariser **602** of FIGS. **12**A-F, the automotive display **100** of FIG. **13**, the pupillating display **100** of FIGS. **14**B-C and the output optical stacks arranged to receive light from the output polariser **218** of the spatial light modulator **48** of FIGS. **17**A-B, and FIG. **18**.

(394) By way of comparison with the optical profiles provided by backlight **20** of FIG. **7**A, the output luminance profile of emissive displays is typically more widely distributed and further levels of luminance suppression are often desirable. Further illustrative embodiments will now be described.
(395) FIG. **19**B is a schematic diagram illustrating in perspective side view a polar angle control display device **100** comprising an emissive spatial light modulator **48**, a polariser **310** that is the output polariser **218** of the spatial light modulator **48**, a polar control retarder **300** comprising a layer **314** of liquid crystal material **315** and a passive compensation retarder **330**, an additional polariser **318** that is an in-plane polariser **610**, a polarisation switch **601** and an out-of-plane polariser **602**. Features of the embodiment of FIG. **19**B not discussed in further detail may be assumed to correspond to the features with equivalent reference numerals as discussed above, including any potential variations in the features.
(396) In comparison to FIG. **19**A, a polar control retarder **300** is arranged between the additional polariser **318** that is the in-plane polariser **610** and the polariser **310** that is the output display polariser **218**. Advantageously improved image security may be provided in desirable non-viewing directions in a privacy mode of operation, and a switchable share mode is provided for viewing at wide viewing angles.
(397) It may be desirable to reduce the thickness of the optical stack.
(398) FIG. **19**C is a schematic diagram illustrating in perspective side view a polar angle control display device **100** comprising an emissive spatial light modulator **48**, the output polariser **218** of the spatial light modulator **48** that is an in-plane polariser **610**A, an out-of-plane polariser **602**, a reflective polariser **302** that is a further in-plane polariser **610**B, a polar control retarder **300** comprising a layer **314** of liquid crystal material **315** and a passive compensation retarder **330**, and an additional polariser that is an in-plane polariser **610**. Features of the embodiment of FIG. **19**C not discussed in further detail may be assumed to correspond to the features with equivalent reference numerals as discussed above, including any potential variations in the features.
(399) By way of comparison with FIG. **19**B, the polarisation switch **601** is omitted and the out-of-plane polariser **602** is arranged between the output polariser **218** of the spatial light modulator **48** and a reflective polariser **302**. The output polariser **218** further provides the polariser **310** for the polar control retarder **300** and the in-plane polariser **610**A of the out-of-plane polariser **602**. Further the reflective polariser **302** provides a further in-plane polariser **610**B of the out-of-plane polariser **602**. FIG. **19**C thus illustrates an embodiment wherein an in-plane polariser **610**B is provided by a reflective polariser **302**.
(400) In operation, the out-of-plane polariser **602** and in-plane polarisers **610**A. **610**B comprising reflective polariser **302** and display polariser **218** provide reduced transmission of light rays in non-viewing directions. The high luminance of the spatial light modulator **48** in non-viewing directions may be advantageously reduced to achieve improved security factor in privacy mode of operation of the polar control retarder **300** as described further hereinbelow with respect to FIGS. **29**A-B and FIGS. **30**A-D.
(401) FIG. **19**D is a schematic diagram illustrating in perspective side view a polar angle control display device **100** comprising an emissive spatial light modulator **48**, the output polariser **218** of the spatial light modulator **48** that is an in-plane polariser **610**A, an out-of-plane polariser **602**A, a reflective polariser **302**, a polar control retarder **300** comprising a layer **314** of liquid crystal material **315** and a passive compensation retarder **330**, an additional polariser **318** that is a further in-plane polariser **610**B, and a further out-of-plane polariser **602**B. Features of the embodiment of FIG. **19**D not discussed in further detail may be assumed to correspond to the features with equivalent reference numerals as discussed above, including any potential variations in the features.
(402) By way of comparison with FIG. **19**C, in the alternative embodiment of FIG. **19**D, an out-of-plane polariser **602**A is provided between the in-plane polariser **610**A that is the display output polariser **218** and the polar control retarder **300**. The out-of-plane polariser **602**A provides a first

luminance reduction for non-viewing directions. A further out-of-plane polariser **602**B is provided to receive light from the additional polariser **318** of the polar control retarder **300** that is the further in-plane polariser **610**B. The further out-of-plane polariser **602**B advantageously achieves further off-axis luminance reduction to that provided by the embodiment of FIG. **19**C.

(403) FIG. **19**D further illustrates that passive compensation retarder **330** may be omitted, for example for off-axis privacy provided by twisted nematic liquid crystal polar control retarder **301** for example as described in U.S. Patent Publ. No. 2023-0254457 and U.S. Pat. No. 11,977,286, both of which are herein incorporated by reference in their entireties. The arrangement of out-of-plane polariser **602** as illustrated in FIG. **12**A and FIG. **12**C may be provided to achieve asymmetric light suppression, for example for use in the vehicle **950** of FIG. **13**.

(404) In alternative embodiments, the polar control retarder **300** may comprise passive compensation retarder **330**. The transmission profiles of the out-of-plane polariser **602**A, **602**B may be symmetric.

(405) An alternative arrangement of reflective privacy display will now be described.

(406) FIG. **19**E is a schematic diagram illustrating in perspective side view a polar angle control display device **100** comprising an emissive spatial light modulator **48**, the output polariser **218** of the spatial light modulator **48**, a reflective polariser **302** that is an in-plane polariser **610**, an out-of-plane polariser **602**, a passive compensation retarder **330**, a polar control retarder **300** comprising a layer of liquid crystal material **314**, and an additional polariser **318**; FIG. **19**F is a schematic diagram illustrating in top view the transmission and reflection of light through the reflective polariser **302**, out-of-plane polariser **602**, polar control retarder **300** and in-plane additional polariser **318** of FIG. **19**E in a privacy mode of operation; and FIG. **19**G is a schematic diagram illustrating in top view the transmission and reflection of light through the reflective polariser **302**, out-of-plane polariser **602**, polar control retarder **300** and in-plane additional polariser **318** of FIG. **19**E in a share mode of operation. Features of the embodiments of FIGS. **19**E-G not discussed in further detail may be assumed to correspond to the features with equivalent reference numerals as discussed above, including any potential variations in the features.

(407) By way of comparison with FIG. **19**C, in the alternative embodiment of FIG. **19**E the out-of-plane polariser **602** is provided between the reflective polariser **302** and the additional polariser **318**. The polar angle control display device **100** may further comprise a reflective polariser **302** arranged on the output side of the output polariser **218**, wherein the reflective polariser **302** is the in-plane polariser **610**.

(408) The operation for transmitted light rays **400**, **402** and for reflected light ray **412** in the absence of out-of-plane polariser **602** is described hereinbelow with respect to FIGS. **29**A-B and FIGS. **30**A-C hereinbelow, wherein various rays are either transmitted, reflected or absorbed.

(409) FIG. **19**F illustrates incident light ray **411** from an ambient light source **450** is polarised with state **372** and converted most generally by the polar control retarder **300** to an elliptical polarisation state which at a design angle (such as 45° from the surface normal **199** direction) is the orthogonal polarisation state **373**. Out-of-plane polariser **602** preferentially transmits the polarisation state **374** that is orthogonal to the electric vector transmission direction **303** of the reflective polariser **302** and is reflected thereby. The reflected polarisation state **375** is transmitted by the out-of-plane polariser **602** to provide linear polarisation state **375** incident onto the polar control retarder **300**. The light ray **412** is then output most generally as elliptical polarisation state **377** that is the linear polarisation state **377** at the design angle and is transmitted by the additional polariser **318**. Advantageously display reflectance is increased for off-axis snooper viewing locations and security factor increased.

(410) Off-axis transmitted rays **402** have a polarisation state **361** incident onto the out-of-plane polariser **602** so that light is at least in part absorbed by the dichroic molecules **603**. Any residual transmitted light is converted to polarisation state **364** by the polar control retarder **300** and absorbed in the additional polariser **318**. Advantageously off-axis luminance is reduced and

security factor increased.
(411) By comparison, on-axis light rays **410**, **400** with linear polarisation state **360**, **362** are transmitted with low loss through the reflective polariser **302**, out-of-plane polariser **602** and additional polariser **318**. High image visibility is provided for on-axis viewing directions.
(412) FIG. **19**G illustrates the arrangement for share mode operation wherein for the incident ray **411** the polar control retarder **300** is arranged to provide small or no phase difference for polarisation state **372** so that polarisation state **373** is directed towards the out-of-plane polariser **602** and absorbed, or transmitted and further transmitted by the reflective polariser **302**. Advantageously off-axis image visibility is improved. Considering light ray **402**, any light that is transmitted by the out-of-plane polariser **602** is transmitted through the additional polariser **318** so that some increase in luminance is provided for off-axis viewing directions. Advantageously off-axis image visibility is improved in comparison to privacy mode of operation.
(413) Arrangements of non-switchable display devices **100** will now be described.
(414) FIG. **20**A is a schematic diagram illustrating in perspective side view a polar angle control display device **100** comprising an emissive spatial light modulator **48**, an in-plane polariser **610** that is the output polariser **218** of the spatial light modulator **48**, and an out-of-plane polariser **602**; FIG. **20**B is a schematic diagram illustrating in perspective side view a polar angle control display device **100** comprising an emissive spatial light modulator **48**, an out-of-plane polariser **602**, and an in-plane polariser **610** that is the output polariser **218** of the spatial light modulator **48**; and FIG. **20**C is a schematic diagram illustrating in perspective side view a polar angle control display device **100** comprising an emissive spatial light modulator **48**, an out-of-plane polariser **602**A, an in-plane polariser **610**A that is the output polariser **218** of the spatial light modulator **48**, a further out-of-plane polariser **602**B and a further in-plane polariser **610**B. Features of the embodiments of FIGS. **20**A-C not discussed in further detail may be assumed to correspond to the features with equivalent reference numerals as discussed above, including any potential variations in the features.
(415) By way of comparison with the embodiments described hereinabove, the embodiments of FIGS. **20**A-C do not comprise a polarisation switch **601** or a polar control retarder **300**. Such embodiments may achieve a low-thickness, low-cost fixed privacy display. Alternatively, the embodiments of FIGS. **20**A-C may be provided with further polarisation switch **601** and/or polar control retarder **300** elements as described hereinabove to advantageously achieve switchable privacy mode operation with improved security factor in non-viewing directions; wherein the additional components may be provided during manufacture or may be added by a user. The embodiments of FIGS. **20**A-C may further be provided for transmissive spatial light modulator **48**, and the arrangements of out-of-plane polariser **602** may be provided with an out-of-plane polariser **602** that is arranged on the input side of the spatial light modulator **48** and the input display polariser **210** may be an in-plane polariser **610**.
(416) The alternative embodiment of FIG. **20**A illustrates an arrangement with an output out-of-plane polariser **602**. Advantageously reduced thickness may be achieved.
(417) The alternative embodiment of FIG. **20**B illustrates an arrangement wherein the out-of-plane polariser **602** is provided between the retarder **272** and the in-plane polariser **610** that is the output polariser **218**. The output polariser **218** may provide protection of the out-of-plane polariser **602**, to advantageously achieve increased robustness.
(418) In comparison to the embodiment of FIG. **20**B, the further out-of-plane polariser **602**B and further in-plane polariser **610**B may achieve reduced luminance in the non-viewing directions, advantageously achieving increased security factor.
(419) Out-of-plane polarisers **602** comprising discotic dichroic molecules **607** will now be described.
(420) FIG. **20**D is a schematic diagram illustrating in perspective side view operation of an out-of-plane polariser comprising discotic dichroic molecules, and an in-plane polariser for light rays inclined in lateral and elevation directions. Features of the embodiment of FIG. **20**D not discussed

in further detail may be assumed to correspond to the features with equivalent reference numerals as discussed above, including any potential variations in the features.
(421) By way of comparison with FIG. **3**B, the discotic molecules **607** may provide reduced transmission about a single axis for the polarisation state **642**. Such an arrangement may be provided for non-switching transmission reduction. Layers of discotic molecules aligned with optical axis **622** direction k.sub.e may be provided in the arrangements of FIGS. **20**A-C and other non-switching arrangements of out-of-plane polariser **602** as described hereinabove.
(422) Optical components **102** comprising out-of-plane polariser **602** will now be described.
(423) FIG. **21** is a schematic diagram illustrating in perspective side view a polar angle control component comprising an out-of-plane polariser **602**; FIG. **22** is a schematic diagram illustrating in perspective side view a polar angle control component comprising an out-of-plane polariser **602** and a polarisation switch **601**; FIG. **23** is a schematic diagram illustrating in perspective side view a polar angle control component comprising an out-of-plane polariser **602** and an in-plane polariser **610**; and FIG. **24** is a schematic diagram illustrating in perspective side view a polar angle control component comprising a polarisation switch **601** arranged between an out-of-plane polariser **602** and an in-plane polariser **610**. Features of the embodiments of FIGS. **21-24** not discussed in further detail may be assumed to correspond to the features with equivalent reference numerals as discussed above, including any potential variations in the features.
(424) In the alternative embodiments of FIGS. **21-24**, a polar angle control component **102** for assembly with a display device **100** comprising a spatial light modulator **48** is provided. The polar angle control component **102** comprising an out-of-plane polariser **602** having an absorption axis **622** in a direction having a component out of the plane of the out-of-plane polariser **602**. Out-of-plane polarisers **602** may comprise rod-like dichroic molecules **603**. In alternative embodiments, the out-of-plane polariser **602** may be provided by a discotic material **607** having an absorption axis **622** in a direction having a component out of the plane of the out-of-plane polariser **60** and an absorption axis **622** in a direction having a component in the plane of the out-of-plane polariser **60**.
(425) By way of comparison with FIG. **21**, in the alternative embodiment of FIG. **22** the polar angle control component **102** further comprises a polarisation switch **601**, the polarisation switch **601** being switchable between a first mode in which it is arranged to change a polarisation state of the light passing therethrough and a second mode in which it is arranged to affect the polarisation state of the light passing therethrough differently from the first mode.
(426) By way of comparison with FIG. **21**, in the alternative embodiment of FIG. **23** the polar angle control component **102** further comprises an in-plane polariser **610** having an absorption axis **620** in a plane of the in-plane polariser **610**.
(427) By way of comparison with FIG. **23**, in the alternative embodiment of FIG. **24** the polar angle control component **102** further comprises an in-plane polariser **610** having an absorption axis **620** in a plane of the in-plane polariser **610**, the polarisation switch **601** being provided between the in-plane polariser **610** and the out-of-plane polariser **602**.
(428) Alternative arrangements of collimated backlights **20** will now be described.
(429) FIG. **25**A is a schematic diagram illustrating in perspective side view an alternative backlight **20** comprising addressable first and second arrays of light sources **15**A, **15**B; and FIG. **25**B is a schematic diagram illustrating in perspective side view an alternative backlight **20** comprising first and second waveguides **1**A, **1**B and respective aligned first and second arrays of light sources **15**A, **15**B. Features of the arrangements of FIGS. **25**A-B not discussed in further detail may be assumed to correspond to the features with equivalent reference numerals, including any potential variations in the features.
(430) The alternative embodiments of FIGS. **25**A-B provide first and second light cones **455**A, **455**B in dependence on the array **15**A. **15**B that is illuminated respectively. In wide-angle mode, light source **15**B may provide light cone **455**B and optionally light source **15**A may provide some light in light cone **445**A. In privacy mode only light source **15**A is illuminated and light primarily

directed into light cone **445**A.

(431) The operation of the embodiment of FIG. **25**B will now be further described.

(432) FIG. **26**A is a schematic diagram illustrating in top view operation of the backlight **20** of FIG. **25**B; FIG. **26**B is a schematic diagram illustrating in perspective rear view a light-turning component **50**; and FIG. **26**C is a schematic diagram illustrating in top view a light-turning component **50**. Features of the arrangements of FIGS. **26**A-C not discussed in further detail may be assumed to correspond to the features with equivalent reference numerals, including any potential variations in the features.

(433) The backlight **20** comprises: at least one first light source **15**A arranged to provide input light; at least one second light source **15**B arranged to provide input light in an opposite direction from the at least one first light source **15**A; a waveguide arrangement **11** comprising at least one waveguide **1**, the waveguide arrangement **11** being arranged to receive the input light from the at least one first light source and the at least one second light source and to cause light from the at least one first light source and the at least one second light source to exit from the waveguide arrangement **11** by breaking total internal reflection; and an optical turning film component **50** comprising: an input surface **56** arranged to receive the light exiting from a waveguide **1** through a light guiding surface **8** of the waveguide **1** by breaking total internal reflection, the input surface **56** extending across the plane; and an output surface **58** facing the input surface **56**, wherein the input surface **56** comprises an array of prismatic elements **51**. The prismatic elements **51** may be elongate.

(434) The waveguide arrangement **11** comprises: a first waveguide **1**A extending across a plane and comprising first and second opposed light guiding surfaces arranged to guide light along the waveguide, the second light guiding surface being arranged to guide light by total internal reflection; and a first input end **2**A arranged between the first and second light guiding surfaces **6**A, **8**A and extending in a lateral direction between the first and second light guiding surfaces **6**A, **8**A; wherein the at least one first light source **15**A is arranged to input light **445** into the first waveguide **1**A through the first input end, and the first waveguide **1**A is arranged to cause light from the at least one first light source **15**A to exit from the first waveguide **1**A through one of the first and second light guiding surfaces **6**A, **8**A by breaking total internal reflection; a second waveguide **1**B extending across the plane arranged in series with the first waveguide **1**A and comprising first and second opposed light guiding surfaces **6**B, **8**B arranged to guide light along the waveguide **1**B, the second light guiding surface **8**B being arranged to guide light by total internal reflection, and a second input end **2**B arranged between the first and second light guiding surfaces **6**B, **8**B and extending in a lateral direction between the first and second light guiding surfaces **6**B. **8**B; wherein the at least one second light source **15**B is arranged to input light **447** into the second waveguide **1**B through the second input end **2**B, and the second waveguide **1**B is arranged to cause light from the at least one second light source **15**B to exit from the second waveguide **1**B through one of the first and second light guiding surfaces **6**B. **8**B by breaking total internal reflection, and wherein the first and second waveguides **1**A, **1**B are oriented so that at least one first light source **15**A and at least one second light source **15**B input light **445**, **447** into the first and second waveguides **1**A, **1**B in opposite directions.

(435) The optical turning film component **50** comprises: an input surface **56** arranged to receive the light **444**A, **444**B exiting from the waveguide arrangement **11** through a light guiding surface of the at least one waveguide **1**A, **1**B of the waveguide arrangement by breaking total internal reflection, the input surface **56** extending across the plane; and an output surface **58** facing the input surface, wherein the input surface **56** comprises an array of prismatic elements **52**. The prismatic elements each comprise a pair of elongate facets **52** defining a ridge **54** therebetween. Angles ϕ.sub.A, ϕ.sub.B of prism surfaces **53**A, **53**B are provided to direct the nominal light output from waveguides **1**A, **1**B to directions **445**, **447** by refraction and reflection at surfaces **53**A, **53**B. Advantageously desirable illumination directions such as illustrated in FIGS. **4**A-F may be

achieved by selection of angles ϕ.sub.A, ϕ.sub.B.
(436) The backlight **20** of FIG. **26**A may provide two different luminance profiles, for example for use in the passenger infotainment display device **100** of FIGS. **19**A-B. In operation, the light **444**A from the first light source **15**A exits the backlight **20** with a first angular distribution **445** towards the passenger **45** and the light from the second light source **15**B exits the backlight **20** with a second angular distribution **457** towards the driver. The first angular distribution **455** may be symmetrical about an axis **199** of symmetry of the backlight **20** and the second angular distribution **457** is asymmetrical about the same axis **199** of symmetry of the backlight **20**. In a left-hand drive vehicle, the asymmetrical distribution **457** may be to the left of the axis **199** of symmetry of the backlight **20** and in a right-hand drive vehicle the asymmetrical distribution **457** may be to right of the axis **199** of symmetry of the backlight **20**.
(437) Waveguides **1**A, **1**B comprise surface relief features that are arranged to leak some of the guiding light either towards the rear reflector **3** or towards the light-turning component **50**. Each waveguide **1**A, **1**B comprises a surface relief **30** arranged on the first side **6**A, **6**B that may comprise prism surfaces **32**, **33**. Further the second sides **8**A, **8**B may further comprise surface relief **31** that may comprise elongate features or prism features. In operation the surface reliefs **30**, **31** provide leakage of light **445**, **447** from waveguide **1**A, **1**B for light guiding along the waveguide **1**A, **1**B.
(438) FIG. **27** is a schematic diagram illustrating in perspective side view an alternative backlight **20** comprising an array of light sources **15***a-n* that may be mini-LEDs and an array of light-deflecting wells **40***a-n*. Features of the arrangement of FIG. **27** not discussed in further detail may be assumed to correspond to the features with equivalent reference numerals, including any potential variations in the features.
(439) Backlight **20** is described in U.S. Patent Publ. No 2022-0404540, which is herein incorporated by reference in its entirety. The backlight **20** is arranged to illuminate a predetermined area of a transmissive spatial light modulator **48**. Backlight **20** and spatial light modulator **48** are controlled by means of controller **500**.
(440) The size and profile of the light output cone **455** is determined by the structure and operation of the backlight **20** and other optical layers in the optical stack **5**. As will be described hereinbelow the backlight **20** is arranged to provide a distribution of luminous intensity within a relatively small cone angle **402** in comparison with conventional backlights using brightness enhancement films such as BEF™ from 3M corporation.
(441) Backlight **20** comprises a support substrate **17**, reflective layer **3**, an array of light emitting elements **15** and an optical waveguide **1** comprising light input wells **30** and light-deflecting wells **40**. The light emitting elements **15** are aligned to the light input wells **30**. The light-deflecting wells **40** are arranged in an array between the light input wells **30**.
(442) The waveguide **1** comprises rear and front light guiding surfaces **6**, **8** and may comprise a light transmitting material such as PMMA, PC, COP or other known transmissive material. The light input wells may comprise air between the rear light guiding surface **6** and the end **34**. The waveguide **1** comprises an array of catadioptric elements wherein light is refracted at the light input well and is reflected by total internal reflection and/or reflection at coated reflective surfaces.
(443) The backlight **20** further comprises a reflective layer **3** behind the rear light guiding surface **6** that is arranged to reflect light extracted from the waveguide **1** through the rear light guiding surface **6** back through the waveguide **1** for output forwardly.
(444) The backlight **20** further comprises a light-turning optical arrangement that is a light-turning optical component **50** arranged to direct light output rays **415**G from the waveguide **1** into desirable light output cone **402**. Light-turning optical component **50** may comprise a film. Advantageously low thickness may be achieved.
(445) Control system **500** is arranged to control the light emitting elements **15** and the pixels **220**R, **220**G, **220**B of the spatial light modulator **48**. High resolution image data may be provided to the

spatial light modulator **48** and lower resolution image data may be provided to the light emitting elements **15** by the control system. The display device **100** may advantageously be provided with high dynamic range, high luminance and high efficiency as will be described further hereinbelow.
(446) It may be desirable to provide a backlight **20** comprising brightness enhancement films **41**A, **41**B.
(447) FIG. **28**A is a schematic diagram illustrating in perspective side view an alternative backlight **20** comprising a light-scattering waveguide **1**, a rear reflector **3**, crossed prismatic films **40**A, **40**B and a light control film **700**; and FIG. **28**B is a schematic diagram illustrating in side view operation of the backlight **20** of FIG. **28**A. Features of the arrangements of FIGS. **28**A-B not discussed in further detail may be assumed to correspond to the features with equivalent reference numerals, including any potential variations in the features.
(448) The backlight apparatus **20** of FIGS. **28**A-B comprises a rear reflector **3**; and an illumination apparatus comprising waveguide **1** and light sources **15**. Light rays **412** from the source **15** are input through input side **2** and guide within the surfaces **6**, **8** of the waveguide **1**. Light is output by means of extraction features **12** and is incident onto rear reflector **3** which may reflect light either by scattering or specular reflection back through the waveguide **1**.
(449) In alternative embodiments (not shown), the light sources **15** and waveguide **1** may be replaced by a two-dimensional array of mini-LEDs arrayed across the area of the spatial light modulator **48** and optionally various scattering layers including wavelength conversion layers provided.
(450) Output light is directed towards crossed brightness enhancement films **41**A, **41**B that are arranged to receive light exiting from the first surface **6** of waveguide **1**. In the present embodiments, ‘crossed’ refers to an angle of substantially 90° between the optical axes of the two retarders in the plane of the retarders.
(451) Brightness enhancement films **41**A, **41**B each comprise a prismatic layer with prismatic surfaces **42**A, **42**B arranged between the optical waveguide **1** and the spatial light modulator **48** to receive output light from the optical waveguide **1** or array of mini-LEDs. Light rays **412** from the waveguide **1** or array of mini-LEDs are directed through the spatial light modulator **48**.
(452) The prismatic surfaces **42**A, **42**B are elongate and the orientation of the elongate prismatic surfaces of the turning film and further turning film are crossed. Light that is in directions near to the optical axis **199** are reflected back towards the reflector **3**, whereas light rays **410** that are closer to grazing the surface **6** are output in the normal direction.
(453) Optionally reflective polariser **208** may be provided between the input display polariser **210** and backlight **20** to provide recirculated light and increase display efficiency. Advantageously efficiency may be increased.
(454) The light recirculating components **3**, **41**A, **41**B, **208** of backlight **20** achieve a mixing of output light from the waveguide. Such recirculation is tolerant to manufacturing defects and backlights **20** may advantageously be provided with larger size, lower cost and higher luminance uniformity than the collimated backlights illustrated elsewhere herein. However, the backlights of FIG. **28**A-B provide increased luminance at higher polar angles that may degrade security factor in privacy mode as will be described below.
(455) It would be desirable to provide high uniformity backlights with low manufacturing cost while achieving high security factor in privacy mode, and achieving desirable luminance in the public mode of operation.
(456) A light control film **700** is arranged between the backlight **20** and the spatial light modulator **48**. The light control film **700** comprises an input surface **706**, an output surface **708** facing the input surface **706**, an array of light transmissive regions **704** extending between the input surface **706** and the output surface **708**, and absorptive regions **702** between the transmissive regions and extending between the input surface and the output surface.
(457) Light control film **700** is arranged between the reflective polariser **208** of the backlight **20**

and the display input polariser **210**. Light control film **700** may further comprise a support substrate **710**. Advantageously the flatness of the light control film may be increased to achieve increased uniformity. The structure and operation of the light control film will be further described hereinbelow.
(458) The arrangements of FIGS. **28**A-B in combination with liquid crystal polar control retarders are described further in U.S. Pat. No. 11,099,447, which is herein incorporated by reference in its entirety.
(459) Advantageously the embodiments of FIGS. **28**A-B used for the backlight **20** of the present embodiments may provide reduce cost of manufacture. Improved wide-angle mode visibility may be achieved and high security factor for viewers **47** in privacy mode.
(460) The principles of operation of the switchable polar control retarders of FIG. **3**A will now be described further.
(461) FIG. **29**A is a schematic diagram illustrating in top view propagation of transmitted light through a polar control retarder **300** arranged between a reflective polariser **302** and an additional polariser **318** in privacy mode of operation. Features of the embodiment of FIG. **29**A not discussed in further detail may be assumed to correspond to the features with equivalent reference numerals as discussed above, including any potential variations in the features.
(462) FIG. **29**A illustrates the output polariser **218**, reflective polariser **302** that is a display polariser **310** for the polar control retarder **300** and additional polariser **318** wherein the polar control retarder **300** comprises a liquid crystal polar control retarder **301** and passive compensation retarder **330**. The propagation of polarised light will now be described.
(463) When the layer **314** of liquid crystal material **315** is driven to operate in the privacy mode, the retarders **300** provide no overall transformation of polarisation component **360** to output light rays **400** passing therethrough along an axis perpendicular to the plane of the switchable retarder, but provides an overall transformation of polarisation component **361** to light rays **402** passing therethrough for some polar angles which are at an acute angle to the perpendicular to the plane of the retarders.
(464) Polarisation component **360** from the output polariser **218** is transmitted by reflective polariser **302** and incident on retarders **300**. On-axis light has a polarisation component **362** that is unmodified from component **360** while off-axis light has a polarisation component **364** that is transformed by the retarders **300**. At a minimum, the polarisation component **361** is transformed to a linear polarisation component **364** and absorbed by additional polariser **318**. More generally, the polarisation component **361** is transformed to an elliptical polarisation component, that is partially absorbed by additional polariser **318**.
(465) The polar distribution of light transmission illustrated in FIG. **8**B modifies the polar distribution of luminance output of the underlying spatial light modulator **48**. In the case that the spatial light modulator **48** comprises a directional backlight **20** then off-axis luminance may be further be reduced as described above.
(466) Advantageously, a privacy display is provided that has low luminance to an off-axis snooper while maintaining high luminance for an on-axis viewer.
(467) The operation of the reflective polariser **302** for light from ambient light source **404** will now be described for the display operating in privacy mode.
(468) FIG. **29**B is a schematic diagram illustrating in top view propagation of ambient light through a polar control retarder **300** arranged between a reflective polariser **302** and an additional polariser **318** in privacy mode of operation. Features of the embodiment of FIG. **29**B not discussed in further detail may be assumed to correspond to the features with equivalent reference numerals as discussed above, including any potential variations in the features.
(469) Ambient light source **404** illuminates the display device **100** with unpolarised light. Additional polariser **318** transmits light ray **410** normal to the display device **100** with a first polarisation component **372** that is a linear polarisation component parallel to the electric vector

transmission direction **319** of the additional polariser **318**.
(470) In both states of operation, the polarisation component **372** remains unmodified by the retarders **300** and so transmitted polarisation component **382** is parallel to the transmission axis of the reflective polariser **302** and the output polariser **218**, so ambient light is directed through the spatial light modulator **48** and lost.
(471) By comparison, for ray **412**, off-axis light is directed through the retarders **300** such that polarisation component **374** incident on the reflective polariser **302** may be reflected. Such polarisation component is re-converted into component **376** after passing through retarders **300** and is transmitted through the additional polariser **318**.
(472) Thus when the layer **314** of liquid crystal material is in the second state of said two states, the reflective polariser **302** provides no reflected light for ambient light rays **410** passing through the additional polariser **318** and then the retarders **300** along an axis perpendicular to the plane of the retarders **300**, but provides reflected light rays **412** for ambient light passing through the additional polariser **318** and then the retarders **300** at some polar angles which are at an acute angle to the perpendicular to the plane of the retarders **300**; wherein the reflected light **412** passes back through the retarders **300** and is then transmitted by the additional polariser **318**.
(473) The retarders **300** thus provide no overall transformation of polarisation component **380** to ambient light rays **410** passing through the additional polariser **318** and then the retarder **300** along an axis perpendicular to the plane of the switchable retarder, but provides an overall transformation of polarisation component **372** to ambient light rays **412** passing through the absorptive polariser **318** and then the retarders **300** at some polar angles which are at an acute angle to the perpendicular to the plane of the retarders **300**.
(474) The polar distribution of light reflection illustrated in FIG. **7**C thus illustrates that high reflectivity can be provided at typical snooper locations by means of the privacy state of the retarders **300**. Thus, in the privacy mode, the reflectivity for off-axis viewing positions is increased as illustrated in FIG. **7**E, and the luminance for off-axis light from the spatial light modulator is reduced as illustrated in FIG. **6**B.
(475) In the wide-angle mode, the control system **710**, **752**, **350** is arranged to switch the switchable liquid crystal retarder **301** into a second retarder state in which a phase shift is introduced to polarisation components of light passing therethrough along an axis inclined to a normal to the plane of the switchable liquid crystal retarder **301**.
(476) By way of comparison, solid angular extent **402**D may be substantially the same as solid angular extent **402**B in a wide-angle mode. Such control of output solid angular extents **402**C, **402**D may be achieved by synchronous control of the sets **15**, **17** of light sources and the at least one switchable liquid crystal retarder **300**.
(477) Advantageously a privacy mode may be achieved with low image visibility for off-axis viewing and a large solid angular extent may be provided with high efficiency for a wide-angle mode, for sharing display imagery between multiple users and increasing image spatial uniformity.
(478) Additional polariser **318** is arranged on the same output side of the spatial light modulator **48** as the display output polariser **218** which may be an absorbing dichroic polariser. The display polariser **218** and the additional polariser **318** have electric vector transmission directions **219**, **319** that are parallel. As will be described below, such parallel alignment provides high transmission for central viewing locations.
(479) A transmissive spatial light modulator **48** is arranged to receive the output light from the backlight; an input polariser **210** is arranged on the input side of the spatial light modulator between the backlight **20** and the spatial light modulator **48**; an output polariser **218** is arranged on the output side of the spatial light modulator **48**; an additional polariser **318** is arranged on the output side of the output polariser **218**; and a switchable liquid crystal retarder **300** comprising a layer **314** of liquid crystal material is arranged between the at least one additional polariser **318** and the output polariser **318** in this case in which the additional polariser **318** is arranged on the output

side of the output polariser **218**; and a control system **710** is arranged to synchronously control the light sources **15**, **17** and the at least one switchable liquid crystal retarder **300**.

(480) Control system **710** further comprises control of voltage controller **752** that is arranged to provide control of voltage driver **350**, in order to achieve control of switchable liquid crystal retarder **301**.

(481) Advantageously, a privacy display is provided that has high reflectivity to an off-axis snooper while maintaining low reflectivity for an on-axis viewer. As described above, such increased reflectivity provides enhanced privacy performance for the display in an ambiently illuminated environment.

(482) The embodiments of FIGS. **29**A-B may alternatively be provided without the reflective polariser **302**. Thickness and complexity is reduced. Ambient light absorbed with the display optical stack. In alternative embodiments as illustrated hereinabove, the display polariser **310** may be the input polariser **210** and the additional polariser **318** arranged between a backlight **20** and the input polariser **210**.

(483) Operation in wide-angle mode will now be described.

(484) FIG. **30**A is a schematic diagram illustrating in side view propagation of output light from a spatial light modulator through the optical stack of FIG. **29**A in a wide-angle mode; and FIG. **30**B is a schematic graph illustrating the variation of output luminance with polar direction for the transmitted light rays in FIG. **30**A. Features of the embodiment of FIG. **30**A and FIG. **30**B not discussed in further detail may be assumed to correspond to the features with equivalent reference numerals as discussed above, including any potential variations in the features.

(485) When the liquid crystal retarder **301** is in a first state of said two states, the retarders **300** provide no overall transformation of polarisation component **360**, **361** to output light passing therethrough perpendicular to the plane of the switchable retarder **301** or at an acute angle to the perpendicular to the plane of the switchable retarder **301**. That is, polarisation component **362** is substantially the same as polarisation component **360** and polarisation component **364** is substantially the same as polarisation component **361**. Thus the angular transmission profile of FIG. **30**B is substantially uniformly transmitting across a wide polar region. Advantageously a display may be switched to a wide field of view.

(486) FIG. **30**C is a schematic diagram illustrating in top view propagation of ambient illumination light through the optical stack of FIG. **29**A in a wide-angle mode; and FIG. **30**D is a schematic graph illustrating the variation of reflectivity with polar direction for the reflected light rays in FIG. **30**C. Features of the embodiment of FIG. **30**C and FIG. **30**D not discussed in further detail may be assumed to correspond to the features with equivalent reference numerals as discussed above, including any potential variations in the features.

(487) Thus when the liquid crystal retarder **301** is in the first state of said two states, the retarders **300** provide no overall transformation of polarisation component **372** to ambient light rays **412** passing through the additional polariser **318** and then the retarders **300**, that is perpendicular to the plane of the retarders **300** or at an acute angle to the perpendicular to the plane of the retarders **300**.

(488) In operation in wide-angle mode, input light ray **412** has polarisation state **372** after transmission through the additional polariser **318**. For both head-on and off-axis directions, no polarisation transformation occurs and thus the reflectivity for light rays **402** from the reflective polariser **302** is low. Light ray **412** is transmitted by reflective polariser **302** and lost in the display polarisers **218**, **210** or the backlight of FIG. **1**A.

(489) Advantageously in a wide-angle mode, high luminance and low reflectivity is provided across a wide field of view. Such a display can be conveniently viewed with high contrast by multiple viewers. Other types of switchable privacy display will now be described.

(490) A display device **100** that may be switched between privacy and wide-angle modes of operation comprises an imaging waveguide and an array of light sources as described in U.S. Pat. No. 9,519,153, which is herein incorporated by reference in its entirety. The imaging waveguide

images an array of light sources to optical windows that may be controlled to provide high luminance on-axis and low luminance off-axis in a privacy mode, and high luminance with a large solid angle cone for share operation.
(491) It may be desirable to provide high image visibility for viewer movement in the elevation direction in both privacy and share modes.
(492) FIG. **31**A is a schematic diagram illustrating in perspective front view a polar transmission control arrangement **600** comprising an in-plane polariser **610** that is the display output polariser **218**, a polarisation switch **601** comprising a homeotropic alignment layer **617**B and a homogeneous alignment layer **617**A and an out-of-plane polariser **602**; FIG. **31**B is a schematic diagram illustrating in perspective side view the arrangement of FIG. **31**A; and FIG. **31**C is a schematic diagram illustrating in top view the arrangement of FIG. **31**A. Features of the embodiment of FIGS. **31**A-C not discussed in further detail may be assumed to correspond to the features with equivalent reference numerals as discussed above, including any potential variations in the features.
(493) Most generally in the present embodiments, the polarisation switch **601** comprises two surface alignment layers **617**A. **617**B disposed adjacent to the layer **601** of liquid crystal material **615** on opposite sides thereof and each arranged to provide alignment in the adjacent liquid crystal material **615**. One or both of the surface alignment layers **617**A, **617**B may be arranged to provide homogeneous alignment in the adjacent liquid crystal material; and one or both of the surface alignment layers **617**A. **617**B is arranged to provide homeotropic alignment in the adjacent liquid crystal material **615**.
(494) More specifically in the alternative embodiment of FIGS. **31**A-C, one of the surface alignment layers **617**B is arranged to provide homogeneous alignment in the adjacent liquid crystal material **615** and the other of the surface alignment layers **617**A is arranged to provide homeotropic alignment in the adjacent liquid crystal material **615**.
(495) FIG. **32**A is a schematic graph illustrating the polar variation of luminance transmission for the arrangement of FIGS. **31**A-C operating in the first mode and as described in TABLE 12; and FIG. **32**B is a schematic graph illustrating the polar variation of luminance transmission for the arrangement of FIG. **31**A operating in the second mode and as described in TABLE 12.
(496) TABLE-US-00013 TABLE 12 Item Value Out-of-plane polariser Material 603 ordinary refractive index, {right arrow over (n.sub.o)} at 550 nm 1.506 + 0.00165i 602 Material 603 extraordinary refractive index, {right arrow over (n.sub.e)} at 550 nm 1.53 + 0.116i   Thickness, d 6 μm Absorption axis 622 tilt ϕ to surface normal 199   0° Polarisation switch 601 Layer 614 of liquid crystal material 615 retardance 1000 nm Layer 614 of liquid crystal material 615 in-plane alignment 90° direction, 619Ap angle θ Layer 614 of liquid crystal material 615 in-plane alignment 180°   direction, 619Bp angle θ Privacy mode voltage 14 V Share mode voltage 2 V In-plane polariser 610 Absorption axis 620 in-plane angle 90°
(497) By way of comparison with the embodiment of FIG. **7**F, the alternative embodiments of FIG. **32**B achieves increased symmetry about the lateral direction in share mode of operation as illustrated in FIG. **32**B. Further the adiabatic propagation of polarisation states through the layer **614** of the polarisation switch **601** provides reduced visibility of colour variations in share mode of operation in comparison to the embodiments of FIGS. **34**A-B or FIGS. **36**A-B hereinbelow.
(498) FIG. **33**A is a schematic diagram illustrating in perspective side view a polar transmission control arrangement **600** comprising an in-plane polariser **218**, a splayed discotic passive compensation retarder **630**, a polarisation switch **601** comprising a homeotropic alignment layer **617**B and a homogeneous alignment layer **617**A and an out-of-plane polariser **602**; FIG. **33**B is a schematic diagram illustrating in perspective side view the arrangement of FIG. **31**B operating in a first mode of operation; FIG. **33**C is a schematic diagram illustrating in perspective side view the arrangement of FIG. **31**B operating in a second mode of operation. Features of the embodiment of FIGS. **33**A-C not discussed in further detail may be assumed to correspond to the features with equivalent reference numerals as discussed above, including any potential variations in the features.

(499) By way of comparison with FIGS. **31**A-C, in the alternative embodiment of FIGS. **33**A-C both alignment layers **617**A, **617**B provide homeotropic alignment in the liquid crystal material **615**. Further passive retarder **630** that is a negative C-plate is arranged to compensate for residual splay artefacts of the alignment of the polarisation switch **601**. Improved control of the polar luminance profiles may be provided in at least one of share and privacy modes of operation. Further variation of colour with viewing angle may be reduced.
(500) FIG. **34**A is a schematic diagram illustrating in perspective side view a polar transmission control arrangement **600** comprising an in-plane polariser **218**, a polarisation switch **601** comprising two homogeneous alignment layers **617**A, **617**B and an out-of-plane polariser **602** arranged in a first mode of operation; and FIG. **34**B is a schematic diagram illustrating in perspective side view the arrangement of FIG. **34**A arranged in a second mode of operation. Features of the embodiment of FIGS. **34**A-B not discussed in further detail may be assumed to correspond to the features with equivalent reference numerals as discussed above, including any potential variations in the features.
(501) By way of comparison with the embodiment of FIGS. **31**A-C, the alternative embodiment of FIGS. **34**A-B provides homogeneous alignment layers **617**A, **617**B. Advantageously reduced visibility of polarisation switch **601** deformation due to liquid crystal material **615** flow under applied pressure may be achieved.
(502) FIG. **35**A is a schematic graph illustrating the polar variation of luminance transmission for the arrangement of FIG. **34**A operating in the first mode and as described in TABLE 13; and FIG. **35**B is a schematic graph illustrating the polar variation of luminance transmission for the arrangement of FIG. **34**B operating in the second mode and as described in TABLE 13.
(503) TABLE-US-00014 TABLE 13 Item Value Out-of-plane polariser Material 603 ordinary refractive index, {right arrow over (n.sub.o)} at 550 nm 1.506 + 0.00165i 602 Material 603 extraordinary refractive index, {right arrow over (n.sub.e)} at 550 nm 1.53 + 0.116i Thickness, d 6 μm Absorption axis 622 tilt ϕ to surface normal 199 0° Polarisation switch 601 Layer 614 of liquid crystal material 615 retardance 750 nm Layer 614 of liquid crystal material 615 in-plane alignment 90° direction, 619Ap angle θ Layer 614 of liquid crystal material 615 in-plane alignment 180° direction, 619Bp angle θ Privacy mode voltage 0 V Share mode voltage 3 V In-plane polariser 610 Absorption axis 620 in-plane angle 90°
(504) By way of comparison with the embodiment of FIGS. **31**A-C, the alternative embodiment of FIGS. **34**A-B provides homogeneous alignment layers **617**A, **617**B. Advantageously reduced visibility of polarisation switch **601** deformation due to liquid crystal material **615** flow under applied pressure may be achieved.
(505) FIG. **36**A is a schematic diagram illustrating in perspective side view a polar transmission control arrangement **600** comprising an in-plane polariser **218**, a polarisation switch **601** comprising two homogeneous alignment layers **617**A, **617**B and an out-of-plane polariser **602** arranged in a first mode of operation; and FIG. **36**B is a schematic diagram illustrating in perspective side view the arrangement of FIG. **34**A arranged in a second mode of operation. Features of the embodiment of FIGS. **36**A-B not discussed in further detail may be assumed to correspond to the features with equivalent reference numerals as discussed above, including any potential variations in the features.
(506) By way of comparison with the embodiment of FIGS. **31**A-C, the alternative embodiment of FIGS. **36**A-B provides homeotropic alignment layers **617**A, **617**B. Advantageously reduced visibility of colour variations with viewing angle may be achieved.
(507) FIG. **37**A is a schematic graph illustrating the polar variation of luminance transmission for the arrangement of FIG. **36**A operating in the first mode and as described in TABLE 14; FIG. **37**B is a schematic graph illustrating the polar variation of luminance transmission for the arrangement of FIG. **36**B operating in the second mode and as described in TABLE 14.
(508) TABLE-US-00015 TABLE 14 Item Value Out-of-plane polariser Material 603 ordinary

refractive index, {right arrow over (n.sub.o)} at 550 nm 1.506 + 0.00165i 602 Material 603 extraordinary refractive index, {right arrow over (n.sub.e)} at 550 nm 1.53 + 0.116i Thickness, d 6 μm Absorption axis 622 tilt ϕ to surface normal 199 0° Polarisation switch 601 Layer 614 of liquid crystal material 615 retardance 750 nm Layer 614 of liquid crystal material 615 in-plane alignment 90° direction, 619Ap angle θ Layer 614 of liquid crystal material 615 in-plane alignment 180° direction, 619Bp angle θ Privacy mode voltage 1.6 V Share mode voltage 2.0 V In-plane polariser 610 Absorption axis 620 in-plane angle 90°

(509) By way of comparison with the embodiment of FIGS. **32**A-B, the alternative embodiment of FIGS. **37**A-B provides improved uniformity in share mode and reduced luminance for off-axis locations near to the optical axis **199** in privacy mode.

(510) It may be desirable to provide high visual security levels for a display device in a privacy mode and to provide high luminance in off-axis viewing angles in the wide-angle mode of the display device. The structure of a switchable privacy display will now be described.

(511) It may be desirable to provide increased security factor in privacy mode for off-axis snoopers and increased image visibility in share mode for off-axis viewers.

(512) FIG. **38**A is a schematic diagram illustrating in perspective side view a switchable privacy display device **100** comprising a backlight **20** comprising a source array, a waveguide **1**, a rear reflector **3** and a light turning component **50**; polar control transmission element **600** comprising a switchable diffractive arrangement **900** comprising a switchable diffractive liquid crystal retarder **901**, and an out-of-plane polariser **602**; and a transmissive spatial light modulator **48**; FIG. **38**B is a schematic diagram illustrating in perspective side view a switchable diffractive liquid crystal retarder **901** component **102**; and FIG. **38**C is a schematic diagram illustrating in perspective front view alignment orientations for an optical stack for use in the display device **100** of FIG. **38**A. Features of the embodiments of FIGS. **38**A-C not discussed in further detail may be assumed to correspond to the features with equivalent reference numerals, including any potential variations in the features.

(513) By way of comparison with FIG. **1**A, the reflective polariser **217** is omitted and the polar transmission control arrangement **600** comprises a switchable diffractive arrangement **900** comprising a switchable diffractive liquid crystal retarder **901** and out-of-plane polariser **602**.

(514) Switchable diffractive arrangement **900** is arranged between the out-of-plane polariser **602** and the display polariser **610**. The switchable diffractive arrangement **900** comprises a switchable diffractive liquid crystal retarder **901** comprising a layer **914** of liquid crystal material **915** arranged between transparent substrates **912**, **916**.

(515) A transmissive electrode arrangement **904** is arranged to drive the layer **914** of liquid crystal material **915** by means of applied voltages V from voltage drivers **950**. The display device **100** further comprises a control system **500** arranged to supply voltages by means of the drivers **950** to the transmissive electrode arrangement **904** for driving the layer **914** of liquid crystal material **915**.

(516) FIG. **38**B is an alternative embodiment illustrating that the switchable diffractive liquid crystal retarder **901** may be provided as a separate component **102**. Component **102** may be added during manufacture of the display device **100** or alternatively may be added to the display device **100** by a display user. Advantageously a switchable privacy display device **100** upgrade may be achieved.

(517) FIG. **38**C illustrates that the backlight **20** typically provides unpolarised or partially polarised light state **21**. Out-of-plane polariser **602** comprising dichroic material **603** with absorption axis **622** direction provides an output that is incident onto the switchable diffractive arrangement **900** with luminance that varies with polar angle as described hereinabove. The electrodes **902** of the switchable diffractive liquid crystal retarder **901** are patterned and arranged to extend along the vertical axis, that is with an orientation angle of 90°. The direction of diffraction orders described hereinbelow is provided along the 0°-180° lateral axis (x-axis direction).

(518) The switchable diffractive liquid crystal retarder **901** comprises alignment layers **617**A, **617**B

arranged to provide alignment of the layer **914** of liquid crystal material **915**. The two surface alignment layers **617**A. **617**B are disposed adjacent to the layer **914** of liquid crystal material **915** and on opposite sides thereof.
(519) The alignment directions **927**A, **927**B at the respective alignment layers **617**A, **617**B provide in-plane components **927**Ap, **927**Bp in the plane of the layer **914** of liquid crystal material **915**.
(520) Further, pretilt of the alignment directions **927**A, **927**B provides an out-of-plane component in the thickness direction {circumflex over (t)} through the layer **914** of liquid crystal material **915** that reduces degeneracy of the structure **965** of liquid crystal material **915** orientations and advantageously improves uniformity across the area **103** of the layer **914** of liquid crystal material **915**.
(521) The alignment layer **617**A on the side of the liquid crystal layer adjacent the array of separated electrodes has a component of alignment in the plane of the layer of liquid crystal material in the direction **197** that is orthogonal to the one direction **195**, and desirably achieves high transmission efficiency and high diffraction efficiency.
(522) Spatial light modulator **48** comprises input polariser **210** which is the display polariser **610** and output display polariser **218** with electric vector transmission directions **211**, **219** respectively.
(523) An illustrative electrode arrangement **904** will now be described.
(524) FIG. **38**D is a schematic diagram illustrating in perspective side view a transmissive electrode arrangement **904** for the switchable diffractive liquid crystal retarder **901** of FIG. **38**A; and FIG. **38**E is a schematic diagram illustrating in front view a transmissive electrode for the transmissive electrode arrangement of FIG. **38**D. Features of the embodiments of FIGS. **38**D-E not discussed in further detail may be assumed to correspond to the features with equivalent reference numerals, including any potential variations in the features.
(525) The electrode arrangement **904** of FIG. **38**D comprises electrodes **902**A, **902**B, **902**C arranged on a first side of the layer **914** of liquid crystal material **915** and the transmissive reference electrode **902**D arranged on the opposite side of the layer **914** of liquid crystal material **915**. Dielectric material **905** such as SiOx or Si.sub.3N.sub.4 may be arranged between the transmissive separated electrodes **902**A, **902**B and transmissive control electrode **902**C. The electrodes **902**A, **902**B, **902**C, **902**D may be provided by transmissive conductive material such as ITO for example.
(526) The electrodes **902**A, **902**B, **902**C, **902**D may be buried by the dielectric material **905** with respective refractive indices arranged to minimise diffraction from the electrodes **902**A, **902**B, **902**C, **902**D and the gaps **932** between the electrodes **902**A, **902**B, **902**C, **902**D in the direction **195**.
(527) The transmissive electrode arrangement **904** comprises an array of separated electrodes **902**A, **902**B and the array of separated electrodes **902**A, **902**B is arrayed in one direction **195**, that is in across the lateral direction (x-axis). The separated electrodes **902**A, **902**B extend across the area of the layer of liquid crystal material in the direction orthogonal to the one direction **195**.
(528) The electrode width w and the electrode pitch p may be selected to provide desirable diffractive properties of the switchable diffractive liquid crystal retarder **901** as will be described further hereinbelow.
(529) In the embodiment of FIG. **38**D, the separated electrodes **902**A, **902**B have a common connection **203**, and may alternatively be referred to as separated electrodes **902**A hereinbelow. In other embodiments such as those described further hereinbelow, the separated electrodes **902**A, **902**B may be connected separately.
(530) Common connection **903** of FIG. **38**D and common connections **903**T, **903**B, **903**L and **903**R of FIG. **38**E may be termed bus bars or shorting bars. The common connection is formed by conductors located outside an area of the spatial light modulator **48**, that is the common connection **903** is illustrated to be arranged outside of the border **101** of the active area **103** of the display device **100**. FIG. **38**D illustrates a common connection **903** to one end of the separated electrodes

902A, **902**B, however the common connection **903** bus bar connection may be extended to enclose the separated electrodes **902**A. **902**B so that the bus bar extends along both ends **903**T, **903**B and optionally the sides **903**L, **903**R. Connecting at both ends enables a substantial reduction in the impedance of the "fingers" of the separated electrodes, which then become electrically connected in parallel. This is important when the separated electrodes **902**A, **902**B are formed from a transparent conductor such as ITO that has a trade-off between transparency and conductivity. Further common electrode connections **903** may be provided by transparent common connection **903** electrodes within the active area or may be provided by transmissive or low impedance materials, such as metals, which are light blocking electrodes outside of the active area **103**. Voltage drops along the transmissive electrodes **902** may be reduced, advantageously achieving increased uniformity.
(531) The transmissive electrode arrangement **904** further comprises a control electrode **902**C extending across the layer **914**, the control electrode **902**C being arranged on the same side of the layer **914** of liquid crystal material **915** as the array of separated electrodes **902**A. **902**B covering the array of separated electrodes **902**A, **902**B. The control electrode **902**C and reference electrode **902**D may be planar electrodes.
(532) The transmissive electrode arrangement **904** further comprises a reference electrode **902**D extending across the entirety of the spatial light modulator **48**, the reference electrode **902**D being arranged on the opposite side of the layer **914** of liquid crystal material **915** from the array of separated electrodes **902**A, **902**B.
(533) Respective voltage drivers **950**A, **950**B at least are provided to drive the electrode arrangement **904** as will be described further hereinbelow.
(534) The operation of the display device **100** of FIG. **38**A operating in wide-angle mode will now be described further.
(535) FIG. **39**A is a schematic diagram illustrating in top view the structure and operation of the optical stack comprising a switchable diffractive arrangement **900** comprising switchable diffractive liquid crystal retarder **901** with the electrode arrangement **904** of FIG. **38**D for wide-angle mode; FIG. **39**B is a schematic diagram illustrating in perspective front view a transmissive electrode arrangement **904** and structure **965** of liquid crystal material **915** orientations for the switchable diffractive liquid crystal retarder **901** in wide-angle mode; and FIG. **39**C is a schematic diagram illustrating in top view a transmissive electrode arrangement **904** and structure **965** of liquid crystal material **915** orientations for the switchable diffractive liquid crystal retarder **901** in wide-angle mode. Features of the embodiment of FIGS. **39**A-C not discussed in further detail may be assumed to correspond to the features with equivalent reference numerals, including any potential variations in the features.
(536) Backlight **20** provides light output in cone **461**, with high luminance in direction **460** and typically lower luminance in directions **462**. Out-of-plane polariser **602** reduces the luminance for off-axis light in direction **460** with the polarisation state **461** that after propagation through the switchable diffractive liquid crystal retarder **901** is transmitted by the display polariser **610** that is the input polariser **210** of the spatial light modulator **48**.
(537) For illustrative purposes, plane waves **470** provide light that propagates in the direction **460**.
(538) Voltages V.sub.AC, V.sub.BC, V.sub.CD, are applied to respective electrodes **902**A, **902**B (connected to electrode **902**A in the embodiment using the electrode arrangement **904** of FIG. **38**D, where driver **950**C may be omitted). Electric fields E.sub.AC, E.sub.BC produce electric field lines **907** that provide reorientation of the liquid crystal material **915** into the gaps **932** to provide a diffractive molecular orientation **965** region **970** in a layer through the thickness direction {circumflex over (t)} that may be greatest in magnitude near the alignment layer **617**A but also through the layer **914** of liquid crystal material **915**.
(539) FIG. **39**D is a schematic graph illustrating a profile **430** of diffracted luminance into diffractive orders for the embodiment of FIG. **39**C in wide-angle mode and TABLES 15-16; and

FIG. **39**E is a schematic graph illustrating a profile **430** of diffracted luminance into diffractive orders for the embodiment of FIG. **39**C and TABLE 15 in wide-angle mode.

(540) TABLE-US-00016 TABLE 15 Illustrative Item Property embodiment Display polariser 610 Electric vector transmission 0° direction, 911 Electrode 902A, 902B Pitch, p 10 μm Width, w 3 μm Alignment layer 617A Type Homogeneous In-plane alignment direction 90° 927Ap angle θ.sub.A Pretilt angle 2° Alignment layer 617B Type Homeotropic In-plane alignment direction 270° 927Bp angle θ.sub.B Pretilt angle 90° LC layer 914 Retardance 1000 nm

(541) The control system **500** of FIG. **38**A is arranged to supply voltages V.sub.AC, V.sub.BC and V.sub.CD to the transmissive electrode arrangement **904** for driving the layer **314** of liquid crystal material **315** and arranged to control switchable light dispersion element **800**.

(542) FIG. **39**E illustrates that the amount of light diffraction provided by the switchable diffractive arrangement **900** may be modified by adjusting the drive voltage levels in the wide-angle mode. The control system **500** may be arranged to provide selection of the peak luminance, power efficiency and image visibility by control of the respective voltage drivers **950**. Advantageously increased display performance may be achieved depending on desirable characteristics for display device **100** operation.

(543) TABLE 16 shows exemplary voltages applied in three different modes of operation. The applied voltages V.sub.AC, V.sub.BC and V.sub.CD are typically alternating voltages so that no net DC voltage is applied for any longer than 1 second to the liquid crystal material **915**. Charge build-up in the layer **914** of liquid crystal material **915** is reduced and advantageously lifetime extended.

(544) TABLE-US-00017 TABLE 16 Item Wide-angle mode Privacy mode FIGURES 39A-H 40A-D V.sub.AC & V.sub.BC −20 V 0 V V.sub.CD −10 V 20 V

(545) The operation of the display device **100** will now be described.

(546) FIG. **39**F is a schematic diagram illustrating in top view the structure and operation of the display device comprising a switchable diffractive arrangement **900** for wide-angle mode. Features of the arrangement of FIG. **39**F not discussed in further detail may be assumed to correspond to the features with equivalent reference numerals, including any potential variations in the features.

(547) Backlight **20** provides light in light cone **461**. The size of cone **461** may for example be determined by the angle of full width half maximum luminance.

(548) Out-of-plane polariser **602** provides a reduction in off-axis luminance so that light cone **461** is output from the display polariser **610**.

(549) In wide-angle mode, diffraction in the switchable diffractive liquid crystal retarder **901** provides output cone **463** that has a wider cone angle than cone **471**.

(550) In operation, viewer **45** in viewing direction **445** and further viewers **47**L, **47**R in directions **447**L, **447**R also see light directed from the display device with higher luminance than would be provided by light from the light cone **471**. Advantageously wide-angle mode luminance is increased.

(551) A description of phase shifts for light that is diffracted in diffractive liquid crystal polar control retarders **901** will now be given.

(552) FIG. **39**G is a schematic diagram illustrating in top view the propagation of a first linear polarisation state **909** through a switchable diffractive liquid crystal retarder **901** arranged in wide-angle mode; and FIG. **39**H is a schematic diagram illustrating in perspective front view the propagation of the first polarisation state **909** through the switchable diffractive liquid crystal retarder **901** arranged in wide-angle mode. Features of the arrangement of FIGS. **39**G-H not discussed in further detail may be assumed to correspond to the features with equivalent reference numerals, including any potential variations in the features.

(553) FIG. **39**G illustrates a light ray **460** provided by a plane waves **470** incident onto a liquid crystal polar control retarder **901**.

(554) A plane wave **470** propagates through the spatially varying transparent material of the switchable diffractive liquid crystal retarder **901** such that its phase Γ on exiting the material

becomes spatially varied Γ(x). This spatial variation of phase Γ(x) leads to diffraction whereby the light couples into a series of plane waves propagating at varying angles away from the material.

(555) The transmissive electrode arrangement **904** is patterned to be capable of driving the layer **914** of liquid crystal material **915** into a structure **965** of orientations providing relative phase shifts Γ(x) that vary spatially across the area **103** of the layer **914** of liquid crystal material **915** so that the layer **914** of liquid crystal material **915** provides a diffractive effect. Further, the transmissive electrode arrangement **904** is patterned to be capable of driving the layer **914** of liquid crystal material into a structure **965** of orientations providing relative phase shifts Γ(x) that vary spatially in one direction **195** across the area **103** of the layer **914** of liquid crystal material **915** so that the layer **914** of liquid crystal material **915** provides a diffractive effect in the one direction **195**.

(556) In FIG. **39**A, the control system **500** is arranged in a wide-angle mode, to supply voltages to the transmissive electrode arrangement **904** that are selected to drive the liquid crystal material **915** into the structure **965** of orientations providing relative phase shifts Γ(x) that vary spatially across the area **103** of the layer **914** of liquid crystal material **915** so that the layer **914** of liquid crystal material **915** provides a diffractive effect.

(557) The operation of the display device **100** operating in privacy mode will now be described.

(558) FIG. **40**A is a schematic diagram illustrating in top view the structure and operation of the optical stack **104** comprising a switchable polar control retarder **900** for privacy mode; FIG. **40**B is a schematic diagram illustrating in perspective front view an arrangement **904** of electrodes **902**A, **902**B, **902**C, **902**D and structure **965** of liquid crystal material **915** orientations for a switchable diffractive liquid crystal retarder **901** in privacy mode; and FIG. **40**C is a schematic diagram illustrating in side view an arrangement **904** of electrodes **902**A, **902**B, **902**C, **902**D and structure **965** of liquid crystal material **915** orientations for a switchable diffractive liquid crystal retarder **901** in privacy mode. Features of the arrangements of FIGS. **40**A-C not discussed in further detail may be assumed to correspond to the features with equivalent reference numerals, including any potential variations in the features.

(559) In FIG. **40**A, the control system **500** of FIG. **38**A is arranged in a narrow-angle mode, to supply voltages to the transmissive electrode arrangement **904** that are selected to drive the liquid crystal material **915** into a structure **965** of orientations providing relative phase shifts Γ(x) that are uniform across the area **103** of the layer **914** of liquid crystal material **915**.

(560) A uniform voltage V.sub.AC, V.sub.BC is applied to the spaced electrodes **902**A, **902**B so that a uniform structure **965** of orientations of liquid crystal molecules **977** is provided across the area **103**. The transmissive electrode arrangement **904** drives the layer **914** of liquid crystal material **915** into a structure **965** of orientations providing uniform phase shifts/o across the area **103** of the layer **914** of liquid crystal material **915** so that the layer **914** of liquid crystal material **915** provides no diffractive effect.

(561) Comparing FIG. **40**B with FIG. **39**B, the present embodiments typically achieve switching between a wide-angle mode with optical axis **977** of the liquid crystal material **915** with an alignment direction along the direction **195**; and narrow-angle mode(s) with optical axis **977** of the liquid crystal material **915** with an alignment direction perpendicular to the direction **195**, for example provided by the alignment direction **927**Ap. In other words switching may be provided by in-plane rotation of the liquid crystal material **915** by application of suitable drive voltages.

(562) Such arrangements advantageously achieve high image security at desirable non-viewing direction **447** in privacy mode, while providing switching into a wide-angle mode with high image visibility in viewing direction **447** for example.

(563) FIG. **40**D is a schematic diagram illustrating in top view the structure and operation of the display device **100** comprising a switchable polar control retarder **900** for wide-angle mode. Features of the arrangement of FIG. **40**D not discussed in further detail may be assumed to correspond to the features with equivalent reference numerals, including any potential variations in the features.

(564) By way of comparison with FIG. **39**F, the cone **461** is not diffused to cone **463** by diffraction of the switchable diffractive liquid crystal retarder **901**. Further, the layer **914** of liquid crystal material **915** provides luminance reduction in light cones **467** so that the output cone **469** is reduced in size in comparison to the input light cone **461**. Advantageously security factor. S in non-viewing directions **447** is increased. High transmission efficiency of throughput of the switchable polar control retarder **900** is provided.
(565) Alternative electrode arrangements **904** for use in switchable diffractive liquid crystal retarders **901** will now be described.
(566) FIGS. **41**A-B are schematic diagrams illustrating in perspective side views alternative transmissive electrode arrangements **904** comprising interdigitated electrodes **902**A, **902**B; and FIGS. **41**C-D are schematic diagrams illustrating in perspective side views alternative electrode arrangements comprising interdigitated electrodes arranged on a single substrate and further control and reference electrodes. Features of the arrangements of FIGS. **41**A-D not discussed in further detail may be assumed to correspond to the features with equivalent reference numerals, including any potential variations in the features.
(567) By way of comparison to FIG. **38**D, in the alternative embodiment of FIGS. **41**A-B, the array of separated electrodes **902** comprises two interdigitated sets of separated electrodes **902**A, **902**B. Each set of separated electrodes **902**A, **902**B has a common connection **903**A, **903**B respectively.
(568) The common connection **903** for each set of separated electrodes **902**A, **902**B is formed by a respective bar **903**A, **903**B, the bars being located outside the active area **103** of the spatial light modulator **48**. The electrodes **902**A, **902**B may be formed by etching a single layer of transparent conductor. Alternatively, the electrodes may be formed by etching two transparent conductors separated by an insulator (not shown). In this case each of the electrodes **902**A, **902**B may be formed with a bus bar **903**A at each end in order to reduce the electrode impedance, as described in FIGS. **38**D-E.
(569) The alternative embodiment of FIG. **41**A comprises the transmissive reference electrode **902**D, which may be embodied by ITO or silver nanowire for example. FIG. **41**A illustrates voltages V.sub.AD and V.sub.BD which are the voltages applied respectively to the common connection **903**A and **903**B, each with respect to the potential of the reference electrode **902**D. The potentials V.sub.AD and V.sub.BD may be equal and opposite to each other to provide a symmetrical diffraction effect. The reference electrode **902**D can provide a field perpendicular to the plane of the cell. This field can augment or override the effect of the alignment layers **617**A. **617**B (not shown). If a homogeneous alignment layer is used at either side of layer **914**, the electric field can at least partially override the alignment of the layer **914** of liquid crystal material **915** on opposing sides of the layer **914** of liquid crystal material **915**.
(570) The potentials V.sub.AD and V.sub.BD may also be set differently from each other to provide an asymmetrical diffraction effect. The same effect may be produced by using three ground referenced voltages applied to electrode **902**A, **902**B and **902**D. Increased control of the structure **965** of liquid crystal material **915** orientations may be provided. Increased diffusion into light cone **465** may be achieved and advantageously increased visibility in direction **447**.
(571) By comparison, the alternative embodiment of FIG. **41**B has the transmissive reference electrode **902**D omitted. In this case the potential V.sub.AB which will typically be an ac signal such as a square wave or sine wave, is applied directly between the common connections **903**A and **903**B. A symmetrical diffraction effect is produced. Capacitance is reduced. Advantageously cost and complexity may be reduced, and light transmission increased and power consumption reduced.
(572) In comparison to FIGS. **41**A-B, in the alternative embodiments of FIGS. **41**C-D a further control electrode **902**C is provided. The further control electrode **902**C, in conjunction with the reference electrode **902**D provides for a mode in which a uniform field perpendicular to the plane of the of the layer **914** of liquid crystal material **915** may be applied. In this case the potential V.sub.BC and V.sub.AC may be set to zero volts. In a further mode V.sub.CD may also be set to

zero. In these modes the structure may operate like a polar control retarder, as described elsewhere herein. In another mode, when V.sub.AC and V.sub.BC are set to the same non-zero potential then an electric field pattern that produces a periodic phase pattern in the liquid crystal layer **914** is produced.
(573) The structure may also be operated with V.sub.AC and V.sub.BC set to different voltages such as V.sub.BC is the negative waveform to that for V.sub.AC. Different distributions of diffraction orders may be produced. Advantageously the visibility of the wide-angle mode in the direction **447** may be adjusted by the control system **500**.
(574) FIG. **41**D illustrates a case where the additional polar control retarder operation modes are not provided within the diffractive diffuser, and reference electrode **902**D is omitted. In the diffractive diffuser mode, the voltages V.sub.BC and V.sub.AC would be provided as described with reference to FIG. **41**C.
(575) As may be used herein, the terms “substantially” and “approximately” provide an industry-accepted tolerance for its corresponding term and/or relativity between items. Such an industry-accepted tolerance ranges from zero percent to ten percent and corresponds to, but is not limited to, component values, angles, et cetera. Such relativity between items ranges between approximately zero percent to ten percent.
(576) While various embodiments in accordance with the principles disclosed herein have been described above, it should be understood that they have been presented by way of example only, and not limitation. Thus, the breadth and scope of this disclosure should not be limited by any of the above-described exemplary embodiments, but should be defined only in accordance with any claims and their equivalents issuing from this disclosure. Furthermore, the above advantages and features are provided in described embodiments, but shall not limit the application of such issued claims to processes and structures accomplishing any or all of the above advantages.
(577) Additionally, the section headings herein are provided for consistency with the suggestions under 37 CFR 1.77 or otherwise to provide organizational cues. These headings shall not limit or characterize the embodiment(s) set out in any claims that may issue from this disclosure. Specifically and by way of example, although the headings refer to a “Technical Field,” the claims should not be limited by the language chosen under this heading to describe the so-called field. Further, a description of a technology in the “Background” is not to be construed as an admission that certain technology is prior art to any embodiment(s) in this disclosure. Neither is the “Summary” to be considered as a characterization of the embodiment(s) set forth in issued claims. Furthermore, any reference in this disclosure to “invention” in the singular should not be used to argue that there is only a single point of novelty in this disclosure. Multiple embodiments may be set forth according to the limitations of the multiple claims issuing from this disclosure, and such claims accordingly define the embodiment(s), and their equivalents, that are protected thereby. In all instances, the scope of such claims shall be considered on their own merits in light of this disclosure, but should not be constrained by the headings set forth herein.

Claims

1. A polar angle control display device comprising: a spatial light modulator arranged to output light; an in-plane polariser having an absorption axis in a plane of the in-plane polariser arranged on a side of the spatial light modulator; and an out-of-plane polariser having an absorption axis in a direction having a component out of a plane of the out-of-plane polariser arranged on the same side of the spatial light modulator as the in-plane polariser.
2. A polar angle control display device according to claim 1, further comprising a polarisation switch provided between the in-plane polariser and the out-of-plane polariser, the polarisation switch being switchable between a first mode in which it is arranged to change a polarisation state of the light passing therethrough and a second mode in which it is arranged to affect the

polarisation state of the light passing therethrough differently from the first mode.

3. A polar angle control display device according to claim 2, wherein, in the first mode, the polarisation switch is arranged to change the polarisation state of the light passing therethrough from a first linear polarisation state to a second linear polarisation state that is orthogonal to the first linear polarisation state.

4. A polar angle control display device according to claim 2, wherein, in the second mode, the polarisation switch is arranged not to change the polarisation state of the light passing therethrough.

5. A polar angle control display device according to claim 2, wherein the polarisation switch comprises a switchable layer of liquid crystal material and at least one electrode arranged to switch the state of the liquid crystal material.

6. A polar angle control display device according to claim 5, wherein the polarisation switch further comprises two surface alignment layers disposed adjacent to the switchable layer of liquid crystal material on opposite sides thereof and each arranged to provide alignment in the adjacent liquid crystal material.

7. A polar angle control display device according to claim 6, wherein one or both of the surface alignment layers is arranged to provide homogeneous alignment in the adjacent liquid crystal material.

8. A polar angle control display device according to claim 6, wherein one or both of the surface alignment layers is arranged to provide homeotropic alignment in the adjacent liquid crystal material.

9. A polar angle control display device according to claim 6, wherein one of the surface alignment layers is arranged to provide homogeneous alignment in the adjacent liquid crystal material and the other of the surface alignment layers is arranged to provide homeotropic alignment in the adjacent liquid crystal material.

10. A polar angle control display device according to claim 6, wherein each of the surface alignment layers has a pretilt having a pretilt direction with a component in the plane of the switchable layer of liquid crystal material that is parallel or anti-parallel or orthogonal to the electric vector transmission direction of the in-plane polariser.

11. A polar angle control display device according to claim 6, wherein each alignment layer has a pretilt having a pretilt direction with a component in the plane of the switchable layer of liquid crystal material and the components are orthogonal.

12. A polar angle control display device according to claim 5, wherein the polarisation switch further comprises at least one passive retarder.

13. A polar angle control display device according to claim 1, further comprising a biaxial retarder arrangement arranged between the out-of-plane polariser and the in-plane polariser.

14. A polar angle control display device according to claim 13, wherein the biaxial retarder arrangement comprises a B-plate.

15. A polar angle control display device according to claim 14, wherein the B-plate has principal components of refractive index nx, ny, nz and a thickness d, and wherein for light at a wavelength of 550 nm: the value of (nx−ny) d is in a range between −130 nm and −170 nm, the value of (nx−nz) d is in a range between +270 nm and +330 nm, and the value of a parameter Rth is in a range between +340 nm and +400 nm, wherein Rth=(nx+ny)/2−nz)d.

16. A polar angle control display device according to claim 13, wherein the biaxial retarder arrangement comprises a C-plate arranged to receive the light output from an A-plate.

17. A polar angle control display device according to claim 16, wherein for light at a wavelength of 550 nm: the A-plate has a retardance in a range between +85 nm and +115 nm, and either: the C-plate is a negative C-plate with a retardance in a range between −190 nm and −250 nm, or the C-plate is a positive C-plate with a retardance in a range between +220 nm and +280 nm.

18. A polar angle control display device according to claim 1, wherein the direction of the absorption axis of the out-of-plane polariser is normal to the plane of the out-of-plane polariser.

19. A polar angle control display device according to claim 1, wherein the direction of the absorption axis of the out-of-plane polariser is inclined at an acute angle to the normal orthogonal to the plane of the out-of-plane polariser.
20. A polar angle control display device according to claim 1, wherein the direction of the absorption axis of the out-of-plane polariser changes monotonically along a predetermined axis across the polar angle control display device.
21. A polar angle control display device according to claim 1, wherein the polar angle control display device is curved with a concave curvature as viewed from an output side of the polar angle control display device.
22. A polar angle control display device according to claim 1, wherein said side of the spatial light modulator is an output side of the spatial light modulator and the spatial light modulator comprises an output polariser.
23. A polar angle control display device according to claim 22, wherein the output polariser is the in-plane polariser.
24. A polar angle control display device according to claim 22, wherein the in-plane polariser is a different component from the output polariser.
25. A polar angle control display device according to claim 22, further comprising: an additional polariser arranged on the output side of the output polariser; and at least one polar control retarder arranged between the output polariser and the additional polariser.
26. A polar angle control display device according to claim 25, wherein the additional polariser is the in-plane polariser.
27. A polar angle control display device according to claim 25, further comprising a reflective polariser arranged on the output side of the output polariser, wherein the reflective polariser is the in-plane polariser.
28. A polar angle control display device according to claim 1, wherein said side of the spatial light modulator is an input side of the spatial light modulator and the spatial light modulator comprises an input polariser.
29. A polar angle control display device according to claim 22, wherein the in-plane polariser is an input polariser.
30. A polar angle control display device according to claim 22, further comprising an input polariser, wherein the in-plane polariser is a different component from the input polariser.
31. A polar angle control display device according to claim 28, further comprising: an additional polariser arranged on the input side of the input polariser; and at least one polar control retarder arranged between the input polariser and the additional polariser.
32. A polar angle control display device according to claim 31, wherein the additional polariser is the in-plane polariser.
33. A polar angle control display device according to claim 1, wherein the spatial light modulator is a transmissive spatial light modulator.
34. A polar angle control display device according to claim 1, wherein the spatial light modulator is an emissive spatial light modulator and said side of the spatial light modulator is an output side of the spatial light modulator.
35. A polar angle control display device according to claim 1, further comprising: at least one polar control retarder arranged between the in-plane polariser and the out-of-plane polariser, the at least one polar control retarder including a switchable liquid crystal retarder comprising a layer of liquid crystal material; and a transmissive electrode arrangement arranged to drive the layer of liquid crystal material, wherein the transmissive electrode arrangement is patterned to be capable of driving the layer of liquid crystal material into a structure of orientations providing relative phase shifts that vary spatially across an area of the layer of liquid crystal material so that the layer of liquid crystal material provides a diffractive effect.
36. A polar angle control display device according to claim 35, wherein the transmissive electrode

arrangement is also capable of driving the layer of liquid crystal material into a structure of orientations providing uniform phase shifts across the area of the layer of liquid crystal material so that the layer of liquid crystal material provides no diffractive effect.

37. A polar angle control display device according to claim 35, wherein the transmissive electrode arrangement comprises an array of separated electrodes.

38. A polar angle control display device according to claim 37, wherein the array of separated electrodes is arrayed in one direction and the separated electrodes extend across the area of the layer of liquid crystal material in the direction orthogonal to the one direction.

39. A polar angle control display device according to claim 37, wherein the array of separated electrodes comprises two interdigitated sets of separated electrodes.

40. A polar angle control display device according to claim 37, wherein the transmissive electrode arrangement further comprises a control electrode extending across the entirety of the spatial light modulator, the control electrode being arranged on the same side of the layer of liquid crystal material as the array of separated electrodes, outside the array of separated electrodes.

41. A polar angle control display device according to claim 37, wherein the transmissive electrode arrangement further comprises a reference electrode extending across the entirety of the spatial light modulator, the reference electrode being arranged on the opposite side of the layer of liquid crystal material from the array of separated electrodes.

42. A polar angle control display device according to claim 35, further comprising a control system arranged to supply voltages to the transmissive electrode arrangement for driving the layer of liquid crystal material.

43. A polar angle control display device according to claim 42, wherein the control system is arranged: in a narrow-angle mode, to supply voltages to the transmissive electrode arrangement that are selected to drive the layer of liquid crystal material into a structure of orientations providing relative phase shifts that are uniform across the area of the layer of liquid crystal material; and in a wide-angle mode, to supply voltages to the transmissive electrode arrangement that are selected to drive the layer of liquid crystal material into the structure of orientations providing relative phase shifts that vary spatially across the area of the layer of liquid crystal material so that the layer of liquid crystal material provides a diffractive effect.

44. A polar angle control display device according to claim 35, wherein the switchable liquid crystal retarder comprises two surface alignment layers disposed adjacent to the layer of liquid crystal material and on opposite sides thereof.

45. A polar angle control display device according to claim 38, wherein the switchable liquid crystal retarder comprises two surface alignment layers disposed adjacent to the layer of liquid crystal material and on opposite sides thereof, and the alignment layer on the side of the layer of liquid crystal material adjacent the array of separated electrodes has a component of alignment in the plane of the layer of liquid crystal material in the direction that is orthogonal to the one direction.

46. A polar angle control component for assembly with a display device comprising a spatial light modulator, the polar angle control component comprising an out-of-plane polariser having an absorption axis in a direction having a component out of the plane of the out-of-plane polariser.

47. A polar angle control component according to claim 46, wherein the polar angle control component further comprises a polarisation switch, the polarisation switch being switchable between a first mode in which it is arranged to change a polarisation state of the light passing therethrough and a second mode in which it is arranged to affect the polarisation state of the light passing therethrough differently from the first mode.

48. A polar angle control component according to claim 47, wherein the polar angle control component further comprises an in-plane polariser having an absorption axis in a plane of the in-plane polariser, the polarisation switch being provided between the in-plane polariser and the out-of-plane polariser.

49. A polar angle control component according to claim 46, wherein the polar angle control component further comprises an in-plane polariser having an absorption axis in a plane of the in-plane polariser.