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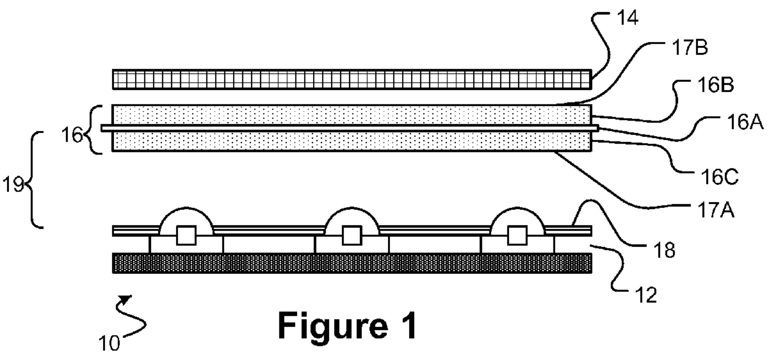

Figure 1

(57) Abstract: Displays comprise light control layers in an optical path between a light source, such as an array of light emitting diodes and a spatial light modulator such as a liquid crystal display panel. The light control layer comprises an enhanced specular reflector (ESR) film in optical contact to at least one layer of a transparent or translucent material. The light control layer transmits light from the light source more readily than the ESR film standing on its own. In some embodiments the display may provide enhanced contrast and peak luminance.

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DISPLAYS INCORPORATING LEAKY REFLECTORS

Reference to Related Applications

[0001] This application claims Paris Convention priority from United States Patent Applications No. 61/241,681 filed 11 September 2009, and No. 61/287,117 filed 16 December 2009 . For the purposes of the United States of America, this application claims the benefit under 35 U.S.C. §119 of United States Patent Applications No. 61/241,681 filed 11 September 2009, and No. 61/287,117 filed 16 December 2009, both of which are hereby incorporated by reference.

Technical Field

[0002] The invention relates to backlit displays. Embodiments may provide displays such as televisions, computer displays, special purpose displays such as medical imaging displays or virtual reality displays, video game displays, advertising displays, and the like.

Background

[0003] A wide variety of electronic displays are presently in use in a multitude of different applications, including televisions, computer displays, special purpose displays such as medical imaging displays or virtual reality displays, video game displays, advertising displays, and the like. Some electronic displays include a backlit light modulator. The light modulator is controllable to adjust the light passing through its pixels to display an image. In some such displays the backlight is controllable to cause a non-uniform distribution of light on the light modulator.

[0004] There exists a need for practical improved displays, and methods and apparatus for illuminating light modulators in displays capable of displaying high quality images. There is a particular need for practical displays capable of displaying images with enhanced contrast and peak luminance.

Summary of the Invention

[0005] The invention has a wide range of different aspects, some of which are as follows.

[0006] One aspect provides a display comprising a light source, a spatial light modulator, and a light control layer in an optical path between the light source and the spatial light modulator. The light control layer comprises an enhanced specular reflector layer and at least a first optical layer in optical contact with a first side of the enhanced specular reflector layer. The first optical layer is at least one of substantially transparent and substantially translucent. In some embodiments: the light control layer is coextensive with the spatial light modulator, the light source comprises a plurality of individually-controllable light emitters arranged in an array, the display comprises a back reflector spaced apart from and parallel to the light control layer, and/or the first optical layer comprises a rear layer located between the enhanced specular reflector layer and the back reflector, an optical cavity is defined between the back reflector and the enhanced specular reflector layer, and the rear layer occupies at least 3/4 of a thickness of the optical cavity.

[0007] Another aspect provides a backlight assembly comprising a light control layer and a light source configured to emit light toward the light control layer. The light control layer comprises an enhanced specular reflector layer and a first optical layer in optical contact with a first side of the enhanced specular reflector layer. The first optical layer is substantially transparent and/or substantially translucent. In some embodiments: the light control layer is coextensive with the spatial light modulator, the light source comprises a plurality of individually-controllable light emitters arranged in an array, and/or the first optical layer comprises a rear layer located between the enhanced specular reflector layer and the back reflector, an optical cavity is defined between the back reflector and the enhanced specular reflector layer, and the rear layer occupies at least 3/4 of a thickness of the optical cavity.

[0008] Another aspect provides a light control layer comprising an enhanced specular reflector layer and a first optical layer in optical contact with a first side of the enhanced specular reflector layer. The first optical layer is substantially transparent and/or substantially translucent. In some embodiments: the light control layer is coextensive with the spatial light modulator, the light source comprises a plurality of individually-controllable light emitters arranged in an array, the display comprises a back reflector spaced apart from and parallel to the light control layer; the backlight assembly comprises a back reflector spaced apart from and parallel to the light control layer, and/or the first optical layer comprises a rear layer located between the enhanced specular reflector layer and the back reflector, an optical cavity is defined between the back reflector and the enhanced specular reflector layer, and the rear layer occupies at least 3/4 of a thickness of the optical cavity.

[0009] Another aspect provides a light emitter comprising a light emitting region and a package, the package comprising a back reflector and a light control layer mounted on the back reflector and enclosing the light emitting region therebetween. In some embodiments according to this aspect the light control layer comprises an enhanced specular reflector layer and a first optical layer in optical contact with a first side of the enhanced specular reflector layer. The first optical layer is substantially transparent and/or substantially translucent. In some such embodiments, the first side of the enhanced specular reflector layer faces the light emitting region. In other such embodiments, the first side of the enhanced specular reflector layer faces away from the light emitting region.

[0010] Another aspect provides a control system for a display comprising a light source configured to emit light through a light control layer onto a light modulator. The control system comprises a light source controller configured to generate control signals for controlling the light source, a light field simulator configured to generate a light field simulation of the light field produced at the light modulator by light emitted from the light source that passes through the light control layer, and a light modulator controller configured to generate light modulator control signals for controlling the light modulator based at least in part on the light field simulation. The light field simulator includes a model that models or estimates the effect of the light control layer, as described herein, on light propagating from the light source.

[0011] Another aspect provides a method for controlling a display comprising a light source configured to emit light through a light control layer onto a light modulator. The method comprises generating light source control signals for controlling the light source, generating a light field simulation of the light field produced at the light modulator by light emitted from the light source in response to the light source control signals and passing through the light control layer, and generating light modulator control signals for controlling the light modulator based at least in part on the light field simulation.

[0012] Further aspects of the invention and features of specific embodiments of the invention are described below.

Brief Description of the Drawings

[0013] The accompanying drawings illustrate non-limiting example embodiments of the invention.

[0014] Figure 1 is a schematic cross-section of a portion of a display according to an example embodiment.

[0015] Figure 1A is a schematic view of a display according to an example embodiment.

[0016] Figure 2 is a schematic cross-section of a portion of a light control layer according to an example embodiment

[0017] Figure 3 is a graph showing point spread functions of light from a light emitter.

[0018] Figure 4A is schematic plan view of a portion of a light control layer according to an example embodiment deployed over an array of light emitters.

[0019] Figure 4B is schematic plan view of a portion of a light control layer according to an example embodiment deployed over an array of light emitters.

[0020] Figure 4C is schematic plan view of a portion of a light control layer according to an example embodiment deployed over an array of light emitters.

[0021] Figure 5 is a schematic cross-section of a portion of a display according to an example embodiment.

[0022] Figure 6 is a schematic cross-section of a portion of a display according to an example embodiment.

[0023] Figure 7 is a schematic cross-sectional depiction of an optical path between a light source and light modulator.

[0024] Figure 8 is a graph of light intensity as a function of position on a light modulator for typical and enhanced point spread functions of a single light emitter.

[0025] Figure 8A is a graph of light intensity as a function of position on a light modulator for a plurality of light emitters.

[0026] Figure 8B is a graph of light intensity as a function of position on a light modulator for a plurality of light emitters.

[0027] Figure 9 is a block diagram of a control system for controlling a display.

[0028] Figure 10 is a schematic cross-section of a portion of a display according to an example embodiment.

[0029] Figure 11 is a schematic cross-section of a portion of a light control layer according to an example embodiment.

[0030] Figure 12 is an isometric view of a light-emitting tile according to an example embodiment.

[0031] Figure 13 is a schematic isometric view of a light-emitting diode according to an example embodiment.

[0032] Figure 14 is a schematic cross-section of a portion of a display 10 according to an example embodiment.

[0033]Figure 15A is a schematic view of light in a part of a display.

[0034]Figure 15B is a schematic view a point spread function of light from light emitters.

[0035]Figure 15C is a schematic view of a spread function of light from light emitters.

[0036]Figures 16A is a cross-sectional schematic view of an optical element according to an example embodiment.

[0037]Figure 16B is a graph of intensity of light along a line.

[0038]Figure 17 is a perspective view of a part of a display according to an example embodiment.

[0039]Figure 18A is a cross-sectional schematic view of an optical element according to an example embodiment.

[0040]Figure 18B is a graph of reflectance for various incident angles.

[0041]Figure 18C is a graph of intensity of light along a line.

[0042]Figure 19 is a schematic view of a conventional liquid crystal display stack.

[0043]Figure 20 is a schematic view of a liquid crystal display stack according to an example embodiment.

[0044]Figure 21 is a diagram of a pattern of light from several light emitters on a light modulator.

[0045]Figure 22 is a diagram of point spread functions overlaid on a grid.

<u>Description</u>

[0046] Throughout the following description, specific details are set forth in order to provide a more thorough understanding of the invention. However, the invention may be practiced without these particulars. In other instances, well known elements have not been shown or described in detail to avoid unnecessarily obscuring the invention. Accordingly, the specification and drawings are to be regarded in an illustrative, rather than a restrictive, sense.

[0047] Figure 1 shows a display **10** according to an example embodiment. Display **10** comprises a light source **12** that is configured to emit light to illuminate a transmission-type light modulator **14**. Light modulator **14** may, for example, comprise a liquid crystal display panel (LCD panel). Light modulator **14** may comprise an array of pixels which are controllable to vary the amount of incident light that is transmitted by light modulator **14**. In some embodiments the pixels comprise individually controllable color sub-pixels.

[0048] A light control layer **16** is located between light source **12** and light modulator **14**. Light from light source **12** passes through light control layer **16** to reach light modulator **14**. Light control layer has a back side **17A** facing toward light source **12** and a front side **17B** facing toward light modulator **14**.

[0049] Light control layer **16** comprises a layer **16A** of an enhanced specular reflector (ESR). The ESR layer **16A** may comprise a multilayer dielectric film that reflects and transmits light over substantially all visible wavelengths and at a wide range of angles of incidence with low absorption. ESR layer **16A** may comprise a highly reflective ESR film that reflects a substantial proportion of visible light. ESR film is commercially available from 3M Electronic Display Lighting Optical Systems Division of St. Paul, MN, USA under the brand name Vikuiti™. Vikuiti™ Enhanced Specular Reflector film is stated to be 98.5% reflective over the entire visible spectrum, regardless of the angle of incidence.

[0050] ESR layer **16A** may be thin. For example, one type of Vikuiti™ ESR film suitable for application in an embodiment as shown in Figure 1 has a thickness of 65 μm.

[0051] Light control layer **16** also comprises at least one layer of a transparent or translucent material having an index of refraction that is greater than that of air (e.g. greater than 1) and is in optical contact with ESR layer **16A**. In the illustrated embodiment, light control layer comprises both a front layer **16B** and a rear layer **16C**. Other embodiments have only one of layers **16B** and **16C**.

[0052] Due to the presence of layers **16B** and/or **16C**, light control layer **16** has a reflectivity significantly lower than ESR layer **16A** would have if standing on its own in air. Layers **16B** and/or **16C** act to reduce the reflectivity of ESR layer **16A**. Layers **16B** and/or **16C** may comprise, for example, suitable plastics such as:

- polycarbonates;
- Poly(methyl methacrylate) (e.g. Plexiglas™);
- acrylics; and
- polyurethane;
- birefringent polyester;
- isotropic polyester; and
- syndiotactic polystyrene.

Layers **16B** and **16C** may be made out of suitable glasses, or other materials that are substantially clear or translucent to wavelengths of light in the visible range.

[0053] The thicknesses of layers **16B** and **16C** may be varied. In some embodiments, layers **16B** and **16C** have thicknesses in excess of ½ mm (500 μm). For example, in an example embodiment, layers **16B** and **16C** have thicknesses in the range of 1mm to 5mm. In some cases, layers **16B** and **16C** are significantly thicker than ESR layer **16A**. For example, one or both of layers **16B** and **16C** may have a thickness that is at least 5 times that of a thickness of ESR layer **16A**.

[0054] As shown in Figure 1, display **10** comprises a reflector **18** at or behind light source **12**. Reflector **18** may, for example, comprise an ESR layer or a diffuse scatterer such as a suitable white ink or white paint. An optical cavity **19** is defined between reflector **18** and layer **16A** of light control layer **16**. In the illustrated embodiment, light is emitted by light source **12** toward light control layer **16**. At light control layer **16**, some of the light is reflected and some of the light is transmitted. The transmitted light passes to light modulator **14**. Reflected light passes to reflector **18** and is recycled by being reflected back toward light control layer **16**.

[0055] In some embodiments, light source **12** comprises a plurality of individually-controllable light emitters. The light emitters may be arranged such that the amount of light emitted by light source **12** can be made to vary from location to location across light source **12** by controlling the amounts of light emitted by different ones of the individually-controllable light emitters. Providing a light control layer **16** as described herein can provide special advantages in some embodiments that also have a locally-controllable light source **12**.

[0056] The reflectivity of light control layer **16** may be controlled by choosing an appropriate material for layers **16B** and **16C** (or one of these layers if the other is not present). A main parameter that affects the reflectivity of light control layer **16** is the index of refraction of the material of layers **16B** and **16C** that is in optical contact with ESR layer **16A**. The reflectivity of light control layer **16** may be controlled to adjust the point spread function of light from light source **12** that emerges from layer **16**. In general, the higher the reflectivity of layer **16**, the more layer **16** will broaden the point spread function of light from light source **12**. Increased broadening may be desirable, for example, where light source **12** comprises a relatively sparse array of LEDs and where light source **12** comprises LED that output light over a narrow angular aperture. In some embodiments, light control layer **16** reflects in the range of about 65% to 85% of the light incident on it. In some embodiments light control layer **16** reflects approximately 73% ±5% of the light incident on it. In some embodiments, light control layer **16** specularly reflects in the range of about 5-20% of the light incident on it.

[0057] By way of non-limiting example, a light control layer as described herein may be incorporated between a light source and light modulator in displays having architectures as described in any of :

- United States Patent No. 6891672 issued 10 May 2005 and entitled High Dynamic Range Display Devices,
- United States Patent No. 7403332 issued 22 July 2008 and Entitled High Dynamic Range Display Devices,
- United States Patent publication No. 2008/0180466 published 31 July 2008 and entitled Rapid Image Rendering on Dual-modulator Displays,

- PCT Publication No. WO 2002/069030 published 6 September 2002 and entitled “High Dynamic Range Display Devices”;
- PCT Publication No. WO 2003/077013 published 18 September 2003 and entitled “High Dynamic Range Display Devices”;
- PCT Publication No. WO 2005/107237 published 10 November 2005 and entitled “Method for Efficient Computation of Image Frames for Dual Modulation Display Systems Using Key Frames”;
- PCT Publication No. WO 2006/010244 published 2 February 2006 and entitled “Rapid Image Rendering on Dual-Modulator Displays”.
- PCT Publication No. WO 2006/066380 published 29 June 2006 and Entitled: Wide Color Gamut Displays; and
- PCT Publication No. WO 2008/092276 published 7 August 2008 and entitled: Calibration of Displays Having Spatially-Variable Backlight;

all of which are hereby incorporated herein by reference for all purposes.

[0058] The construction of light control layer **16** may be varied in a number of ways. These include:

- whether one, or the other, or both of layers **16B** and **16C** are present;
- the relative thicknesses of layers **16B** and **16C** (in some embodiments, layer **16B** is thicker than layer **16C**);
- the materials of which layers **16B** and **16C** are made (it is not mandatory that layers **16B** and **16C**, if both present, be made of the same material);
- the indices of refraction of layers **16B** and/or **16C** (it is not mandatory that layers **16B** and **16C**, if both present, have the same index of refraction);
- the construction of ESR layer **16A** (in some embodiments, ESR layer **16A** is constructed to provide a reflectivity of less than 96% in the absence of layers **16B** and **16C**);
- the number of ESR layers present in light control layer **16**;
- the spacing between refraction layer **16B** and light modulator **14** may be eliminated or increased to provide control over the spread of light incident on light modulator **14**;

- the presence or absence of surface-relief holographic diffuser elements on surfaces of layers **16B** and/or **16C**; and
- the presence or absence of scattering centers in layers **16B** and/or **16C** and, in embodiments where such scattering centers are present, the nature of the scattering centers and their distribution in three dimensions within the layer **16B** and/or **16C**.

[0059] Scattering centers in layers 16B and/or 16C may comprise, for example, one or more of:

- particles of any suitable pigment, the pigment may comprise TiO_2, for example;
- refractive light scatterers such as small glass beads or other refractive light scatterers (in some embodiments the refractive light scatterers comprise, for example, a high refractive index glass and/or a material having an index of refraction of at least 1.6 or at least 1.7);
- dislocations, bubbles or other discontinuities of the material of layers **16B** and **16C**; and
- the like.

Scattering centers may range in size from, for example, nanometers to 100 micrometers. In some embodiments the scattering centers are Lambertian or nearly so. In alternative embodiments the scattering centers may be ansiotropic scatterers. In some embodiments the anisotropic scatterers are oriented such that they scatter light traveling in certain preferred directions more than light traveling in other directions and/or tend to scatter light more in some directions than in others. For example, in some embodiments, anisotropic scatterers are oriented such that they tend to scatter light more in the direction of modulator **14** than in the direction of reflector **18** or directions generally parallel to the plane of layer **16**.

[0060] Figure 1A is a schematic depiction of a display **10** according to an example embodiment. Display **10** has a light source **12** (e.g. backlight) that is operable to emit light. Light from light source **12** is delivered to a spatial light modulator **14** through an optical path **13**. In some embodiments, optical path **16** comprises an optical element assembly **15**. Spatial light modulator **14** comprises light modulating elements (LMEs) **22** that modulate light from light source **12**. In a simple embodiment, light source **12** and spatial light modulator **14** are parallel and juxtaposed such that light emitted by light source **12** passes directly through optical path **16** onto spatial light modulator **14**.

[0061] Display **10** comprises a controller **28**. Controller **28** receives input signals **29**. Input signals **29** may comprise image data, video data, or the like. Controller **28** generates output signals **30** that supply driving values for LMEs **22** of spatial light modulator **14**. LME driving values determine what proportion of the light incident on LMEs **22** from light source **12** is passed on (transmitted or reflected) to a viewing area. Controller **28** also generates output signals **24** that supply driving values for light emitters **12A** of light source **12**.

[0062] In embodiments comprising individually-controllable light emitters **12A**, output signals **24** may comprise driving signals that can directly or indirectly drive light emitters **12A** to emit light. Output signals **24** may control one or more of: the overall intensity of light emitted by light source **12**, the spatial distribution of light emitted by light source **12**, one or more color characteristics of light emitted by light source **12** or the like.

[0063] In the illustrated example embodiment, light source **12** comprises an array of light emitters **12A**. Each of light emitters **12A** may comprise one or more light-emitting elements such as light-emitting diodes (LEDs) or other light-emitting devices.

[0064] In some embodiments, output signals **30** may be generated based in part on characteristics of light from light source **12** at spatial light modulator **14**. Such characteristics may be spatially-dependent. Characteristics of light from light source **12** on spatial light modulator **14** may be determined by calculation, estimation, measurement, a combination thereof, or the like. Determination of characteristics of light from light source **12** on spatial light modulator **14** may comprise comprising contributions to the light from individual light emitters **12A**. The contribution to the light incident at a particular point on spatial light modulator **14** from a light emitter **12A** may be determined based upon factors including known characteristics of the light emitter **12A** and the optical path from light emitter **12A** to spatial light modulator **14** as well as the spatial relationship of the point on the spatial light modulator **14** and the light emitter **12A.** As one skilled in the art can appreciate, calculation of characteristics of light that are contributed to by light from multiple light emitters may be computationally expensive.

[0065] Some non-limiting examples of general approaches that may be implemented in controller **28** for generating output signals **30** and **24** are described in:

- WO02/069030 entitled HIGH DYNAMIC RANGE DISPLAY DEVICES;
- WO03/077013 entitled HIGH DYNAMIC RANGE DISPLAY DEVICES;
- WO 2006/010244 entitled RAPID IMAGE RENDERING ON DUAL-MODULATOR DISPLAYS;
- US 61/105,419 filed on 14 October 2008 and entitled: light source SIMULATION AT REDUCED RESOLUTION TO DETERMINE SPATIAL MODULATIONS OF LIGHT FOR HIGH DYNAMIC RANGES IMAGES;

which are hereby incorporated herein by reference.

[0066]Light emitters **12A** emit light in a manner such that the intensity of emitted light at planes perpendicular to the optical axis of the light emitter is distributed according to a spread function. Where light source **12** comprises such light emitters, the degree of spatial-uniformity of light achievable at light modulator **14** depends on the arrangement of light emitters **12A**, the spread functions of light emitters **12A**, and the distance between light source **12** and light modulator **14**. For some light emitters **12A** the spread function is characterized by monotonically decreasing intensity in directions away from the optical axis. The spread functions of light emitters **12A** may be affected by the optical characteristics of optical path **13**, including optical element assembly **15**, if present.

[0067]Display **10** may be called on to show visual images that comprise large, bright, uniform features (e.g., a blue-sky). Because the ability of light modulator **14** to modulate the intensity of light from light source **12** may be limited, in cases where light from light source **12** is insufficiently spatially-uniform, visible artefacts may appear in what should be uniform image features (e.g., bright spots within the blue-sky). Though the intensity of spatially non-uniform light may be lowered to enable light modulator **14** to provide uniform image features without visible artefacts, this approach reduces the brightness of the image displayed. It is accordingly desirable that light source **12** be able to provide spatially-uniform high intensity light. To provide illumination that is more spatially-uniform, light emitters **12A** are typically arranged so that the light from different light emitters **12A** can overlap spatially at spatial modulator **14**.

[0068]In some embodiments, light emitters **12A** are individually controlled. Separately controlling light emitters enables spatial variation of the intensity of light incident on light modulator **14**. Advantageously, spatially varying the intensity of light provided to a light modulator may be used to enhance contrast and provide a greater dynamic range of brightness between light and dark areas of an image (e.g., between a bright sky and a dark mountain). In order to provide sharper contrast, it is desirable that light from individual light emitters not provide light that is spread over too large an area of light modulator **14**. For example, it is desirable that only a small proportion of the light emitters that provide light to the area of a light modulator **14** that displays a bright sky also provide light to the area of a light modulator **14** that displays a dark mountain.

[0069]Providing a desired degree of overlap of spread functions of light emitters **12A** at spatial light modulator **14** may be achieved by spacing light source **12** apart from spatial light modulator **14** to provide an optical cavity between light source **12**

and spatial light modulator **14**. The distribution of light from any one light emitter **12A** on spatial light modulator **14** then depends on a number of factors including:

- the intrinsic spread function for the light emitters **12A**;
- the spacing between the light source **12** and spatial light modulator **14**; and
- optical characteristics of light source **12** and spatial light modulator **14** that affect the degree to which light spreads in directions parallel to spatial light modulator **14**.

A desired balance between overlap of light from different light emitters **12A**, the ability to locally dim areas of an image and optical efficiency can be achieved by adjusting these factors as well as the arrangement of light emitters **12A** on light source **12**. For some applications, such designs result in a display that is undesirably thick and/or requires an undesirably large number of light emitters **12A**.

[0070] Optical element assembly **15** may comprise optical elements that affect light from light source **12**. For example, optical elements may cause light to change direction by causing light to undergo refraction, reflection, diffraction, a combination of these, or the like. Optical elements may also absorb and/or scatter light. Optical elements in optical element assembly **15** may be provided to spread light from light source **12** so that a desired degree of overlap in the spread functions of light emitters **12A** may be achieved at a relatively closer spacing between light source **12** and light modulator **14** than would be possible, absent such optical elements. This advantageously enables display **10** to be thinner.

[0071] Where a light source comprises individually-controllable light emitters, optical elements in optical element assembly **15** may shape spread functions to cause illumination from light source **12** to vary more smoothly between differently-controlled light emitters, thereby reducing or eliminating to certain visible artefacts.

[0072] Figure 2 is a schematic expanded cross section of a portion of light control layer **16** according to an example embodiment. In the illustrated embodiment, layers **16B** and **16C** of light control layer **16** are configured to diffuse light that passes through them. By way of example, layers **16B** and/or **16C** may comprise scattering centers **17** distributed in their bulk. The presence and type of scattering centers **17** and the way in which the scattering centers **17** are distributed in three dimensions within layers **16B** and/or **16C** can effect the distribution of light that passes through light control layer **16**. In some embodiments, scattering centers **17** are uniformly distributed in one or both of layers **16B** and **16C**. In some embodiments, scattering centers **17** are distributed non-uniformly in at least one of layers **16B** and **16C**.

[0073] Figure 3 is a graph which includes curve **25A** which is a point spread function for a light emitter with an air gap in place of light control layer **16** and a curve **25B** which is a point spread function for the light emitter with a light control layer **16**. Curves **25A** and **25B** may, for example, represent the distribution of light from one light emitter at a spatial light modulator **14**. By comparing curves **25A** and **25B** it can be seen that the presence of light control layer **16** has significantly reduced the relative amounts of amount of energy in the tails **26** of the point spread function as compared to the amount of energy in a central part of the point spread function.

[0074] In Figure 3, the light control layer **16** in the display for which curve **25B** was measured was made up of a layer of 3M Vikuiti™ ESR film sandwiched between two 5 mm thick layers of polyester resin doped with three 0.04 mL drops of Castin' Craft™ white opaque pigment, which is available from Environmental Technology Inc. of Fields Landing, California.

[0075] In some embodiments, the presence of light control layer **16** increases the ratio of the amount of light energy in a central portion of the point spread function to an amount of light energy in tails of the point spread function by a factor **A** as follows:

$$A = \frac{\left(E_{CF} / E_{TF} \right)}{\left(E_{CW} / E_{TW} \right)} \qquad (1)$$

where: E_{CF} is the optical energy in a central part of the point spread function with a light control layer **16** (within one full-width at half maximum of the point spread function); E_{TF} is the optical energy in tails of the point spread function with a light control layer **16** (outside of twice the full width at half-maximum of the point spread function); E_{CW} is the optical energy in a central part of the point spread function without a light control layer **16**; and E_{TW} is the optical energy in tails of the point spread function without a light control layer **16**. In some embodiments **A** is in the range of 0.7 to 1.8. Providing modified point spread functions in which the amount of energy in tails **26** is reduced can have a number of benefits including a significant increase in achievable contrast. In addition, in some embodiments reducing the amount of energy in tails **26** facilitates reducing the number of light emitters that need to be taken into account to estimate the intensity of light at a given location on spatial light modulator **14**.

[0076] In some embodiments, light control layer **16** is constructed to have properties that vary periodically across light control layer **16**. Where light source **12** comprises discrete light emitters arranged in a spatially periodic manner the spatial periodicity of light control layer **16** may be matched to the spatial periodicity of the light emitters of light source **12**. In some embodiments the variability in one or more properties of light control layer **16** in its parts adjacent to a light emitter are symmetrical with respect to an optical axis of the light emitter. In some embodiments, the spatial variation in the properties of light control layer **16** is configured so that the point spread functions for all or selected groups of the light emitters of light source **12** are modified in the same manner. One property that may be varied to achieve such control over the point spread functions is the density of scattering centers in layers **16B** and/or **16C** and/or on surfaces of layers **16B** and/or **16C**. It has been found that regions with higher densities of scattering centers obtain greater transmission of light. Accordingly, the distribution of scattering centers with respect of the optical axis of a light emitter may be used to concentrate or disperse light from the light emitter with respect to its optical axis.

[0077] Figure 4A shows schematically a portion of light control layer **16** deployed over an array of light emitters **12A**. Locations of optical axes of the light emitters are marked by + symbols. In this example embodiment the density of scattering centers in layers **16B** and/or **16C** is relatively low in regions **31** immediately over each light emitter and increases as one moves away from the optical axis of the light emitter. In this example embodiment, the variation in density of the scattering centers is circularly symmetrical in the vicinity of each light emitter **12A**. In some embodiments the scattering centers have an increased density in an array of annular regions. In some embodiment, the annular regions are aligned with optical axes of light emitters **12A**.

[0078] Figure 4B shows another example embodiment similar to Figure 4A in which a region **32** having a higher-density of scattering centers is present directly over each light emitter **12A** and an annular region **33** in which the density of scattering centers in layers **16B** and/or **16C** is relatively low surrounds each region **32**. In some embodiments, the changes in the density of scattering centers follow smooth gradients.

[0079] Figure 4C shows another example embodiment in which light source **12** comprises three distinct types of light emitters **12A**, **12B** and **12C** having locations indicated respectively by + symbols, × symbols and ◦ symbols. The different light emitters may, for example, emit light of different colors. In this embodiment, light emitters **12A**, **12B** and **12C** are each distributed in a regular 2-dimensional array pattern but the patterns are not all the same. In this embodiment, the density of the scattering centers in layers **16B** and/or **16C** varies differently in the vicinity of light emitters of the different types.

[0080] In some embodiments, one or both surfaces of light control layer **16** are patterned, textured, treated or otherwise made to scatter light that interacts with the surfaces. Such patterning, texturing treatment etc. may be uniform over light control layer **16** or may have some desired spatial variations over one or both surfaces **17A** and **17B** of light control layer **16**. For example, patterns of dimples, frosting, prism-shaped indentations, or other surface features may be formed in back and/or front surfaces **17A** and **17B**. As another example, patterns of light scattering material may be deposited on back and/or front surfaces **17A** and **17B**. A number of example ways in which surfaces of light control layer **16** may be treated to achieve desirable light distribution properties is described in co-pending United States patent application No. 61/241681 filed on 11 September 2009 and entitled Methods and Apparatus for Providing Illumination to a Light Modulator, which is hereby incorporated herein by reference for all purposes. In some embodiments, layers **16B** and/or **16C** may each comprise one or more sublayers, and surface features may be patterned on the surfaces of the sub-layers.

[0081] Figures 15A, 15B, and 15C illustrate how a display that comprises an optical element **36** that increases the angular spread of light, from a light emitter, may provide sufficiently spatially-uniform light to a light modulator while permitting a relatively smaller separation between the light source and the light modulator and/or a relatively greater spacing between light emitters of the light source.

[0082] Figure 15A is a diagrammatic illustration of light in a part of a display **34**. Light emitters **35** emit light **37** in the direction of optical element **36**. Light **37** from light emitters **35** passes through optical element **36** to light source-facing surface (face) of light modulator **38**. The angular spread **b** of light **37A** emerging from optical element **36** is larger than the angular spread **a** of light **37** entering optical element **36**. The change in the angular spread causes light **37A** to fall on a portion **38A** of light modulator **38** that is larger than the portion **38B** that light **37** would have fallen in the absence of optical element **36**. The change in the angular spread of light **37** also causes overlap **39A** of light **37A** from adjacent light emitters **35** to be larger than the overlap **39B** that would occur in the absence of optical element **36**. It will be appreciated that a display may achieve the same overlap using a thinner construction by incorporating an optical element **36** that spreads light.

[0083] Figure 15B is a diagrammatic illustration of the spread functions **37B** of light **37** from light emitters **35** at light modulator **38** that would occur in the absence of optical element **36**. Spread functions **37B** represent the intensity of light from individual light emitters **35** along a line across light modulator **38**. Envelope **39C** represents the intensity of the combined light along a line across light modulator **38**.

[0084] Figure 15C is a diagrammatic illustration of the spread functions **37C** of light **37A** from light emitters **35** at light modulator **38** that occurs when light **37** passes through optical element **36**. Spread functions **37C** represent the intensity of light from individual light emitters **35** along a line across light modulator **38**. Envelope **39D** represents the intensity of the combined light along a line across light modulator **38**.

[0085] In comparison with spread functions **37B**, spread functions **37C** are broader, overlap more and have a smaller intensity range. These differences indicate that providing optical element **36** between light emitters **35** and light modulator **38** causes light from light emitters **35** to be distributed over a larger area of light modulator **38**. In comparison with envelope **39C**, envelope **39D** has a smaller range and varies more smoothly. This indicates that providing optical element **36** between light emitters **35** and light modulator **38** causes light incident at light modulator **38** to be more spatially-uniform. Accordingly, a display that comprises an optical element that spreads light, like optical element **36**, may achieve sufficiently spatially uniform light with a construction that is thinner than a display that does not comprise an optical element that spreads light. This may be particularly advantageous where the display comprises a light source with individually controllable light emitters.

[0086] Optical element **36** may for example comprise one or more light management films, such as, for instance, multi-layer optical films. Some examples of such films are described, for example, in U.S. patents 5600462, 6846089, and 7220026, which are hereby incorporated herein by reference.

[0087] Some embodiments provide optical elements that change the shape of the point spread function of light from light emitters. For example, optical elements may cause the point spread function of light from light emitters to be less spread and more locally-uniform. Some embodiments provide an optical element having optical characteristics that vary spatially. The optical characteristics may vary spatially in a manner that is periodic with a period equal to a spatial period of light emitters **12A** of light source **12**. In some embodiments, optical elements comprise surface features that affect light transmission through the optical element. The surface features may have a periodicity that matches a periodicity of light emitters **12A** arrayed in light source **12.**

[0088] Figure 16A is a cross-sectional schematic view of an optical element **240** according to an example embodiment. Light emitter **241** emits light **242** in the direction of optical element **240.** The light spreads through an angle **a**. Light **242** enters optical element **240** at interface **240A**, and exits optical element **240** at interface **240B**.

[0089] Surface features **246** are located at interface **240B**. In some embodiments surface features **246** are external to optical element **240**. Surface features may, for example, comprise one or more materials applied to or embedded in optical element **240** or a surface treatment or texturing of optical element **240**. Surface features may also comprise surface deformations, such as deformations caused by, for example, stamping, etching, pitting, abrading, localized annealing and the like. In some embodiments, an optical element is provided with both material deposits and surface deformations. In an example embodiment, the features comprise diffusing material, such as a translucent white paint applied to optical element **240** or a layer adjacent to optical element **240**.

[0090] Light exiting optical element **240** through interface **240B** interacts with surface features **246**. In general, light interacting with one or more surface features may undergo refraction, reflection, scattering, absorption, diffraction, combinations thereof, or the like. Surface features may be configured to cause the point spread function of light from light emitters to be changed.

[0091] Figure 16B shows a graph **250** of intensity of light along a line across a plane parallel to and distant from exit interface **240B** of optical element **240**. Spread functions **252** and **254** represent the intensity of light from light emitters **241** along a line parallel to surface, with light intensity increasing along axis **251**. Point spread function **252** represents the intensity of light from light emitter **241** that would be observed in the absence of surface features **246**. Point spread function **254** represents the intensity of light from light emitter **241** that is observed when surface features **246** that scatter light are present. Point spread function **252** is relatively narrower (less spread) and more locally uniform than point spread function **254**.

[0092] Algorithms to calculate configurations and/or compositions of material deposits and/or surface texturing, modifications and the like that achieve particular effects on light are well known to those skilled in the art. These algorithms may be applied to determine configurations and/or compositions of material deposits that alter the point spread function of light from light emitters to achieve desired design goals such as optimal spread and local uniformity for a specific application. In some embodiments, surface features may be applied to change the point spread function of light from substantially Gaussian to substantially Fermi-Dirac or substantially Super-Gaussian.

[0093] In the illustrated embodiment, surface features are distributed symmetrically about the optical axis of light emitter **241** and the density of the surface features decreases with the distance from the optical axis of light emitter **241**. Some light emitters have point spread functions characterized by decreasing intensity in the directions away from their optical axis. For example, point spread function **252** of light emitter **241** is generally Gaussian with maximum intensity along the optical axis of light emitter **241**. Where light from such a light emitter interacts with surface features that are arranged symmetrically about the light emitter's optical axis and scatter light in a manner that decreases with distance from the optical axis of the light emitter, the relatively more intense light exiting the optical element will be relatively more affected by surface features. Where surface features scatter incident light, this arrangement tends to distribute light away from the optical axis of the light emitter. In embodiments where the composition of material deposits varies spatially, composition may vary spatially with a periodicity such that light from each light emitter interacts with essentially the same pattern surface features. In some embodiments the surface features have a spatial frequency that is equal to or a multiple of a spatial frequency of light emitters arrayed in a light source.

[0094] In the illustrated embodiment, surface features are located on one interface of optical element **240**. In other embodiments, surface features are located on a plurality of interfaces of an optical element. For example, in some embodiments, surface features are located on one or more interfaces though which light enters an optical element.

[0095] In some embodiments, surface features are arranged on an optical element in a pattern of repeating configurations that corresponds to the arrangement of light emitters of a light source. Figure 17 is a perspective view of a part of a display **260** according to an example embodiment. Display **260** comprises light source **262** and optical element **266**. Light emitters **264** of light source **262** are configured to provide light incident on optical element **266**. Optical element **266** comprises surface features **268** in a repeating arrangement that corresponds to the arrangement of light emitters **264**. Each surface feature **268** is aligned with a corresponding light emitter **264**.

[0096] In the example embodiment illustrated in Figure 17, the correspondence between light emitters and repeating arrangements of surface features is one-to-one. In other embodiments, the correspondence between light emitters and repeating arrangements of surface features may be one-to-many, many-to-one, one-to-one, or a combination of these at different locations.

[0097] In some embodiments, an arrangement of light emitters is spatially-periodic and surface features are provided on an optical element with matching spatial-periodicity.

[0098] In some embodiments, surface features are arranged on a plurality of optical element surfaces such that the arrangement of surface features on one optical element surface corresponds to the arrangement of surface features on one or more other optical element surfaces. In some such embodiments, the arrangements of surface features on different optical elements surfaces may be based at least in part on the separation between the different optical element surfaces. In embodiments comprising surface features arranged on multiple optical element surfaces, the optical element surfaces may belong to one or more optical elements. In some embodiments, an optical assembly disposed in the optical path between a light source and a light modulator comprises several optical elements with surface features for changing the point spread function of light. In some such embodiments, the at least some of the plurality of optical elements having surface features are in optical contact.

[0099] Some light sources comprise light emitters that provide different colors of light. In some embodiments, surface features are arranged to correspond to light emitters that emit particular colors of light. For example, a surface feature may be configured to affect light having a particular wavelength or range of wavelengths in a particular way. Such surface features may be arranged on an optical element to correspond with light emitters that provide light of the particular wavelength or range of wavelengths.

[0100] In general, surface features may be provided in any of a wide variety of configurations. The following provides examples only of some possible configurations. Surface features **246** may comprise material deposited on the surface of optical element **240**. Material deposits may comprise materials selected to achieve particular effects on light exiting an optical element, such as refraction, reflection, scattering, absorption, diffraction, combinations thereof, or the like. For example, in some embodiments material deposits may comprise dielectric material with an index of refraction different from the index of refraction of the optical element on which they are deposited in order to cause refraction of light exiting the optical element. Material deposits may comprise dielectric material having a purely real refractive index so that light exiting the optical element is not absorbed by the material. Material deposits may comprise dielectric material having a complex refractive index, so that light exiting the optical element is fully or partially absorbed. In some embodiments, a half-tone pattern of material deposits or other surface features is provided.

[0101] In some embodiments, a plurality of material deposits having different compositions are deposited on an optical element. Material deposits may comprise more than one type of material. In some embodiments, material deposits comprise layers of different materials. Materials that comprise more than one type of material may be, for example, homogeneous mixtures, colloids, suspensions, or the like. Material deposits may comprise interstitial voids, such as, for example, gas bubbles. In some embodiments, the concentration of particles and/or voids varies spatially within a material deposit. In some embodiments, material deposits comprise particles and/or voids that are not optically small, such that the deposited material causes light to be scattered. In some embodiments, material deposits comprise particles and/or voids that are optically small so that they do not scatter much of the light.

[0102] Material deposits may be dimensioned, shaped and/or arranged to achieve particular effects on light exiting an optical element. For example, surface deposits may be formed in geometric shapes, such as, lines, hatches, discs, donuts, squares, triangles or the like, in order to spatially-selectively refract, reflect, scatter, absorb and/or diffract light. The thickness of material deposits may be controlled to affect the distance that light travels in the deposit material, in order to achieve particular amounts of scattering, refraction, absorption or the like.

[0103] In some embodiments, surface features are provided by way of a patterned layer, such as a transparent and/or translucent film applied to the optical element. The patterned layer may have a spatially-varying light scattering and/or light absorbing characteristics. Ths spatial variation may have a periodicity matching that of light emitters in a light source. The spatial variation may be registered with light emitters of the light source.

[0104] In some embodiments, a light source and optical element are configured such that light from light emitters of the light source is reflected within the optical element. The reflection may cause light to spread within the optical element. In some such embodiments, some light may undergo total internal reflection. Where light from many different light emitters is widely spread due to repeated internal reflections, a background level of illumination may result. This background illumination may reduce the dynamic range of the display.

[0105] Internal reflection of light within an optical element can be mitigated and/or eliminated by "frustrating" the internal reflection of light at surface interfaces of the optical element. When TIR occurs at a interface between a first material and a second material, some electromagnetic energy, known as the evanescent wave, penetrates into the second material. The intensity of the evanescent wave decays exponentially with distance into the second material. TIR can be prevented, or "frustrated", by providing a third material of an appropriate refractive index positioned within the evanescent wave region. The third material can couple energy out of the evanescent wave either by transmitting (scattering) it or by absorbing it. It has been found that even though there is no evanescent wave in the absence of TIR, the intensity of partially reflected light (PIR, in analogy to TIR) can be controlled by the presence of material in the evanescent wave region.

[0106] Deposition of material in the evanescent wave region provides control of reflectance that is substantially independent of wavelength and incident angle. (See A. Webster, M. Mossman and L. Whitehead, "Control of reflection at an optical interface in the absence of total internal reflection for a retroreflective display application", App. Opt. 45(6), Feb 2006; M. Mossman and L. Whitehead, "A novel reflective image display using total internal reflection", J. Displays 25(5), Nov 2004; M. Mossman and L. Whitehead, "Controlled frustration of TIR by electrophoresis of pigment particles", Appl. Opt. 44(9), Mar 2005 for more on this phenomenon; and US Patent no. 6,215,920, all of which are hereby incorporated by reference for all purposes.)

[0107] In some embodiments, material is deposited to frustrate TIR and/or PIR at particular locations on or near a surface of an optical element in order that light that would otherwise be internally reflected is absorbed and/or extracted from the optical element. In some such embodiments, material is deposited at or near more than one surface of an optical element. In some embodiments, the surface of the optical element about which material is deposited is rough and/or comprises surface features, such as, for example, hemispheric and/or prismatic structures. In such embodiments, TIR and/or PIR may be frustrated by a combination of deposited material and surface geometry.

[0108] In displays with light sources that comprise arrays of light emitters, it may be desirable that material deposits not cover a large area of optical element interfaces in order that material deposits absorb and/or scatter only small amounts of light that would not be internally reflected. In some embodiments, material is deposited on the surface of an optical element on areas at which an appreciable amount of light would be internally reflected. Such areas may be defined, at least in part, by the angle of incidence of light from one or more light emitters and/or the point spread function of light from the one or more light emitters.

[0109] Figure 18A, 18B and 18C show, respectively, a cross-sectional schematic view of an optical element **270** according to an example embodiment, a graph **280** of the reflectance at the interface of the optical element for various incident angles, and a graph **290** of intensity of light along a line across an interface of the optical element. Light emitter **271** emits light **272** in the direction of optical element **270** in an angle **a**. Light **272** enters optical element **270** at interface **270A** and crosses optical element **270** to interact with interface **270B**. Material deposits **276A** and **276B** are in the evanescent wave region of interface **270B**, which is on the side of interface **270B** external to optical element **270**. Material deposits **276A** and **276B** are patterned on portions of interface **270B** at which an appreciable amount of incident light is reflected.

[0110] Graph **280** comprises curve **281** which indicates reflectance as a proportion of incident light at interface **270B** for light at a range of angles of incidence. The domain **282** of graph **280** is non-linear such that it corresponds to a linear domain of distances along interface **270B** from axis **273**. (Because the dimension of light emitter **271** is sufficiently small that light emitter **271** can be treated as a point light source, the angle of incidence of light from light emitter **271** at a point along interface **270B** can be approximated as the arcsine of the distance between the point of incidence and the point at which light is normally incident at interface **270B**.) Figure 18A and Figure 18B are dimensioned and aligned so that points on the corresponding linear domain of graph **280** are matched with points along interface **270B**.

[0111] Curve **281** indicates that the reflectance of light from light emitter **271** at interface **270B** is uniformly low for low incident angles. Sub-domains **286A** and **286B** each comprise a continuous a range angles of slightly less than and including the critical angle. Curve **281** indicates that reflectance of light from light emitter **271** at interface **270B** increases dramatically across sub-domains **286A** and **286B**. The location of material deposit **276A** on interface **270B** corresponds to sub-domain **286A**, and the location of material deposit **276B** on interface **270B** corresponds to sub-domain **286B**. Accordingly, material deposits **276A** and **276B** are at portions of interface **270B** where reflectance of light from light emitter **271** is appreciable.

[0112] Graph **290** comprises curve **291** which indicates the intensity of light at points along interface **270B**. Figure 18A and Figure 18C are dimensioned and aligned so that points in domain **292** of graph **290** are matched with points along interface **270B**. Curve **291** indicates that the intensity of light along interface **270B** follows a Gaussian distribution centered about the optical axis **273** of light emitter **271**. Curve **291** indicates that the intensity of light from light emitter **271** at interface **270B** is low across sub-domains **296A** and **296B**. Curve **291** indicates that the intensity of light from light emitter **271** at interface **270B** is negligible at locations at distances from axis **293** greater than the upper limits of sub-domains **296A** and **296B**. The location of material deposit **276A** on interface **270B** corresponds to sub-domain **296A**, and the location of material deposit **276B** on interface **270B** corresponds to sub-domain **296B**. Accordingly, material deposits **276A** and **276B** are at portions of interface **270B** where the intensity of light from light emitter **271** is low.

[0113] It will be appreciated that material deposits **276A** and **276B** cover portions of interface **270B** at which the intensity of reflected light would be greatest. At points along interface **270B** nearer to axis **273** than material deposits **276A** and **276B**, the reflectance of light from light emitter **271** is low because the incident angles are sufficiently less than the critical angle. At points along interface **270B** farther from axis **273** than material deposits **276A** and **276B**, the intensity of light at interface **270B** is negligible, so that even if the light undergoes total internal reflection, the intensity of the reflected light will be negligible.

[0114] It will be appreciated that where light emitter **271** is one of a plurality of light emitters arranged in an array, material may be deposited over optical element **270** in a pattern of repeating configurations corresponding to the arrangement of the light emitters. In some embodiments, light emitters and optical elements comprising material deposits are configured so that light rays critically incident and nearly critically incident on the optical element surface that comprises material deposits are of low intensity and are absorbed by material deposits.

[0115] In some embodiments, an optical assembly disposed in the optical path between a light source and a light modulator comprises several optical elements with material deposits for frustrating TIR. In some such embodiments, at least some of the plurality of optical elements with material deposits are in optical contact.

[0116] The use of material deposits to couple light out of optical elements also has application in improving the local spread of light from an individual light emitter while maintaining a thin display. Figure 19 shows a conventional liquid crystal display stack **300**. Stack **300** comprises an LCD light modulator **301**, a microstructured brightness enhancing film **302**, a diffuser **303**, a cavity **304**, a reflective film **305**, LEDs **306** and a circuit board with appropriate thermal management solution **307**. Brightness enhancing film **302** may comprise more than one film, for example, it may comprise a single layer of Vikuiti™ dual brightness enhancing film (DBEF) and a single layer of Vikuiti™ brightness enhancing film (BEF).

[0117] Brightness enhancing film **302** and diffuser **303** typically have low effective transmission, and the bulk of light reflects off of them. To improve light transmission from the stack, reflective film **305** has very high reflectance. High reflectance is important because a light ray may undergo a large number of reflections before achieving transmission through brightness enhancing film **302** and diffuser **303**. For example, in a conventional LCD stack with a single layer of DBEF, single layer of BEF and a standard diffuser, only 30% of incoming light rays will transmit through the diffuser (65% will be reflected), only 50% of those transmitted rays will transmit through the BEF (50% of the transmitted rays will be reflected), and only 50% of the rays transmitted through the BEF will be transmitted through the DBEF (50% will be reflected). Thus, only approximately 8% of incident light rays reach the back of the LCD.

[0118] Nearly all of the rays that do not reach the back of the LCD are reflected back into cavity **304**. With a high reflectance reflective film, approximately 98% of these rays are reflected back to the top of the LCD stack, where 8% will be transmitted to the back of the LCD and the remainder reflected again. The process of multiple reflections between the upper stack layers and reflective film **305** causes the light that is eventually transmitted to the back of LCD **301** to be more diffuse.

[0119] One type of highly reflective film uses a stack of very thin layers in which adjacent layers have different indices of refraction. These films reflect incoming rays through total internal reflection rather than metallic reflection. These films are not designed to reflect incoming light at angles that are almost parallel to the surfaces of the film and light incoming at such angles is transmitted out of the film. Even though such grazing rays do not occur in conventional optical designs, they can be artificially created by depositing material on or near the surface of the film. Material deposited on or near the surface of the film will scatter light incident on the surface in many directions. Some of the scattered light will naturally be grazing incident rays. These "manufactured" grazing incident rays will be transmitted out of the film.

[0120] This characteristic can be exploited to reduce the depth of the cavity in a locally dimming display while increasing local uniformity and preserving a relatively narrow spread for light from individually controllable light emitters of a light source. Figure 20 shows an LCD stack **310** according to an example embodiment. Stack **310** comprises an LCD light modulator **311**, a microstructured brightness enhancing film **312**, a diffuser **313**, a cavity **314**, a reflective film **315**, LEDs **316**, and a circuit board with appropriate thermal management solution **317**. Stack **310** also comprises a second reflective film **318** with material deposits **319** on its surface.

[0121] Because cavity **314** is more reflective than cavity **304**, it is relatively more spatially efficient in achieving diffusion. Consider that after each reflection in a parallel plane reflector optical cavity, a light ray travels some distance parallel to the walls of the cavity as it crosses the cavity. This travel spreads the light in the cavity. A light ray in a relatively more reflective cavity will undergo a greater number of reflections before being transmitted. In comparison with light in a less reflective cavity with the same spacing between reflectors, light in a more reflective cavity will travel a greater distance in direction parallel to the plane of the reflectors. Because the distance that a light ray travels in the direction parallel to the planes of the reflectors is a function of the angle of reflection and the distance between walls of the cavity, a more reflective cavity can achieve the same spreading of light as a less reflective cavity with a smaller spacing between reflectors. As a result, stack **310** can achieve the same light spreading as cavity **300** in with a more compact arrangement.

[0122] Light is extracted from optical cavity **314** by material deposits **319** on reflective film **318**. In other embodiments, material may be deposited on reflective film **315**, but it is preferable that material is deposited on the reflective film **318** that is nearest LCD light modulator **311**. The configuration of the material deposits determines the pattern of light extracted from cavity **314**, and thus determines, in part, the pattern of light on the LCD light modulator **311**. Material deposits **319** are patterned into extraction features that correspond to individual LEDs **316**, so that the amount of light extracted by each feature corresponds to the intensity of a corresponding LED. Algorithms that may be applied to calculate configurations of material deposits that achieve particular output luminance profiles in iterative reflection system like these are well known to those skilled in the art. Patterns for extractors for light guides can be readily applied to this system.

[0123] It will be appreciated that material deposits or other patterning may be applied to standard films simply and inexpensively. In comparison with creating apertures in a film, arranging material deposition on a film may be simpler and more easily adapted to specific applications (e.g., particular arrangements of light emitters). In comparison with partially reflective films, highly reflective films with patterned material depositions may provide more precise control of output luminance profiles.

[0124] In some embodiments a display comprises an optical element having scattering centers distributed in its bulk in addition to or instead of surface features as described above. The optical element may comprise, for example, a layer, sheet, film, multi-layer optical film or the like. The bulk-distributed scattering centers may have a density that varies spatially over the optical element. The spatial variation may have a periodicity that matches a spatial periodicity of light emitters in a light source. The spatial variation may have a periodicity that is registered with optical axes of the light emitters. The bulk-distributed scattering centers and/or surface features may be arranged to reduce a ratio of optical energy in tails of point spread functions of the light emitters to optical energy in central portions of the point spread functions of the light emitters. The bulk-distributed scattering centers and/or surface features may be arranged to broaden central portions of the point spread functions of the light emitters.

[0125] Using features to control the output luminance profile of light from light emitters can simplify the determination of light characteristics for use in controlling a light modulator. In some embodiments, the determination of characteristics of light from light source **12** at points on spatial light modulator **14** comprises referring to or generating a light characteristic map.

[0126] Light characteristic maps may be generated, for example, from a light field simulation of the light from light emitters of a light source. In such light field simulations, suitable models may be applied to determine the characteristics of light emitted by each light emitter in response to applied driving signals and the characteristics of light from individual light emitters at the spatial light modulator.

Such simulations may comprise applying models to determine the effect of optical elements on light from light emitters. Generating a light characteristic map for a light modulator may comprise combining light characteristic maps for light from many individual light emitters that provide light to the light modulator.

[0127] Characteristics of light from a light source at a pixel of a spatial light modulator may be extracted from a light characteristic map and used to determine the amount of light that should be passed by the pixel in order to correctly display a part of a desired image. For example, a plurality of light characteristic maps corresponding to different sets of light source driving values may be stored in a memory, and the appropriate light characteristic map (or maps) accessed via a look-up table using light source driving values as a key. Where the desired image is a color image, the light characteristic map may also be used to determine the amount of color filtration (if any) that should be applied by each of pixel of light modulator to display the desired image.

[0128] Where light from many light emitters overlaps at points on a display, the generation of a light characteristic map may be computationally expensive, and storing light characteristics maps corresponding to a range of light source driving values may require a large amount of memory. Figure 21 is a diagram of a pattern of light from several light emitters on a light modulator. In the particular example shown in Figure 21, the radii of circular areas **322** are equal to the spacing between adjacent light emitters **323**. As a result, light from adjacent light emitters overlaps at particular areas of the light modulator. Pixels inside block **324** are closer to light emitter **321A** than any other light emitter. Light emitter **321A** projects illumination on circular area **322A**. Within block **324**, pixels in regions **326A** and **326B** are illuminated by light from light emitter **321A** and one other light emitter. Pixels in region **326C** are illuminated by light from light emitter **321A** and two other light emitters. Pixels in region **326D** are illuminated by light from light emitter **321A** and three other light emitters. Pixels directly aligned with light embitter **321A** are illuminated by light from light emitter **321A** and four other light emitters.

[0129] Figure 22 shows a diagram **330** of point spread functions **331** and **332** overlaid on a grid **333**. Point spread function **331** is characteristic of the intensity of illumination at a line across a light modulator from a light emitter arranged within grid **333** in a manner analogous to the arrangement of light emitter **321A** in a grid of Figure 21. Point spread function **332** is characteristic of the intensity of illumination at the same line across the light modulator from the same light emitter where the light passes through an optical element that increases the spread of incident light, such as, for example, a diffuser, en route to the light modulator.

[0130] In comparison with point spread function **331**, point spread function **332** is broader and has a smaller intensity range. Whereas point spread function **331** covers only grid areas **335**, **336A** and **336B**, point spread function **332** covers grid areas **335**, **336A**, **336B**, **337A** and **337B**. In determining the characteristics of light at a pixel in grid area **337A**, it would not be necessary to consider the light characterized by point spread function **331**, but it would be necessary to consider the light characterized by point spread function **332**. Accordingly, an optical element that increases the spread of incident light increases the number of pixels affected by the light, and this results in a corresponding increase in the complexity of determining the characteristics of light at the pixels.

[0131] Where a light characteristic map is generated for a target body of pixels by combining emitter-specific light characteristic maps, an optical element that increases the spread of incident light increases the size of emitter-specific light characteristic maps. As a result, the average number of emitter-specific light characteristic maps that must be combined to determine the light characteristic map at points on the light modulator is increased. Because a change to any one of the emitter-specific light characteristic maps affects the result of every combination of emitter-specific light characteristic maps that comprises the changed light characteristic map, the memory required to store multiple light characteristic maps corresponding to different sets of driving values also increases. By using surface features to reduce the spread of light from light emitters, the number of light emitters that must be accounted for in generating light characteristic maps may be reduced in some embodiments. As a result, the computational and storage requirements of using light characteristic maps to determine driving values for a light modulator may also be reduced.

[0132] In some embodiments, the driving signals provided to a light modulator are based at least in part on a determination of light characteristics at the light modulator that takes into account the effects of surface features on light exiting an optical element.

[0133] Optical elements according to embodiments that comprise surface features may be integrated with light sources, such as, for example, light sources. Aspects of the invention may be provided in the form of a program product. The program product may comprise any medium which carries a set of computer-readable information comprising instructions which, when executed by a data processor, cause the data processor to execute a method of the invention. Program products according to the invention may be in any of a wide variety of forms. The program product may comprise, for example, physical media such as magnetic data storage media including floppy diskettes, hard disk drives, optical data storage media including CD ROMs, DVDs, electronic data storage media including ROMs, flash RAM, or the like. The computer-readable information on the program product may optionally be compressed or encrypted.

[0134] A controller such as controller **28** may comprise processors that execute software instructions such as microprocessors, image processors, graphics processors, digital signal processors, CPUs or the like; hard-wired logic circuit or logic pipelines of the like; configurable logic circuits such as suitably configured field-programmable gate arrays (FPGAs); combinations of the above, or the like. The controller may comprise a functional element configured to compute a distribution of light from a light emitter at the spatial light modulator wherein the distribution of light is a distribution resulting from the modification of a point spread function of the light emitter by the presence of the optical element with its spatially-varying optical characteristics. Output from this functional element may be applied to determine an overall distribution of light over the controllable elements of a spatial light modulator. The overall distribution may be applied in conjunction with image data to determine settings for the controllable elements of the spatial light modulator.

[0135] Displays according to some embodiments may comprise optical stacks having components in addition to light control layer **16**. For example, Figure 5 is a schematic cross section through a portion of a display **40** having an optical stack **42** which, in addition to light control layer **16**, comprises a diffuser **43** and a dual brightness enhancing film **44**. In some embodiments, diffuser **43** partially re-collimates light from layer **16**.

[0136] In some embodiments, light control layer **16** in combination with reflector **18** advantageously provides a desired point spread function for light emitters of light source **12** in a relatively thin package. For example, in some embodiments the display thickness (i.e. the distance between reflector **18** and the front surface of light modulator **14**) is ½ inch (approximately 1.25 cm) or less and in some embodiments the distance between reflector **18** and the front surface of light modulator **14** is 1/4 inch (approximately 5/8 cm) or less. In some embodiments, a thickness of layer **16C** of light control layer **16** makes up at least 60%, in some embodiments, at least 80% of a thickness of optical cavity **19**.

[0137] The effectiveness of light control layer **16** at spreading light emitted by localized light emitters over corresponding areas of light modulator **14** in a desired manner while preventing most light from any particular light emitter from spreading very far can also facilitate achieving desired image quality with fewer, more widely-spaced, light emitters than would otherwise be required. This is a particular benefit in embodiments where individual light emitters are controlled in response to image data (for example to provide local dimming of light source **12**).

[0138] In some embodiments light emitted by an individual light emitter is concentrated within a corresponding area of light modulator **14** which has a diameter approximately equal to 6 times a display thickness. For example, a display may have a display thickness of approximately 6 mm and most of the light from a light emitter may be concentrated within a circle having a radius of 18 mm. In some embodiments more than 50% (more than 55% in some embodiments) of the light emitted by the light emitter which reaches light modulator **14** is concentrated within this circle. In some embodiments, individual light emitters of light source **12** are spaced apart from their closest neighbors by distances that are within ±10% of the radius of a circle within which 55% of the light from the light emitters are concentrated at light modulator **14**.

[0139] Figure 6 shows an example display **50** which is thin and lacks any large air gaps between light emitters **52** of light source **12** and light modulator **14**. In this embodiment, light emitters **52** are in physical contact with light control layer **16**. In some embodiments, light emitters **52** may be in optical contact with layer **16**. An optical gel, resin, or the like may be provided to facilitate optical contact between emitters **52** and light control layer **16** or otherwise enhance the transmission of light from emitters **52** into light control layer **16**. In some embodiments, some or all of the layers of display **50** are bonded together.

[0140] The absence of any large air gaps in this embodiment facilitates a mechanically robust construction. In the illustrated embodiment, a structural substrate **54** provides support to light control layer **16** by way of light emitters **52**. Light emitters **52** may project by a small distance past reflector **18** to act as spacers to provide a thin air gap **55** between reflector **18** and light control layer **16**. This air gap may facilitate maximizing the reflectivity of reflector **18** especially in the case that reflector **18** comprises an ESR layer such as a later of 3M Vikuiti™ ESR film. In other embodiments, alternative spacers may be provided. In some embodiments air gap **55** is not present.

[0141] A display **50** as illustrated in Figure 6 may provide some advantages over displays of the type that have a significant air gap between light source layer **12** and light modulator **14**. One advantage is that parallax issues are reduced and the viewing angle through which displayed images have good quality can be increased.

[0142] Figure 7 illustrates schematically a display **58** in which a large air gap **59** is included in an optical path between light source **12** and light modulator **14**. To an observer at viewing angle **60A**, pixels of light modulator **14** are illuminated by corresponding light emitters **61** of light source **12** that are directly behind the pixels. To an observer at viewing angle **60B** pixels of light modulator **14** are illuminated by light emitters that are not directly behind the pixels. Where the light emitters are individually controlled in response to image data (as, for example, in a local dimming display) this apparent misalignment to a viewer at viewing angle **60B** can result in undesirable perceptible visual artefacts.

[0143] By comparing Figures 6 and 7, one can see that the parallax effects are reduced in the embodiment of Figure 6 both because display **50** is thinner than display **58** and also because the light scattering provided by light control layer **16** close to light modulator **14** helps to make the appearance of images displayed display **50** vary less with angle than does the appearance of images on display **58**. In some embodiments, parallax effects are also reduced as a result of layer **16** causing light incident on modulator **14** to be more Lambertian.

[0144] Appropriate design of light control layer **16** can assist in shaping point spread functions which define how light from individual light emitters is distributed over light modulator **14**. Figure 8 is a plot of light intensity as a function of position on light modulator **14** that compares a typical point spread function **70** to an enhanced point spread function **71**. Line **72** indicates the optical axis of the light emitter. In typical point spread function **70**, light is distributed according to a bell-shaped distribution having a curved peak region **74A** and extended tail regions **74B**. Tail regions **74B** contain a significant proportion of the light emitted by the light emitter that reaches the light modulator **14**. By contrast, in enhanced point spread function **71**, tails **75A** are suppressed and peak **75B** is softened. A suitable distribution of scattering centers in light control layer **16** may both soften peaks of point spread functions and suppress tails of point spread functions.

[0145] Figures 8A and 8B illustrate that, where light from light emitters is distributed according to enhanced point spread function **71** and the light emitters are appropriately spaced apart, then a light field can be provided in which the light varies smoothly. In the light field, the light intensity at any point on light modulator **14** is the sum of the light reaching that point from all light emitters of light source **12**. In Figure 8A, all of the light emitters are being operated at the same output level. In Figure 8B, the output level of some light emitters has been reduced. From Figure 8A, it can be seen that the softening of the peaks of point spread functions facilitates achieving a reasonably uniform light field with relatively widely-spaced light emitters. In this example, the light emitters are spaced apart by a distance that is substantially equal to the full-width at half maximum of the point spread functions. From Figure 8B it can be seen that the suppression of tails of point spread functions facilitates greater contrast between the darkest and brightest parts of the light field and facilitates achieving a transitions from bright to dark over shorter distances.

[0146] Figure 9 shows a control system **80** which gives an example of a possible control architecture for a display as described herein. Image data **81** is obtained at an input **82** of a light source controller **83** and an input **84** of a light modulator controller **85**. Light source controller **83** and light modulator controller **85** respectively generate control signals to control a light source driving circuit **86** and a light modulator driving circuit **87**. The control signals for light source **12** may specify directly or indirectly driving parameters to be applied in driving individual light emitters or groups of light emitters of light source **12**. The control signals for light modulator **14**

may specify directly or indirectly the amount of attenuation of light to be applied by each controllable element (e.g. each pixel or subpixel) of light modulator **14**.

[0147] A light field simulator **88** receives control signals for light source **12** and, based on those control signals estimates a light field at light modulator **14**. Light field simulator **88** incorporates a model of the point spread functions of light emitted by light emitters of light source **12** and passing through the optical stack, including light control layer **16**. The model may comprise a function, a parameterized function, a lookup table, or the like, for example. Light field simulator **88** provides a light field estimate **89** to light modulator controller **85**. Light modulator controller **85** derives control signals for light modulator **14** based on the image data **81** and on the light field estimate **89**.

[0148] In embodiments where a light control layer **16** attenuates tails of point spread functions, light field simulations performed by light field simulator **88** may be simplified and made more accurate. Because point spread functions with attenuated tails correspond to effectively illumination of smaller areas on light modulator **14**, better models for point spread functions may be used (e.g., mathematical functions that avoid inaccurate extrapolations and that "cut-off" less, or none, of the actual point spread function tails to reduce computational complexity) and the point spread functions of fewer light emitter need to be accounted for in simulating light fields at particular locations on light modulator **14**. This permits the light field simulation to be performed more quickly and/or with simpler, slower hardware and/or with less memory than might otherwise be required.

[0149] Figure 10 is a cross section through a display **100** in which light control layer **16** provides the additional function of serving as a brightness enhancement film. In display **100**, light control layer **16** acts as a reflective polarizer for light. In the illustrated embodiment, light control layer comprises an ESR layer that is located near to the front side **17A** of light control layer **16**. This may be achieved, for example, by making layer **16A** thin**,** not providing layer **16A** or providing a second ESR layer on the front side of light control layer **16**.

[0150] Figure 11 shows a light control layer **116** according to an alternative embodiment which comprises two or more ESR layers. In the illustrated embodiment, adjacent ESR layers **116A** and **116B** are in optical contact with and spaced apart by a layer **116C** of a material having an index of refraction that is a closer match to the material of the ESR layers than air. Additional layers **116D** and **116E** are provided. In some embodiments the material of one or more of layers **116C**, **116D** and **116E** is a material that diffuses light (e.g. a material that includes a density of light scattering centers).

[0151] In displays according to some embodiments, light source layer **12** comprises light emitters that emit discrete colors of light. For example, light source **12** may emit red, blue and green light at discrete locations. In such embodiments, light control layer **16** may provide the additional function of mixing light of different colors before the light reaches light modulator **14**. This can help to reduce or eliminate color fringing. Color fringing may occur, for example, where red, green and blue emitters are provided at locations that are spaced apart from one another in a single device that has a package that shadows light from the different emitters to different degrees in at least some directions.

[0152] Light control layers as described herein may be incorporated in various display components. Figure 12 shows, for example a light-emitting tile **120** that incorporates one or more light emitters **121** that emit light into a waveguide **122** having a front side faced with a light control layer **16** and a rear reflector **124**.

[0153] Figure 13 shows a light-emitting diode (LED) **130** comprising one or more light-emitting regions **132** in a package **133**. Package **133** comprises a light control layer **16** formed by sandwiching an ESR film **16A** between transparent material **135** of a lower part of the package and an additional layer **136**. A back reflector **138** is provided in the package to define an optical cavity **139** within the package. In some embodiments, LED **130** may be a surface mount LED.

[0154] Figure 14 shows an edge-lit display **140** which is similar to display **10** of Figure 1 except that light source **12** comprises a waveguide **142** that is edge lit by light emitters **144**.

[0155] In any embodiment as described herein it is desirable to avoid the case where too much of the light reflected back by light control layer **16** is absorbed by light emitters of light source **12**. In some embodiments, this is achieved by providing light emitters (for example light-emitting diodes or other light-emitting semiconductors) that are physically small. This permits the coverage of reflector **18** to be maximized. Absorption of back-reflected light by light emitters of light source **12** may also be minimized by providing light emitters with highly reflective packages or embedding light emitters in reflector **18**.

[0156] Some prototype light control layers **16** have been fabricated by casting layers of polyester resin on either side of a sheet of 3M Vikuiti™ ESR film. In these prototypes, the layers of polyester resin each had a thickness of either 2 ½ or 5 mm the 2 ½ mm thick layers were made from polyester resin mixed with one 0.04 mL drop of Castin' Craft™ white opaque pigment per 40g of resin. The 5 mm thick layers were made from polyester resin mixed with either one 0.04 mL drop of Castin' Craft white opaque pigment or three 0.04 mL drops of Castin' Craft white opaque pigment per 40g of resin. Peak luminance and total PSF energy were measured. Total PSF energy was measured by summing luminance values over an entire image. It was found that:

- increasing the thickness of the front layer from 2 ½ to 5 mm tended to increase peak luminance (an average increase of approximately 13% was observed);
- increasing the amount of pigment in the front layer from 1 to 3 drops tended to increase peak luminance (an average increase of 65% was observed);
- increasing the rear layer thickness from 2 ½ mm to 5 mm tended to decrease peak luminance (an average decrease of approximately 8% was observed);

- increasing the amount of pigment in the rear layer from 1 to 3 drops tended to increase peak luminance (an average increase of 42% was observed).
- increasing the thickness of the front layer from 2 ½ to 5 mm tended to increase total PSF energy (an average increase of approximately 7% was observed);
- increasing the amount of pigment in the front layer from 1 to 3 drops tended to increase total PSF energy (an average increase of 14% was observed);
- increasing the rear layer thickness from 2 ½ mm to 5 mm tended to increase total PSF energy (an average decrease of approximately 10% was observed);
- increasing the amount of pigment in the rear layer from 1 to 3 drops tended to increase total PSF energy (an average increase of 10% was observed).

[0157] The relative amounts of energy in the central and tail portions of the point spread functions were measured for the prototype light control layers. It was found that the prototype made with 5mm thick front and rear polyester layers each made with three 0.04 mL drops of pigment provided the lowest ratio of tail energy to central energy in the prototypes tested.

[0158] From the foregoing, it is apparent that inventive aspects as described herein may be embodied in things such as: displays, components for displays, optical stacks useful in displays, controllers for displays, methods for displaying images, and methods for making light control layers.

[0159] Where a component (e.g. a film, light source, controller, processor, assembly, device, circuit, etc.) is referred to above, unless otherwise indicated, reference to that component (including a reference to a "means") should be interpreted as including as equivalents of that component any component which performs the function of the described component (i.e., that is functionally equivalent), including components which are not structurally equivalent to the disclosed structure which performs the function in the illustrated exemplary embodiments of the invention.

[0160] As will be apparent to those skilled in the art in the light of the foregoing disclosure, many alterations and modifications are possible in the practice of this invention without departing from the spirit or scope thereof. For example:

- it is not mandatory that light reflector **18** comprise an ESR layer. In some embodiments, light reflector **18** comprises a diffuse reflector such as a layer of white paint or ink or a metallic reflector.
- In some embodiments a holographic diffuser may be provided to assist in scattering and/or re-collimating light in a desired manner. For example, a holographic diffuser may be used to scatter light in a wider angular distribution after exiting light control layer 16 in the direction of light modulator **14**, to account for angular transmission properties of light modulator **14,** or to provide particular angular distribution characteristics for light exiting light modulator **14**. The holographic diffuser may be integrated with light control layer **16** (as a separate layer, or in place of or integrated with layers **16B** and/or **16C**), provided between light control layer **16** and light modulator **14**, or provided adjacent light modulator **14** and opposite light control layer **16**.
- In some embodiments, light source **12** may emit light in a number of relatively narrow wavelength ranges. In such embodiments, it is not mandatory that ESR layer **16A** be highly reflective at wavelengths that are not emitted by light source **12**. In such embodiments, ESR layer **16A** may be constructed to be highly reflective to light in the specific wavelength ranges emitted by light source **12**.
- In some embodiments in which a plurality of ESR layers are provided, different ones of the ESR layers may be reflective in different wavelength ranges. For example, for a display in which light source **12** comprises emitters of red, green and blue light, two of the colors of light may each be reflected primarily by different ESR layers in a light control layer. As another example, a light control layer as described herein may have one ESR layer that is configured to reflect red light well (and may not reflect blue or green light as well), another ESR layer that is configured to reflect green light well (and may

not reflect blue or red light as well), and another ESR layer that is configured to reflect blue light well (and may not reflect green or red light as well). In some such embodiments, ESR layers configured to reflect light from light emitters of a particular color may be adjacent to layers having patterns or surface features with spatial periodicity matching the spatial periodicity of the light emitters of the particular color.

- In some embodiments, light control layer **16** has properties that are electronically controllable. For example, areas within layer **16B** and/or **16C** may comprise fluids containing scattering centers that can be caused to move by the application of electrical forces. As another example, optical contact between ESR layer **16A** and one or both of layers **16B** and **16C** may be made to be switchable or variable in response to electrical control signals. Such control of the distribution of scattering centers in layers **16B** and/or **16C** may be applied to control the point spread function of light that passes through light control layer **16** and/or to provide enhanced local control of the light field at a light modulator **14**.

[0161] As will be apparent from the foregoing description, the invention has many different aspects, some of which are set out below.

A. A display comprising:

a light source,

a spatial light modulator; and

a light control layer in an optical path between the light source and the spatial light modulator, the light control layer comprising:

an enhanced specular reflector layer, and

a first optical layer in optical contact with a first side of the enhanced specular reflector layer, the first optical layer at least one of substantially transparent and substantially translucent.

B. A backlight assembly comprising:

a light control layer; and

a light source configured to emit light toward the light control layer, the light control layer comprising:

an enhanced specular reflector layer, and

a first optical layer in optical contact with a first side of the enhanced specular reflector layer, the first optical layer at least one of substantially transparent and substantially translucent.

C. A light emitter comprising:

a light emitting region; and

a package,

the package comprising a back reflector and a light control layer mounted on the back reflector and enclosing the light emitting regions therebetween.

C. A light control layer comprising:

an enhanced specular reflector layer, and

a first optical layer in optical contact with a first side of the enhanced specular reflector layer, the first optical layer at least one of substantially transparent and substantially translucent.

E. A control system for a display comprising a light source configured to emit light through a light control layer onto a light modulator, the control system comprising:

a light source controller configured to generate control signals for controlling the light source;

a light field simulator configured to generate a light field simulation of the light field produced at the light modulator by light emitted from the light source in response to the light source control signals and passing through the light control layer; and a light modulator controller configured to generate light modulator control signals for controlling the light modulator based at least in part on the light field simulation.

F. A method for controlling a display comprising a light source configured to emit light through a light control layer onto a light modulator, the method comprising:

generating light source control signals for controlling the light source;

generating a light field simulation of the light field produced at the light modulator by light emitted from the light source in response to the light source control signals and passing through the light control layer; and

generating light modulator control signals for controlling the light modulator based at least in part on the light field simulation.

[0162] Embodiments according to the foregoing exemplary aspects, as well as embodiments according to other aspects, may optionally include or be characterised by one or more of the following features:

- The first optical layer is in optical contact with a side of specular reflector layer that faces the light source
- The first optical layer is in optical contact with a side of specular reflector layer that faces away from the light source
- The first optical layer is in optical contact with a side of specular reflector layer that faces the spatial light modulator
- The first optical layer comprises a dielectric material, such as:
  - TiO2
  - SiO2
  - Tellurium
  - Polymers
- The first optical layer comprises plastic, such as:
  - polycarbonate
  - poly(methyl methacrylate)

    - acrylic
    - polyester resin
    - polyurethane
    - birefringent polyester
    - isotropic polyester
    - syndiotactic polystyrene
- The first optical layer comprises glass
- The first optical layer having thickness > 500 µm
- The first optical layer is thicker than the enhanced specular reflector layer
- The enhanced specular reflector layer is disposed on side of light source that is opposite the side of the light source facing the light control layer
    - The enhanced specular reflector layer comprises ESR film
    - The enhanced specular reflector layer comprises a diffuse reflector
        - The diffuse reflector comprises white paint
        - The diffuse reflector comprises white ink
- The light control layer reflects in the range of 65% to 85% of light incident on it
- The light control layer reflects approximately 73% ±5% of the light incident on it
- The light control layer specularly reflects in the range of 5% to 20% of light incident on it
- The first layer has a thickness of 2.5mm
    - first layer made from polyester resin mixed with 1 drop pigment per 40g of resin
- First layer having a thickness of 5mm
    - first layer made from polyester resin mixed with 1 drop pigment per 40g of resin
    - first layer made from polyester resin mixed with 3 drops pigment per 40g of resin
- The light control layer comprises a second optical layer in optical contact with a second side of the enhanced specular reflector layer opposite the first side

    - The first and second optical layers comprise a same material
    - The first and second optical layers comprise different materials
    - The first and second optical layers have substantially the same index of refraction
    - The first and second optical layers have different indices of refraction
    - The first and second layers each have a thickness of 5mm and are made from polyester resin mixed with 3 drops of pigment per 40g of resin
- The enhanced specular reflector layer has a reflectivity of less than 96% for light entering the layer from air
- The light control layer comprises a plurality of enhanced specular reflector layers
    - The light control layer comprises two enhanced specular reflector layers in optical contact with and spaced apart by an optical layer having an index of refraction closer to the indices of refraction of the enhanced specular reflector layers than the index of refraction of air
- The first optical layer comprises scattering centers
    - The scattering centers comprise pigment
        - The pigment comprises TiO_2
    - The scattering centers comprise refractive light scatters
        - The scattering centers comprise glass beads
            - The glass beads comprise high refractive index glass
        - The refractive light scatters have an index of refraction greater than 1.6
    - The scattering centers comprise discontinuities in the first optical layer
        - The scattering centers comprise air bubbles
        - The scattering centers comprise dislocations
    - The scattering centers comprise lambertian scattering centers
    - The scattering center comprise anisotropic scatterers
    - The scattering centers are distributed in the bulk of the first optical layer

    - The scattering centers are distributed substantially uniformly in the bulk of the first optical layer
    - The scattering centers are distributed non-uniformly in the bulk of the first optical layer
- The first optical layer is configured such that light control layer increases the ratio of the amount of light energy in a central portion of the point spread function to an amount of light energy in tails of the point spread function by a factor **A** as follows:
- $$A = \frac{\left(E_{CF} / E_{TF} \right)}{\left(E_{CW} / E_{TW} \right)}$$
- where:
- E_{CF} is the optical energy within one full-width at half maximum of the point spread function in the presence of the light control layer;
- E_{TF} is the optical energy outside of twice the full width at half-maximum of the point spread function in the presence of the light control layer;
- E_{CW} is the optical energy within one full-width at half maximum of the point spread function in the absence of the light control layer; and
- E_{TW} is the optical energy outside of twice the full width at half-maximum of the point spread function in the absence of the light control layer.
    - A is in the range of 0.7 - 1.8
- The light source comprises a plurality of light emitters
    - The light emitters are individually-controllable
    - The light emitters disposed in a spatially periodic arrangement and light control layer comprises an arrangement of features having the

same spatial periodicity as the periodicity of the arrangement of light emitters

- The light control layer comprises a physical feature that is symmetric about the optical axis of at least one of the plurality of light emitters
    - The physical feature comprises a density gradient of scattering centers in the first optical layer
    - The physical feature comprises a density gradient of scattering centers on a surface of the first optical layer
        - The density gradient of scattering centers increases in directions away from the optical axis of the at least one light emitter
        - The density gradient comprises a first density sub-gradient of scattering centers in an inner region extending radially outwardly from the optical axis of the at least one light emitter and a second density sub-gradient of scattering centers in an outer annular region adjacent the inner region, the first density higher than the second density
            - The first and second density sub-gradients are discontinuous
    - The physical feature comprises a density gradient of scattering centers on a surface of the first optical layer
    - The physical feature is circularly symmetric about the optical axis of the at least one scattering center
- The light source comprises light emitters of different types
    - The light source comprises light emitters of different colors
    - The density of scattering centers varies differently in the vicinity of light emitters of different types
        - The density of scattering centers varies differently in the vicinity of light emitters of different colors

- The light emitters comprise light emitting regions and a package, the package comprising
- a back reflector; and
- a light control layer mounted on the back reflector and enclosing the light emitting regions
    - The light control layer comprises
- a first transparent optical layer mounted on the back reflector;
- an enhanced specularly reflecting film in optical contact with the first transparent layer
        - The light control layer comprises a second transparent optical layer in optical contact with the enhanced specularly reflecting film
- A first surface of the first optical layer comprises a spatially varying surface feature
    - The surface feature comprises dimples
    - The surface feature comprises frosting
    - The surface feature comprises prism-shaped indentations
    - The surface feature comprises deposits of light scattering material
    - The surface feature comprises surface-relief holographic diffuser elements
    - The first surface of the first optical layer is adjacent the enhanced specular reflector layer
    - The first surface of the first optical layer opposite the enhanced specular reflector layer
- The display comprises a diffuser
- The display comprises a dual brightness enhancing film
- A distance between the reflector and a front surface of the light modulator is less than 1.25 cm
- A distance between the reflector and a front surface of the light modulator is less than 0.625 cm

- A thickness of the optical layer proximate the reflector makes up 60% of the thickness of an optical cavity defined between the reflector and the surface of optical layer in contact with the side of the enhanced specular reflector layer that is not in contact with the enhanced specular reflector layer
- A thickness of the optical layer proximate the reflector makes up 80% of the thickness of an optical cavity defined between the reflector and the surface of optical layer in contact with the side of the enhanced specular reflector layer that is not in contact with the enhanced specular reflector layer
- The light control layer is configured to concentrate light emitted by individual light emitters within corresponding areas of the light modulator, the corresponding areas having a diameter substantially equal to six times a distance between the light source and the light modulator
    - more than 50% of the light emitted by the light emitters that reaches the light modulator is concentrated within the corresponding areas
    - more than 55% of the light emitted by the light emitters that reaches the light modulator is concentrated within the corresponding areas
    - The light emitters are spaced apart from their closest neighbour by distances that are within 10% of the radius of the corresponding area
- The light emitters are in optical contact with the light control layer
    - The light emitters project outwardly from the back reflector, and the light control layer is spaced apart from the back reflector by the light emitters
- The light emitters are optically coupled to the light control layer
- The light emitters are embedded in the back reflector

[0163] While a number of exemplary aspects and embodiments have been discussed above, those of skill in the art will recognize certain modifications, permutations, additions and sub-combinations thereof. Features of the embodiments described herein may be combined with features of other embodiments to yield further embodiments. It is therefore intended that the following appended claims and claims hereafter introduced are interpreted to include all such modifications, permutations, additions and sub-combinations as are within their true spirit and scope.

WHAT IS CLAIMED IS:

1. A display comprising:
a light source,
a spatial light modulator; and
a light control layer in an optical path between the light source and the spatial light modulator, the light control layer comprising:
an enhanced specular reflector layer, and
a first optical layer in optical contact with a first side of the enhanced specular reflector layer, the first optical layer at least one of substantially transparent and substantially translucent.

2. A display according to claim 1 wherein the light control layer is coextensive with the spatial light modulator.

3. A display according to claim 1 or claim 2 wherein the first optical layer is in optical contact with a side of specular reflector layer that faces the spatial light modulator.

4, A display according to claim 1 or claim 2 wherein the first optical layer is in optical contact with a side of specular reflector layer that faces away from the spatial light modulator.

5. A display according to any one of claims 1 to 4 wherein the first optical layer is thicker than the enhanced specular reflector layer.

6. A display according to any one of claims 1 to 5 wherein the light control layer reflects in the range of 65% to 85% of light incident thereon.

7. A display according to any one of claims 1 to 6 wherein the light control layer specularly reflects in the range of 5% to 20% of light incident thereon.

8. A display according to any one of claims 1 to 7 wherein the light control layer comprises a second optical layer in optical contact with a second side of the enhanced specular reflector layer opposite the first side.

9. A display according to any one of claims 1 to 8 wherein the light control layer comprises a plurality of enhanced specular reflector layers.

10. A display according to claim 9 wherein the light control layer comprises two enhanced specular reflector layers in optical contact with and spaced apart by an optical layer having an index of refraction closer to the indices of refraction of the enhanced specular reflector layers than the index of refraction of air.

11. A display according to any one of claims 1 to 10 wherein the first optical layer comprises scattering centers.

12. A display according to claim 11 wherein the scattering centers comprise pigment or refractive light scatters or discontinuities in the first optical layer or lambertian scattering centers or anisotropic scattering centers.

13. A display according to claim 11 or claim 12 wherein the scattering centers are distributed in the bulk of the first optical layer.

14. A display according to any one of claims 1 to 13 wherein the first optical layer is configured such that light control layer increases the ratio of the amount of light energy in a central portion of the point spread function to an amount of light energy in tails of the point spread function by a factor **A** as follows:

$$A = \frac{\left(E_{CF} / E_{TF} \right)}{\left(E_{CW} / E_{TW} \right)}$$

where:

E_{CF} is the optical energy within one full-width at half maximum of the point spread function in the presence of the light control layer;

E_{TF} is the optical energy outside of twice the full width at half-maximum of the point spread function in the presence of the light control layer;

E_{CW} is the optical energy within one full-width at half maximum of the point spread function in the absence of the light control layer; and

E_{TW} is the optical energy outside of twice the full width at half-maximum of the point spread function in the absence of the light control layer.

15. A display according to any one of claims 1 to 14 wherein the first surface of the first optical layer comprises a spatially varying surface feature.

16. A display according to claim 15 wherein the surface feature comprises dimples or frosting or prism-shaped indentations or deposits of light scattering material or surface-relief holographic diffuser elements.

17. A display according to any one of claims 1 to 16 wherein the light source comprises a plurality of light emitters.

18. A display according to claim 17 wherein the plurality of light emitters are individually-controllable and arranged in an array.

19. A display according to claim 17 or claim 18 wherein the light emitters are disposed in a spatially periodic arrangement and light control layer comprises an arrangement of features having the same spatial periodicity as the periodicity of the arrangement of light emitters.

20. A display according to claim 17 or claim 18 wherein the light control layer comprises a physical feature that is symmetric about the optical axis of at least one of the plurality of light emitters.

21. A display according to claim 20 wherein the physical feature comprises a density gradient of scattering centers of the first optical layer.

22. A display according to any one of claims 17 to 21 wherein the light emitters are of different types.

23. A display according to any one of claims 17 to 22 wherein the light source comprises a waveguide that is edge-lit by the plurality of light emitters.

24. A display according to any one of claims 17 to 23 wherein the light control layer is configured to concentrate light emitted by individual light emitters within corresponding areas of the light modulator, the corresponding areas having a diameter substantially equal to six times a distance between the light source and the light modulator.

25. A display according to any one of claims 1 to 24 comprising a back reflector spaced apart from and parallel to the light control layer.

26. A display according to any one of claims 17 to 24 comprising a back reflector spaced apart from and parallel to the light control layer, wherein the light emitters project outwardly from the back reflector, and the light control layer is spaced apart from the back reflector by the light emitters.

27. A display according to any one of claims 17 to 24 comprising a back reflector spaced apart from and parallel to the light control layer, wherein the light emitters are embedded in the back reflector.

28. A display according to any one of claims 24 to 27 wherein the first optical layer comprises a rear layer located between the enhanced specular reflector layer and the back reflector, an optical cavity is defined between the back reflector and the enhanced specular reflector layer, and the rear layer occupies at least 3/4 of a thickness of the optical cavity.

29. A display according to any one of claims 1 to 28 wherein an optical transmission coefficient for the light control layer is greater than an optical transmission coefficient for the enhanced specular reflector layer on its own.

30. A display according to any one of claims 1 to 29 wherein the enhanced specular reflector layer has a reflectivity of less than 96% for light entering the enhanced specular reflector layer from air.

31. A display comprising:

a light source comprising an arrangement of a plurality of light emitters;

a spatial light modulator spaced apart from the light source, the spatial light modulator having a face arranged to be illuminated by the light source; and

an optical element disposed between the light source and the spatial light modulator;

wherein a surface of the optical element comprises an arrangement of a plurality of surface features, the arrangement of the plurality of surface features corresponding to the arrangement of the plurality of light emitters.

32. A display according to claim 31 wherein the arrangement of the plurality of light emitters is spatially periodic with a spatial periodicity and the arrangement of the plurality of surface features is spatially periodic with the spatial periodicity of the arrangement of the plurality of light emitters.

33. A display comprising:

an array of light emitters arranged to illuminate a first face of a spatial light modulator by way of an optical path extending through an optical element, the optical element having a first face extending parallel to the face of the spatial light modulator, the first face of the optical element configured to scatter light such that a scattering coefficient of the first face of the optical element varies according to a spatially-repeating pattern having a period equal to a spacing of light emitters in the array of light emitters.

34. A display according to claim 33 wherein the optical element comprises an optically transparent or translucent sheet.

35. A display according to claim 33 wherein the optical element comprises a stack of optically transparent or translucent sheets oriented parallel to the spatial light modulator.

36. A display according to claim 33 wherein the optical element comprises a multi-layer optical film.

37. A display according to claim 33 wherein the first face of the optical element comprises a pattern of light-scattering material deposited on the optical element.

38. A display according to claim 33 wherein the first face of the optical element comprises a pattern of light-scattering material embedded within the optical element.

39. A display according to claim 33 wherein the first face of the optical element comprises a pattern of light-scattering surface deformations.

40. A display according to claim 33 wherein the first face of the optical element comprises a layer of translucent white paint.

41. A display according to any one of claims 33 to 40 wherein the optical element comprises a spatially-varying light absorption characteristic.

42. A display according to claim 41 wherein the light absorption characteristic has a period of spatial variation equal to a spacing of light emitters in the array of light emitters.

43. A display according to claim 33 wherein the optical element is configured to broaden point spread functions of the light emitters.

44. A display according to claim 33 wherein a plurality of faces of the optical element are configured to scatter light.

45. A display according to claim 33 wherein the optical element is configured to reduce a ratio of optical energy in tails of point spread functions of the light emitters to optical energy in central portions of the point spread functions of the light emitters.

46. A display according to claim 33 wherein the scattering coefficient of the first face of the optical element has maxima aligned with optical axes of the light emitters.

47. A display according to any of claims 33 to 46 wherein the light emitters comprises at least first and second sets of light emitters, the first and second sets of light emitters respectively configured to emit light of first and second colors.

48. A display according to claim 47 wherein the optical element comprises first and second sets of surface features corresponding respectively to the first and second

sets of light emitters, the first set of surface features configured to affect light of the first color and the second set of surface features configured to affect light of the second color.

49. A display according to any one of claims 33 to 48 wherein the spatial light modulator comprises a transmission-type spatial light modulator.

50. A display according to claim 49 wherein the spatial light modulator comprises a liquid crystal display panel.

51. A display comprising:

an array of light emitters arranged to illuminate a first face of a spatial light modulator by way of an optical path extending through an optical element, the optical element having a first face extending parallel to the face of the spatial light modulator, the first face configured to provide total internal reflection of at least some light incident on the first face from an interior of the optical element, the first face patterned to variably frustrate the total internal reflection at the first face varies according to a spatially-repeating pattern having a period equal to a spacing of light emitters in the array of light emitters.

52. A display according to claim 51 wherein the optical element comprises an optically transparent or translucent sheet.

53. A display according to claim 51 wherein the optical element comprises a stack of optically transparent or translucent sheets oriented parallel to the spatial light modulator.

54. A display according to claim 51 wherein the optical element comprises a multi-layer optical film.

55. A display according to claim 51 wherein the first face of the optical element comprises a pattern of total internal reflection frustrating material deposited on the optical element.

56. A display according to claim 51 wherein the first face of the optical element comprises a pattern of total internal reflection frustrating material embedded within the optical element.

57. A display according to claim 51 wherein the first face of the optical element comprises a pattern of total internal reflection frustrating surface deformations.

58. A display according to claim 51 wherein the first face of the optical element comprises a patterned layer of translucent white paint.

59. A display according to any one of claims 51 to 58 wherein the optical element comprises a spatially-varying light absorption characteristic.

60. A display according to claim 59 wherein the light absorption characteristic has a period of spatial variation equal to a spacing of light emitters in the array of light emitters.

61. A display according to claim 51 wherein the optical element is configured to broaden point spread functions of the light emitters.

62. A display according to claim 51 wherein the optical element is configured to reduce a ratio of optical energy in tails of point spread functions of the light emitters to optical energy in central portions of the point spread functions of the light emitters.

63. A display according to any of claims 51 to 62 wherein the light emitters comprises at least first and second sets of light emitters, the first and second sets of light emitters respectively configured to emit light of first and second colors.

64. A display according to any one of claims 51 to 63 wherein the spatial light modulator comprises a transmission-type spatial light modulator.

65. A display according to claim 64 wherein the spatial light modulator comprises a liquid crystal display panel.

66. A controller for controlling a display, the display comprising a light source having individually-controllable light emitters and an optical element disposed between the light source and a spatial light modulator, the controller configured to generate a control signal based at least in part on a determination of a characteristic of light from the light source at a location in the display between the optical element and the spatial light modulator.

67. A controller for controlling a display, the display comprising a light source having individually-controllable light emitters and an optical element disposed between the light source and a spatial light modulator, the controller comprising:

a first control signal generator operable to determine first driving signals for the light emitters of the light source based at least in part on image data;

a functional unit operable to estimate an effect of spatially-varying optical characteristics of the optical element on light emitted by the light emitters when driven by the first driving signals;

a second control signal generator connected to receive image data and output from the functional unit and operable to generate a map indicating a distribution on the spatial light modulator of light from the elements of the light source at controllable elements of the spatial light modulator and to determine second driving signals for the controllable elements of the spatial light modulator based at least in part on the image data and the map.

68. An LED light source assembly comprising:

an internally reflective optical cavity defined by an upper sheet and a lower sheet, the upper sheet having an index of refraction greater than an index of refraction of a media adjacent thereto;

an array of LEDs wherein at least one LED of the array of LEDs is configured to provide light to the lower sheet;

wherein material deposited on upper sheet frustrates total internal reflection at an interface between the upper reflective sheet and the media adjacent thereto.

69. Apparatus comprising any new and inventive feature, combination of features or sub-combination of features as described herein.

70. A method comprising any new and inventive step, act, combination of steps and/or acts or sub-combination of steps and/or acts as described herein.

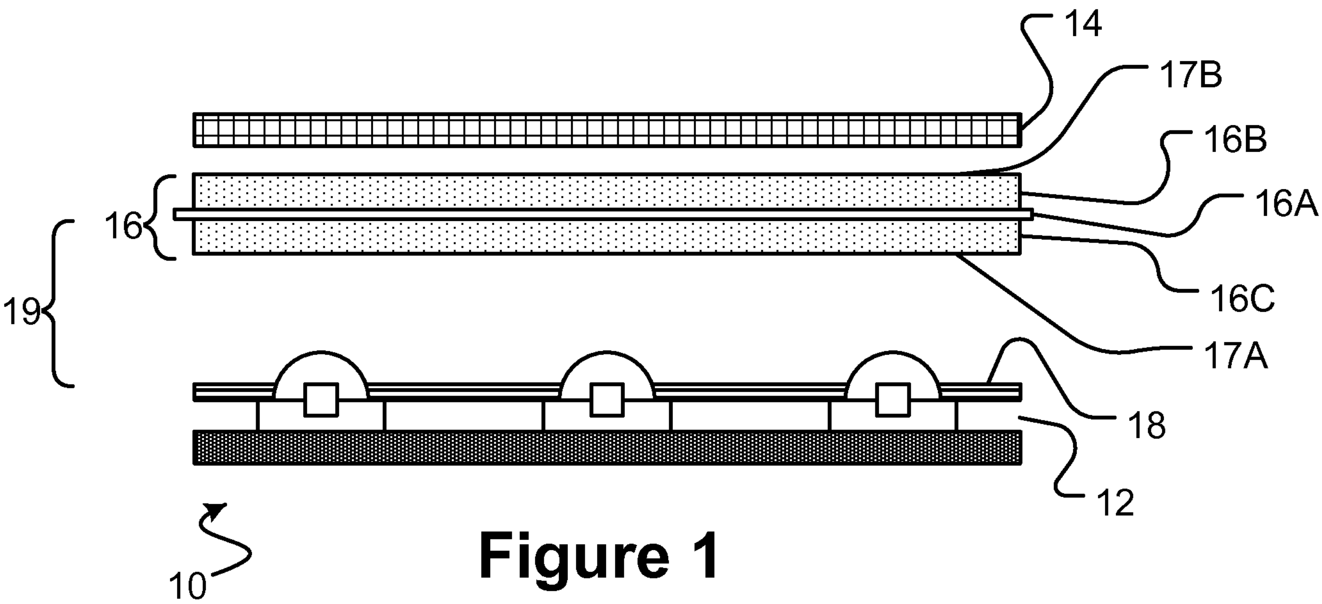

Figure 1

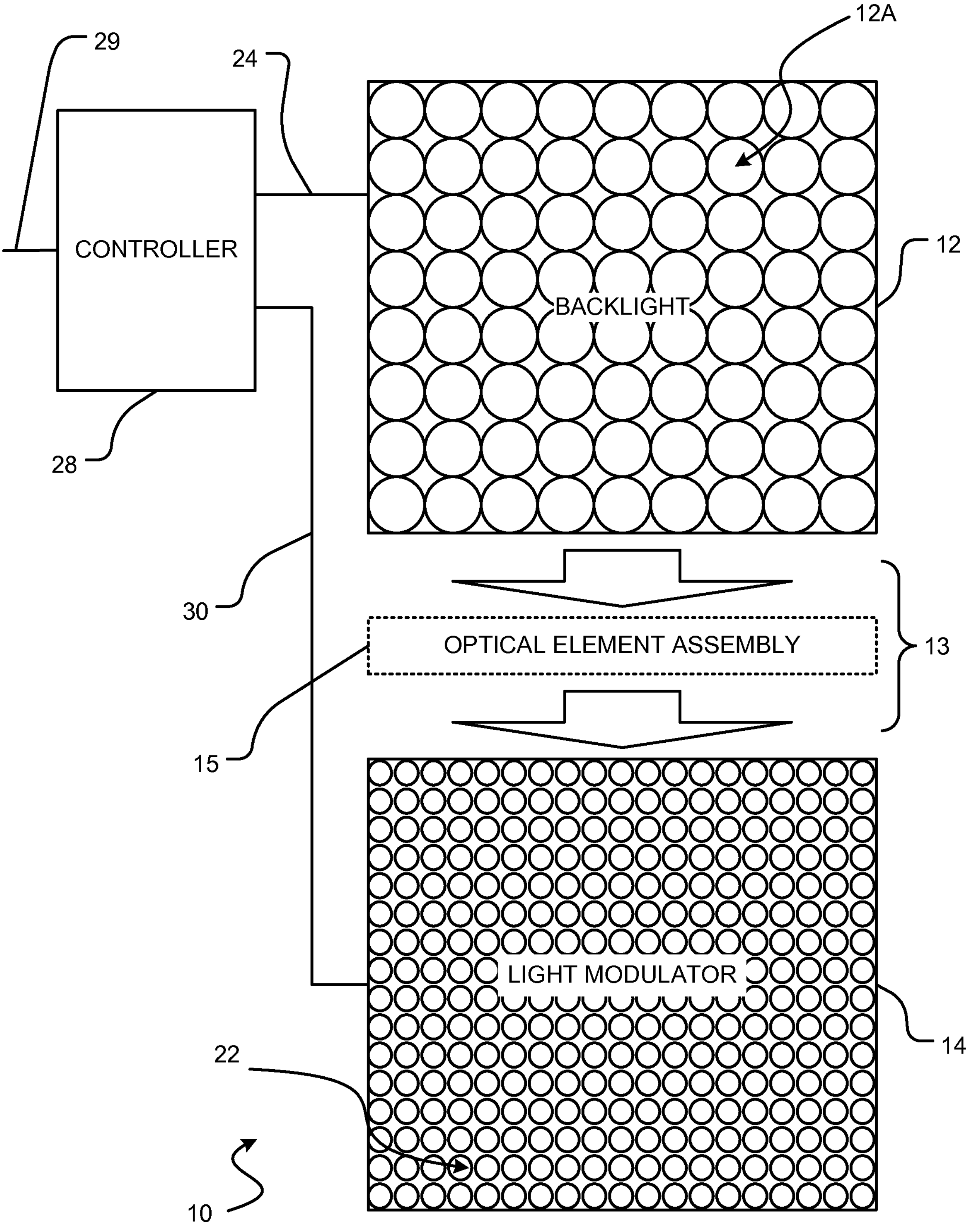
12A
29
24
CONTROLLER
12
BACKLIGHT
28
30
OPTICAL ELEMENT ASSEMBLY
13
15
LIGHT MODULATOR
14
22
10

Figure 1A

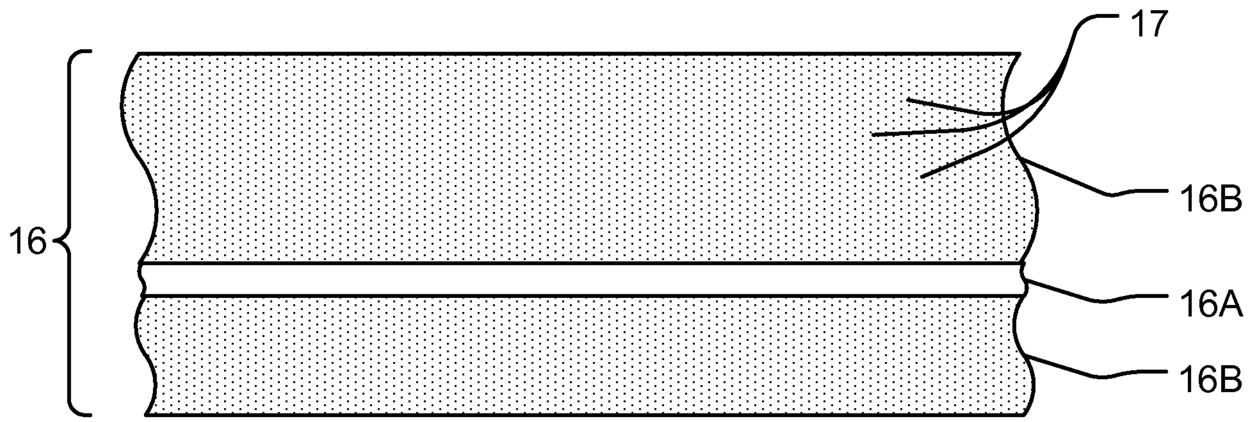

Figure 2

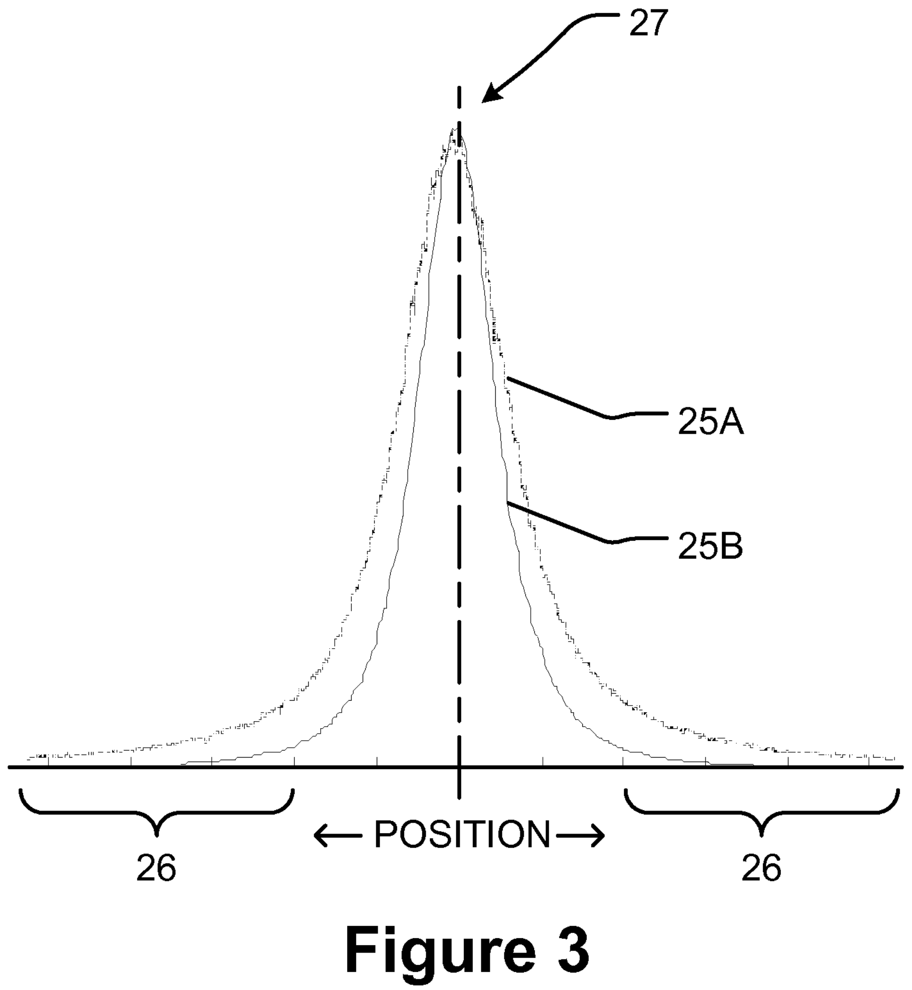

Figure 3

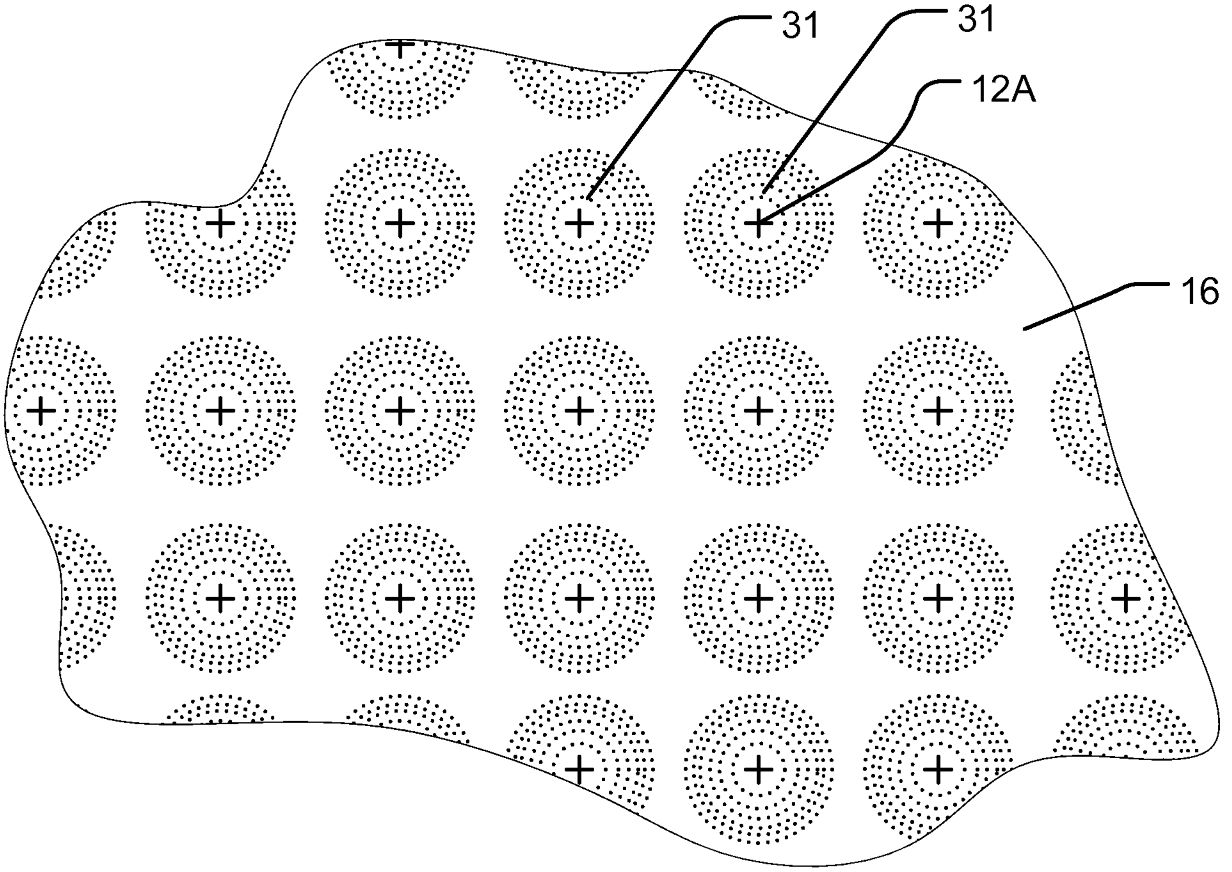

Figure 4A

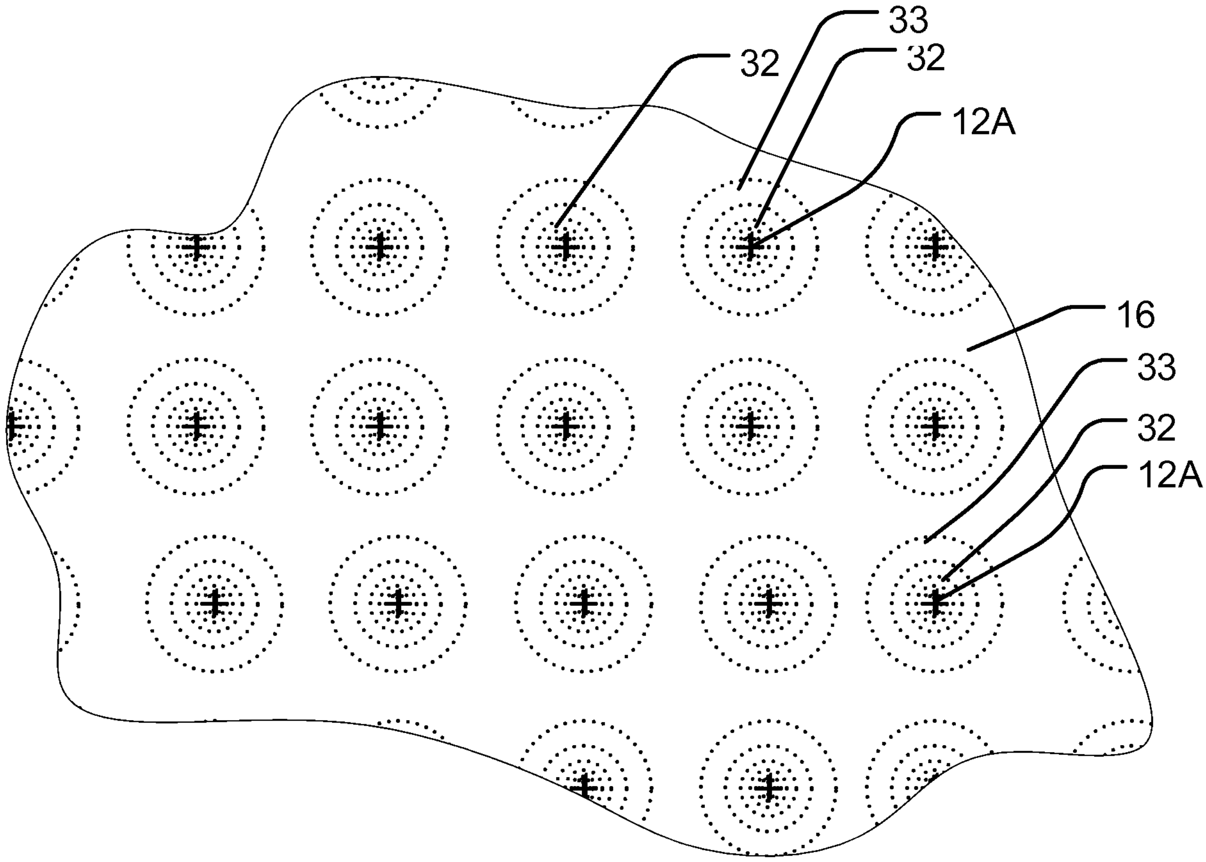

Figure 4B

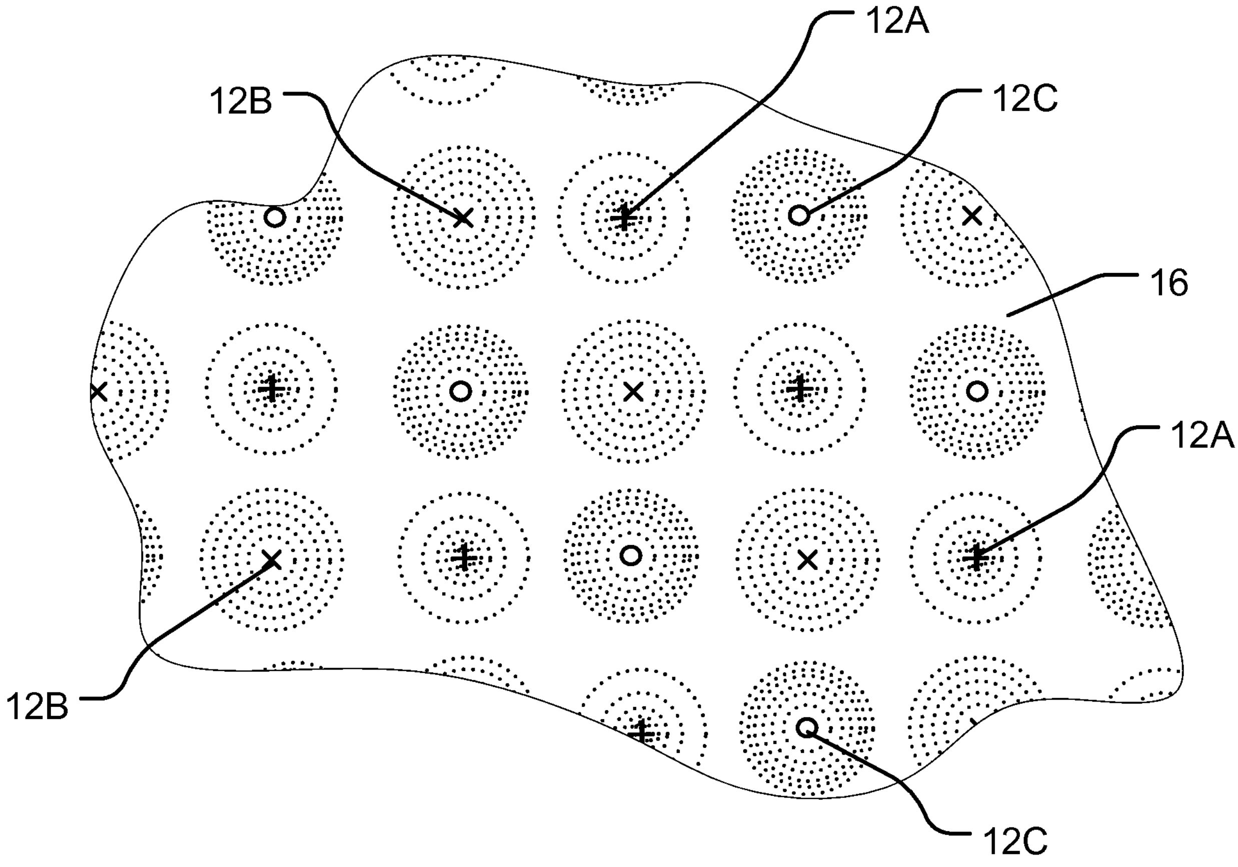

Figure 4C

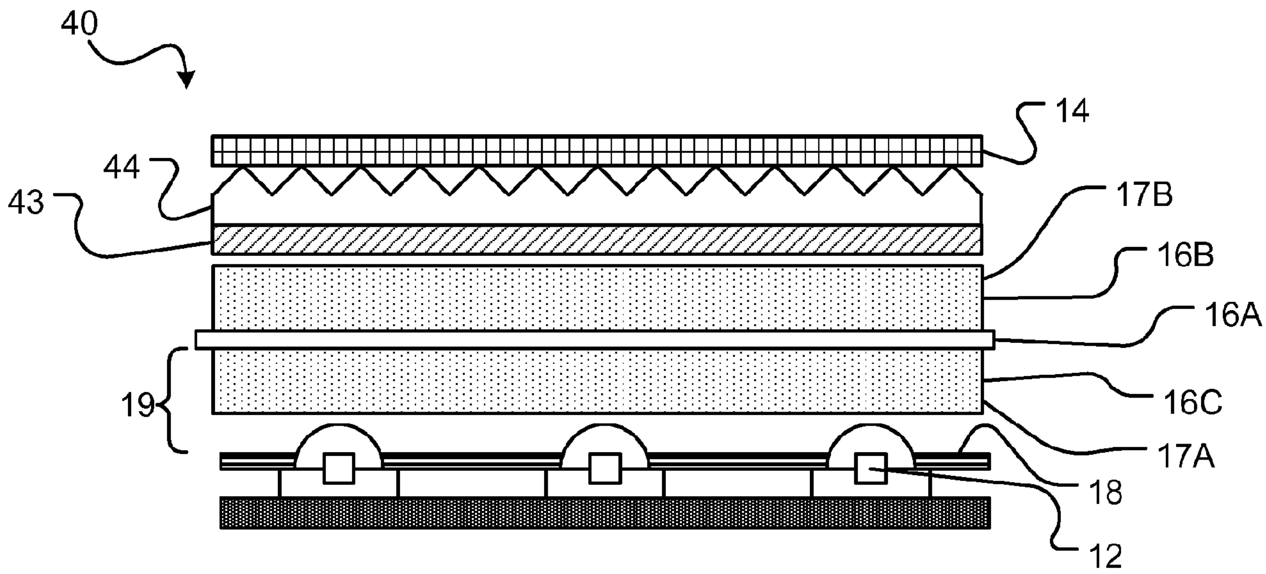

Figure 5

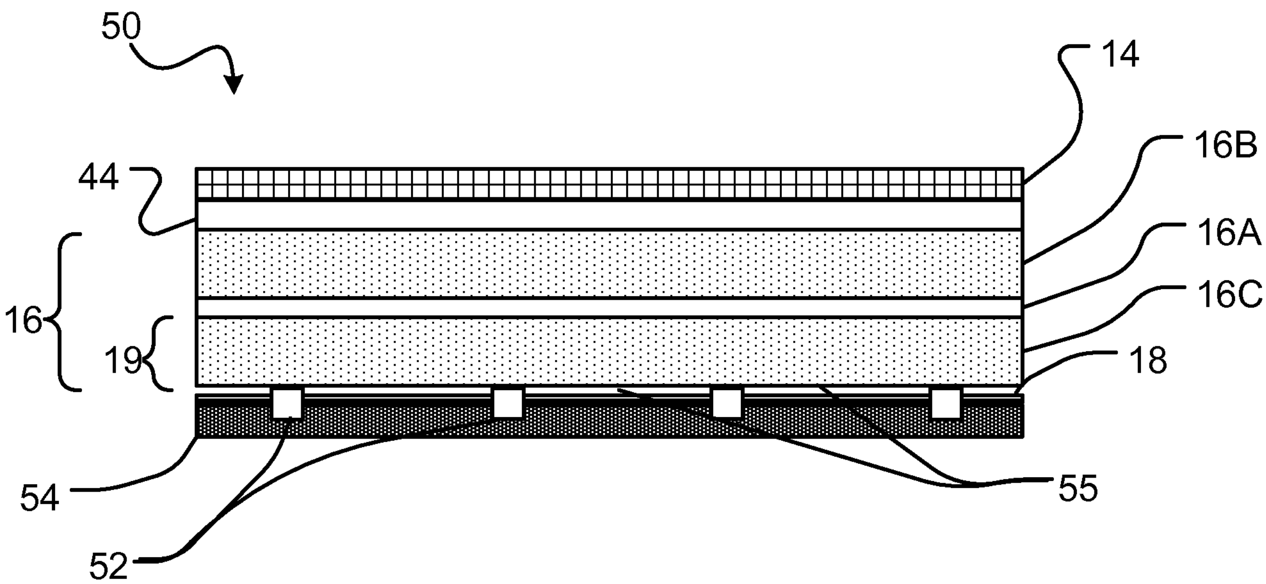

Figure 6

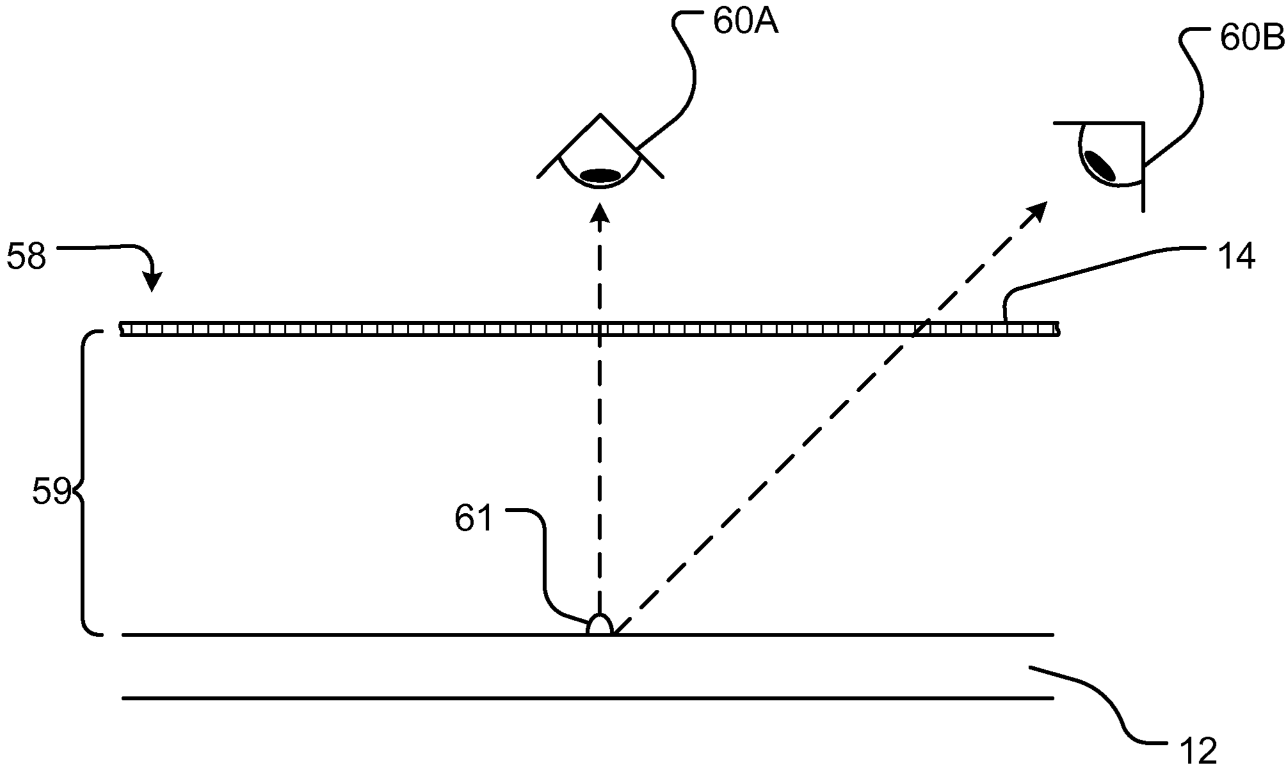

Figure 7

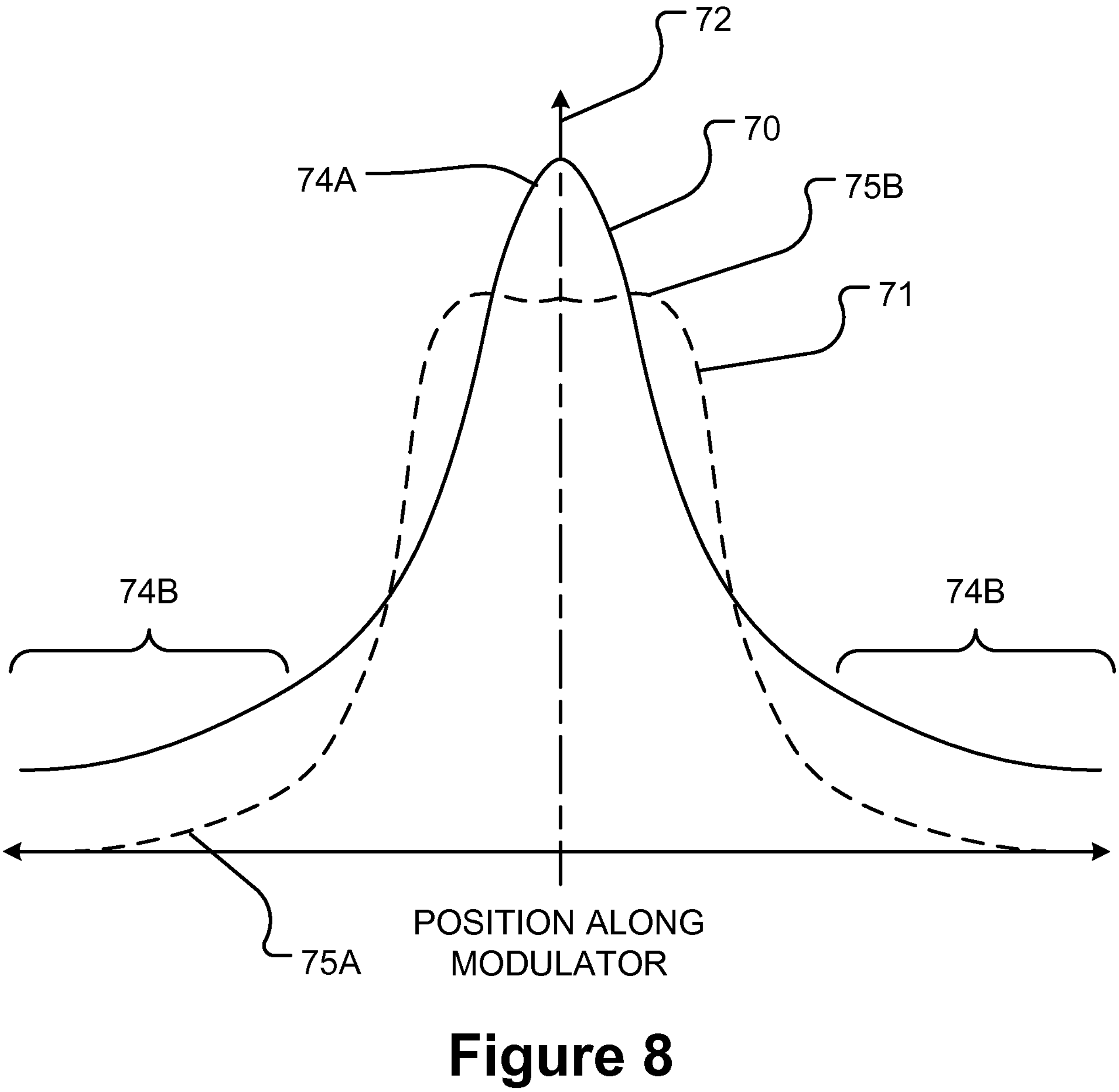

Figure 8

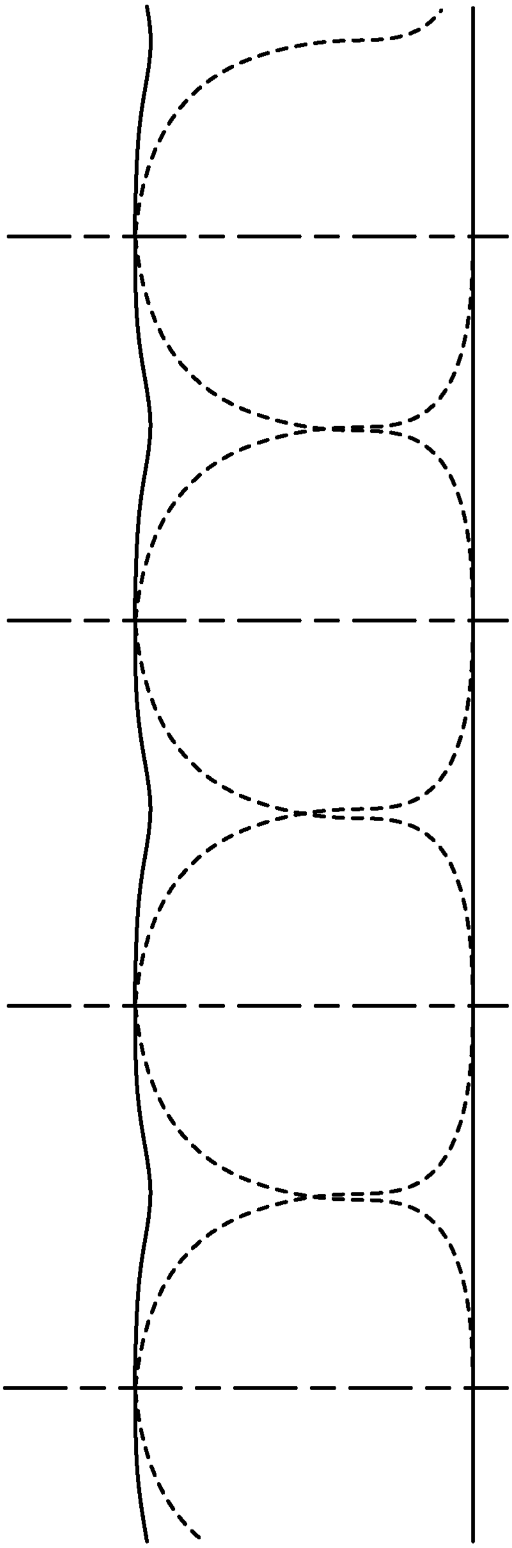

Figure 8A

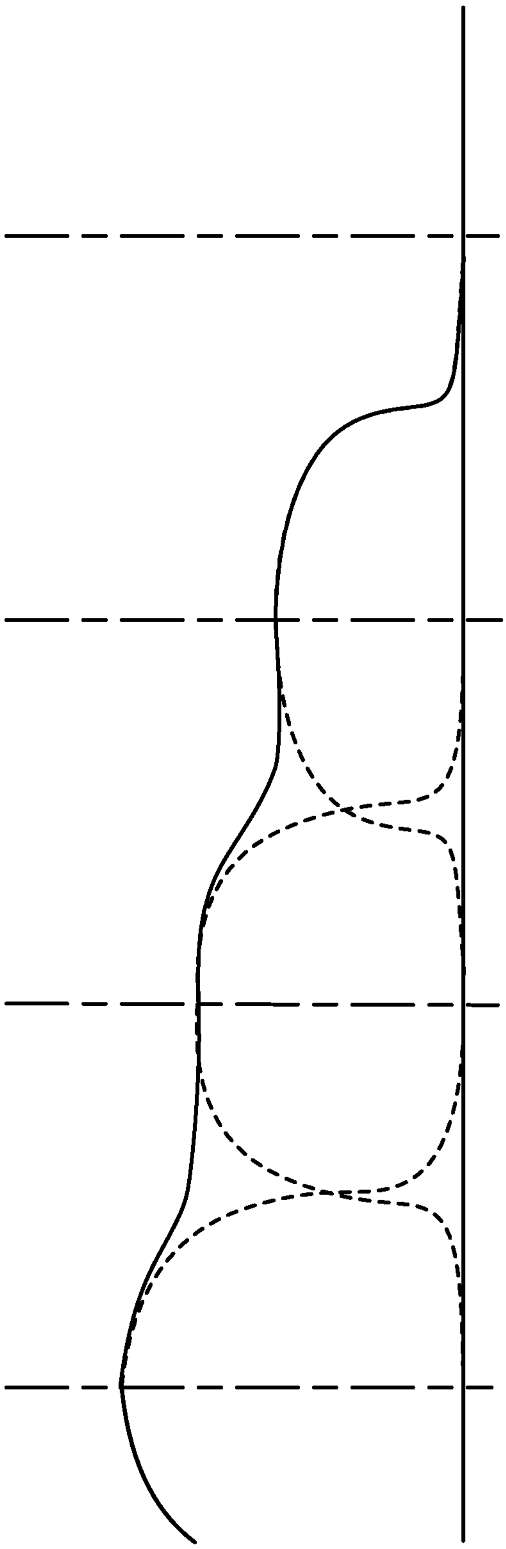

Figure 8B

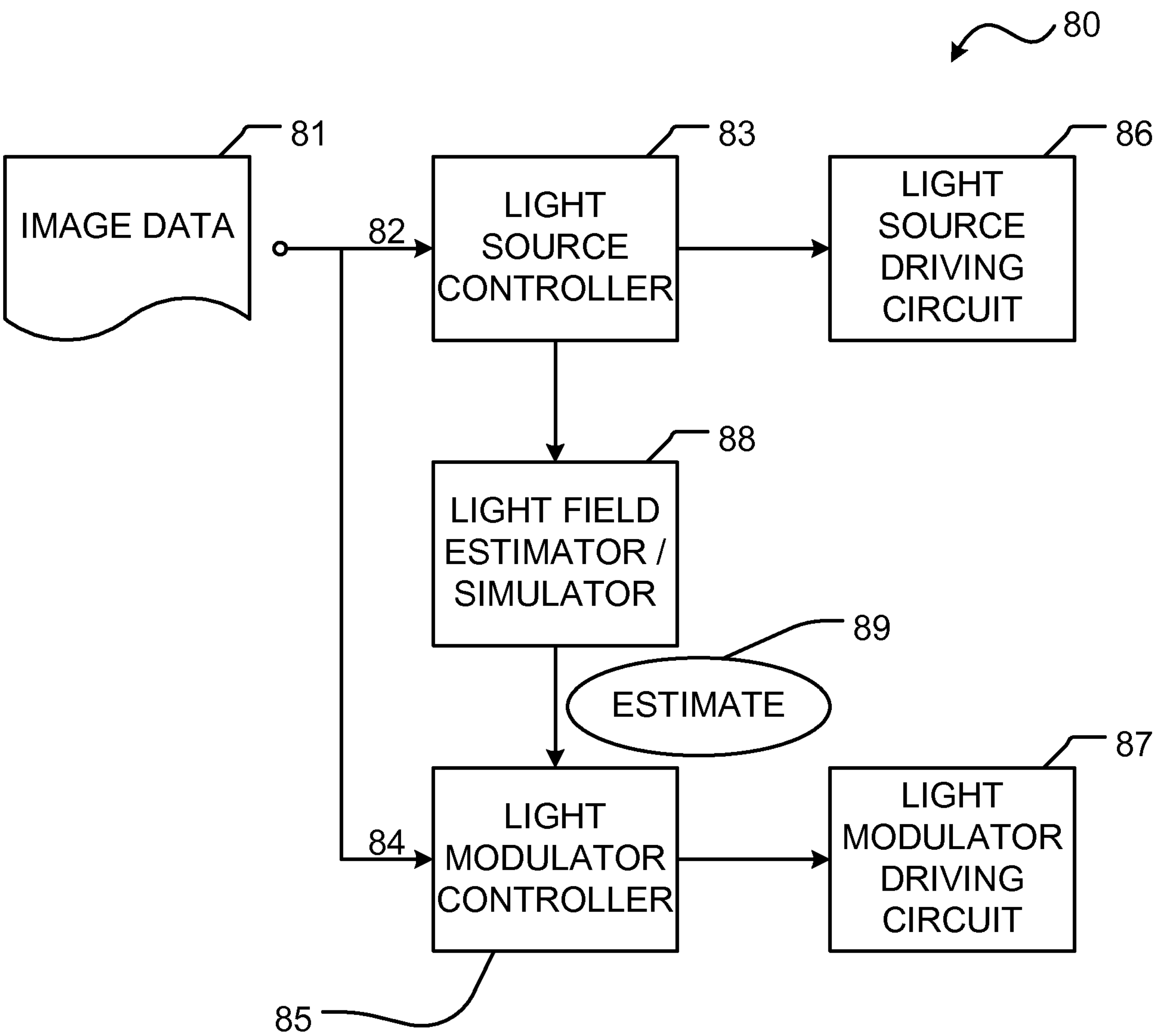
80
81
IMAGE DATA
82
83
LIGHT SOURCE CONTROLLER
86
LIGHT SOURCE DRIVING CIRCUIT
88
LIGHT FIELD ESTIMATOR / SIMULATOR
89
ESTIMATE
84
LIGHT MODULATOR CONTROLLER
87
LIGHT MODULATOR DRIVING CIRCUIT
85

Figure 9

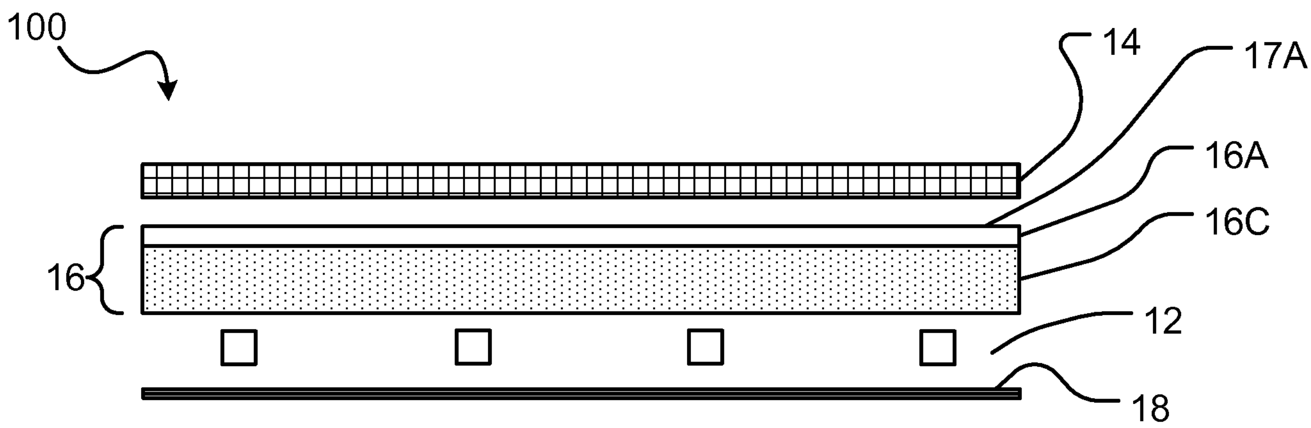

Figure 10

Figure 11

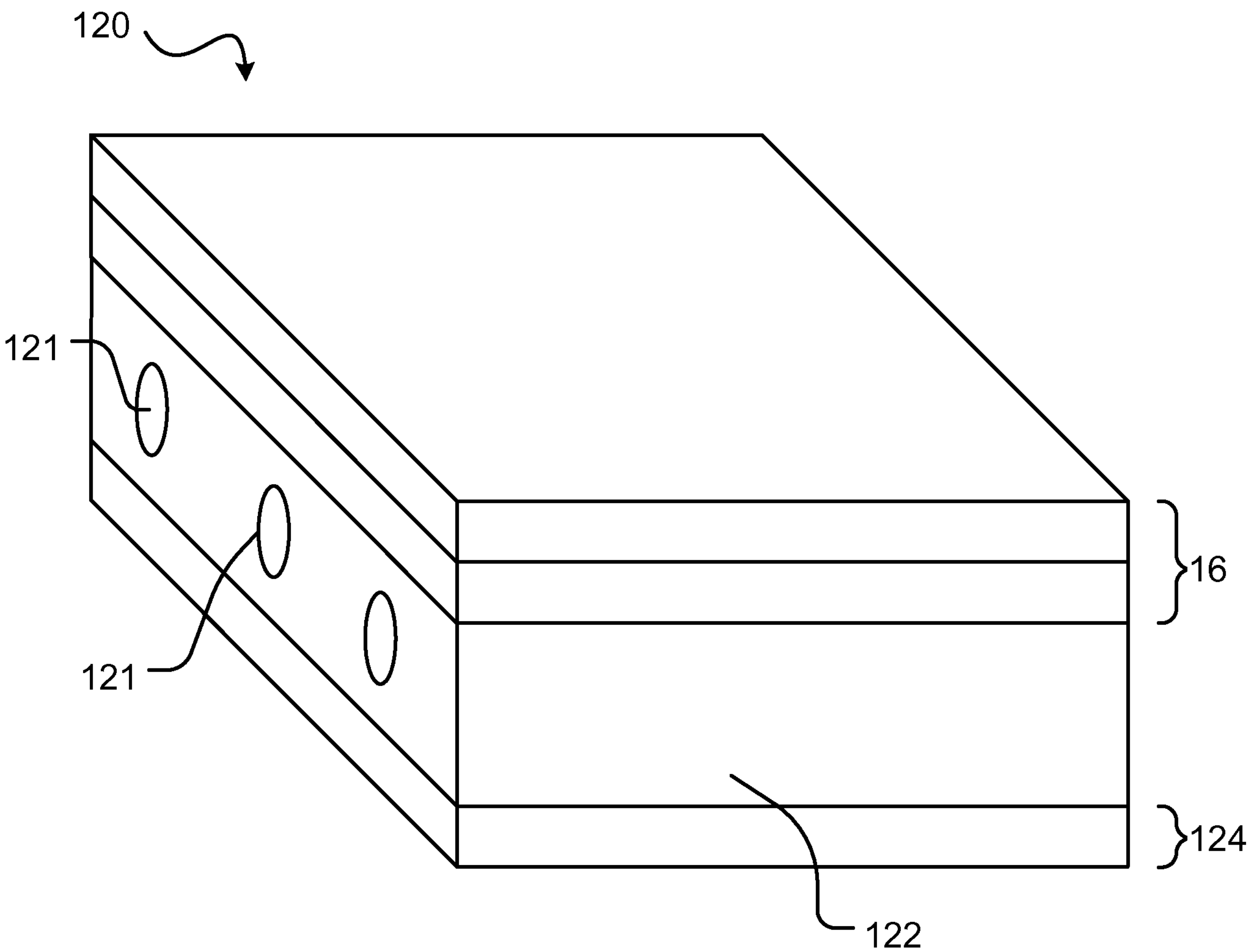

Figure 12

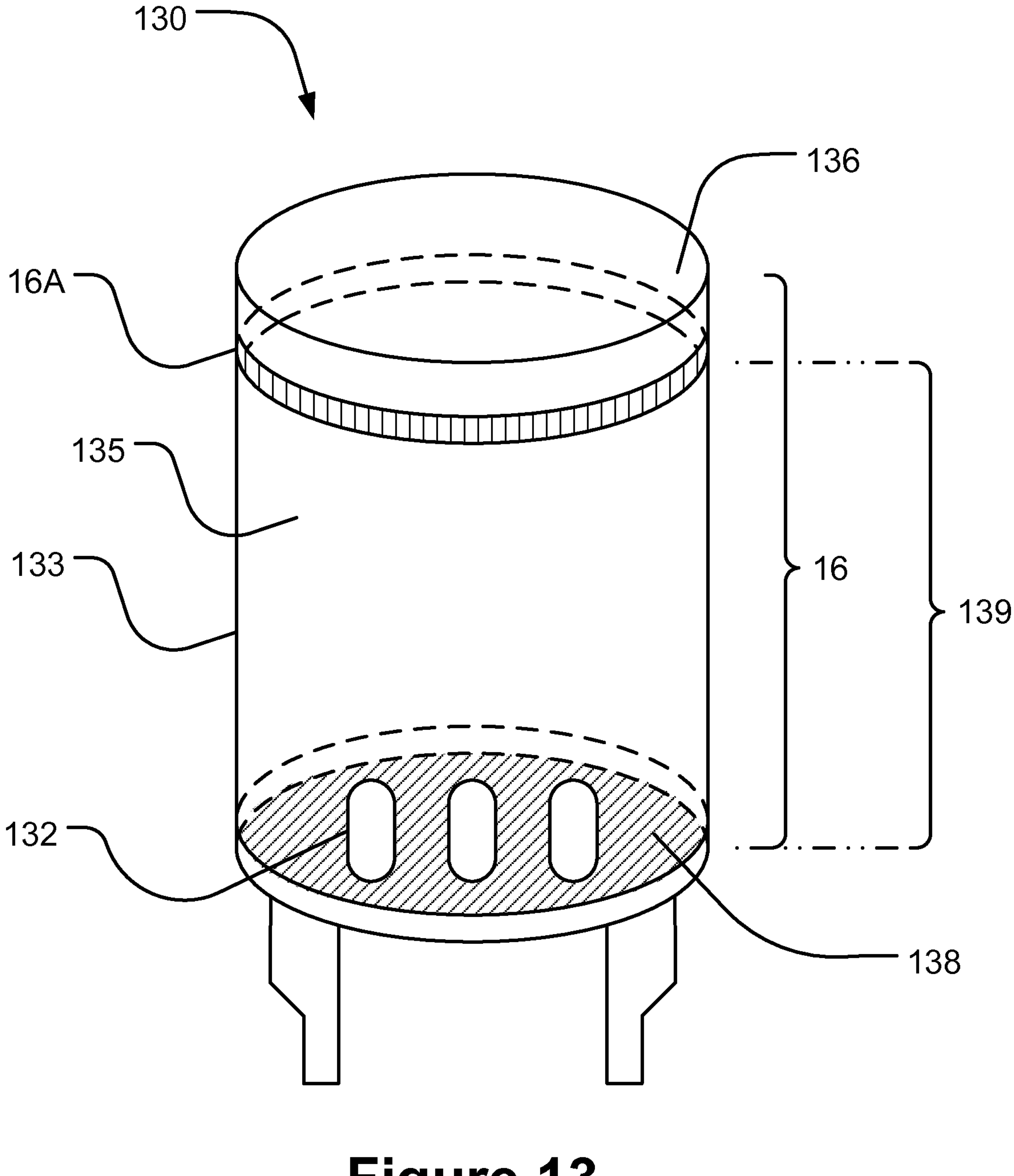

Figure 13

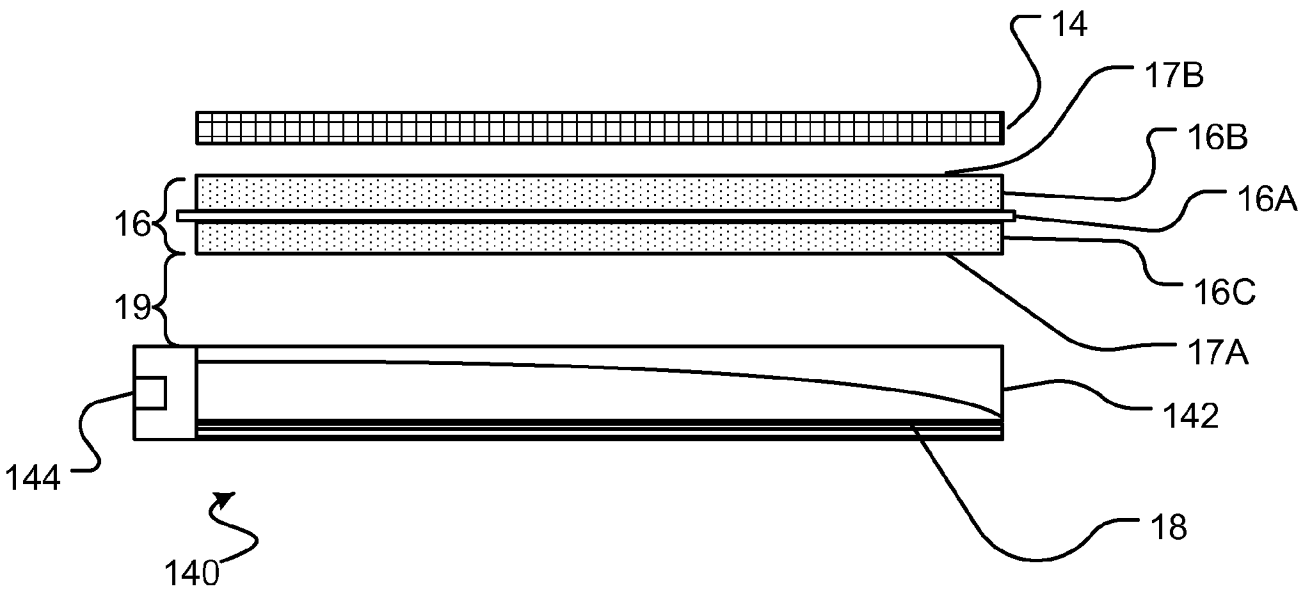

Figure 14

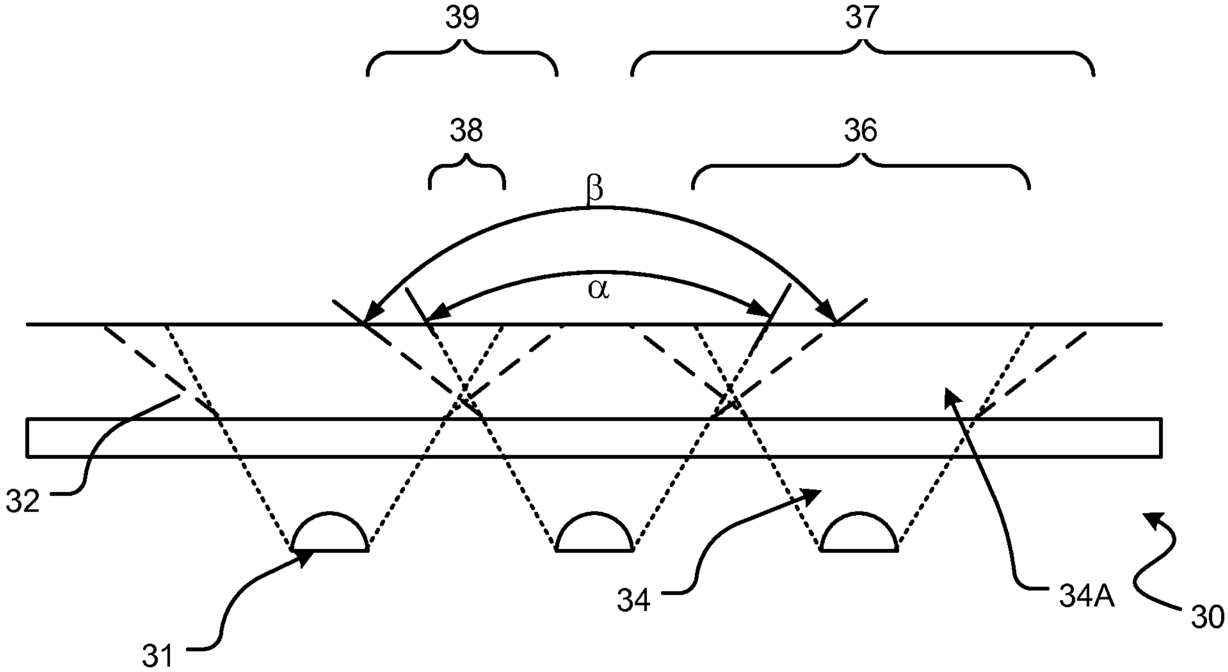

Figure 15A

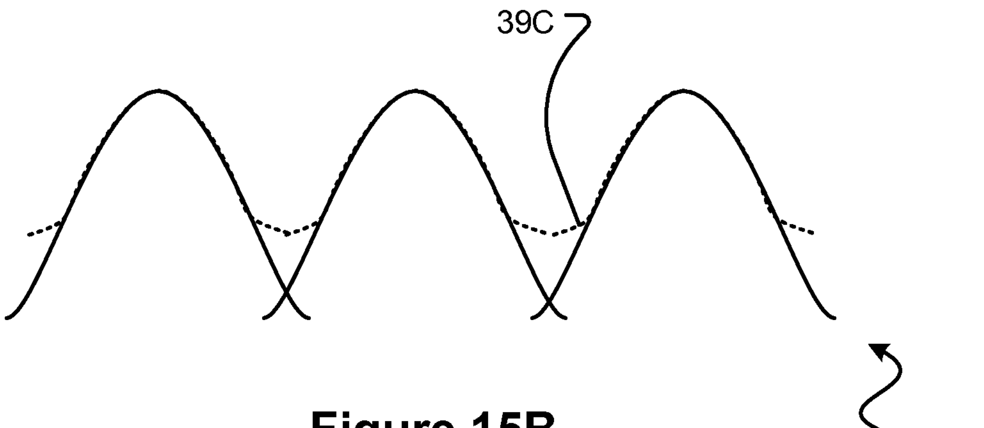

Figure 15B

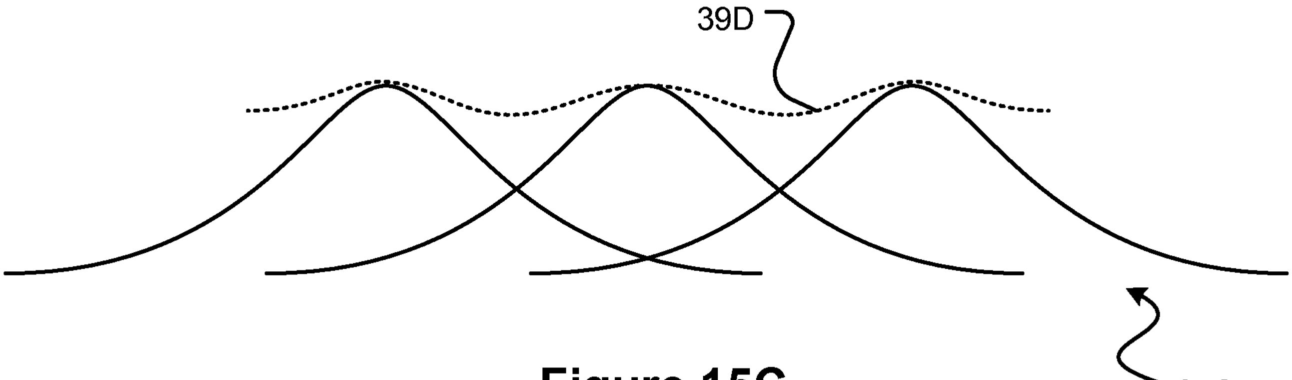

Figure 15C

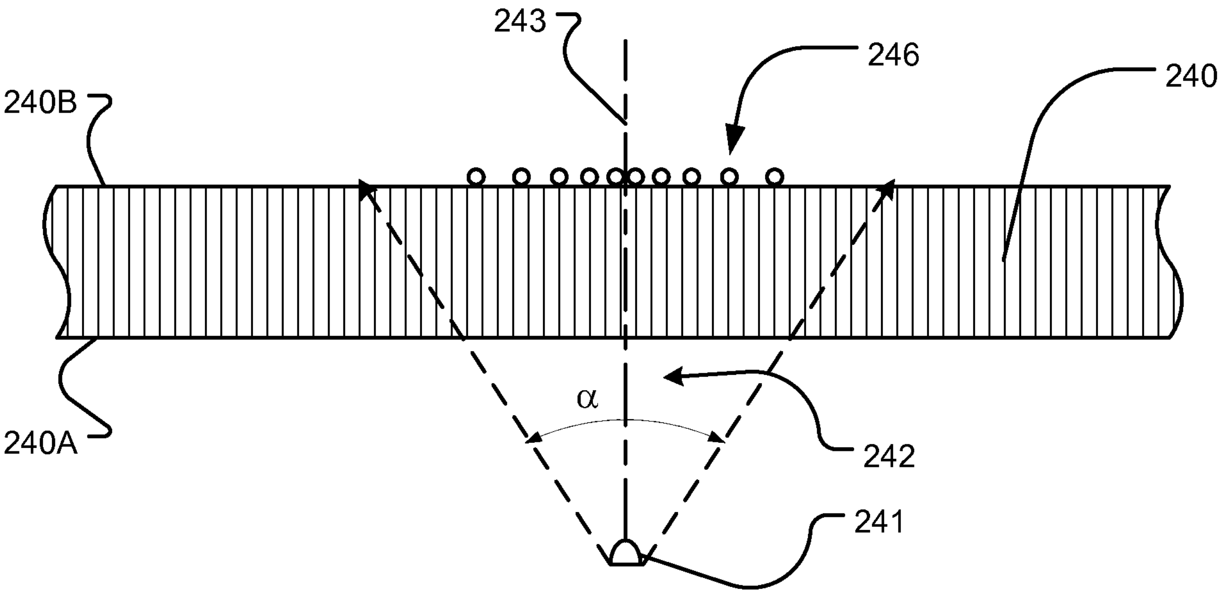

Figure 16A

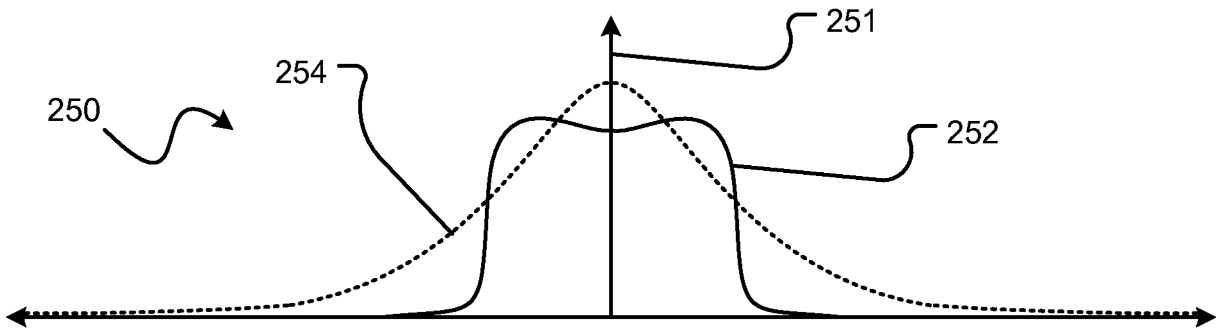

Figure 16B

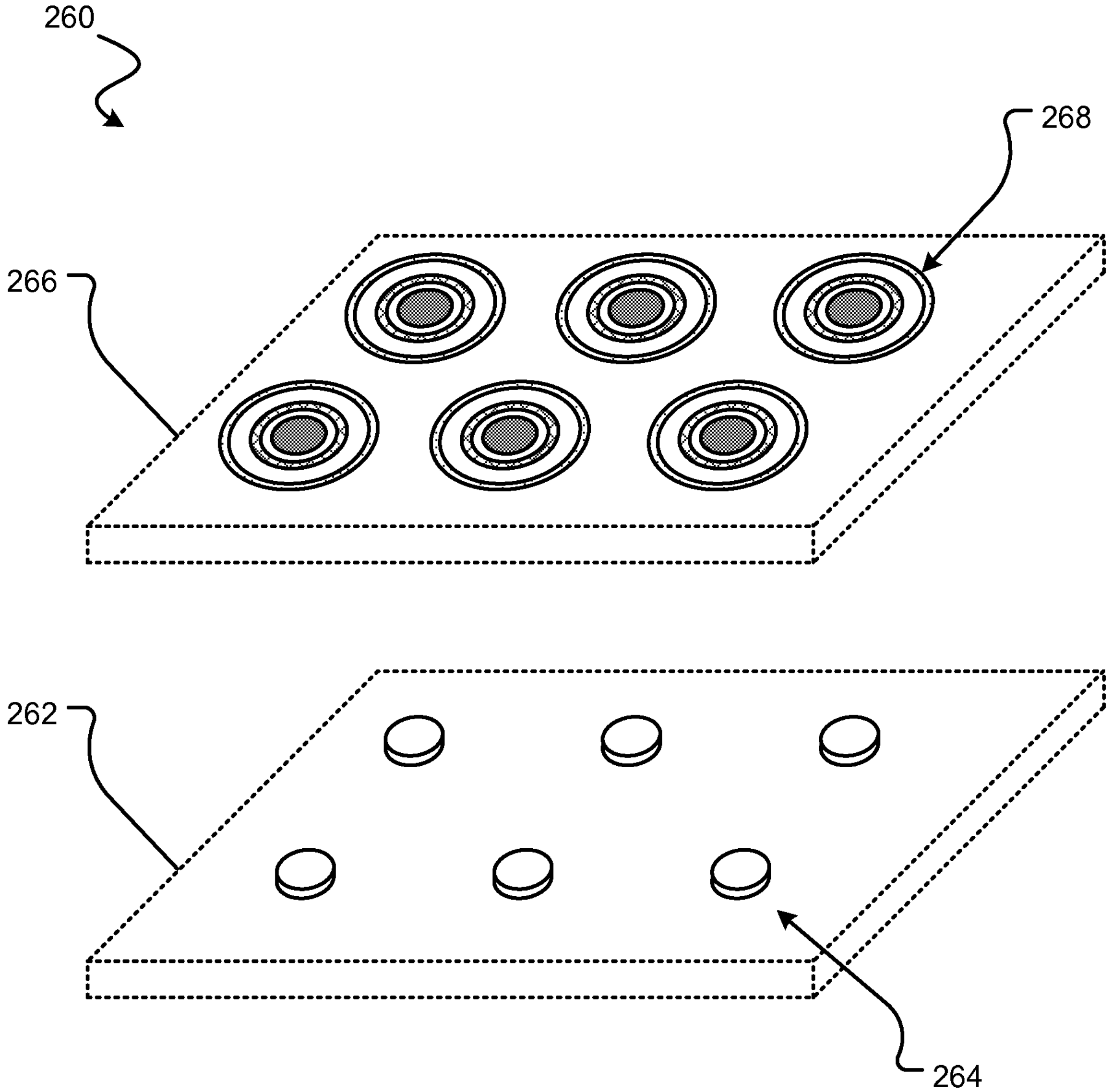

Figure 17

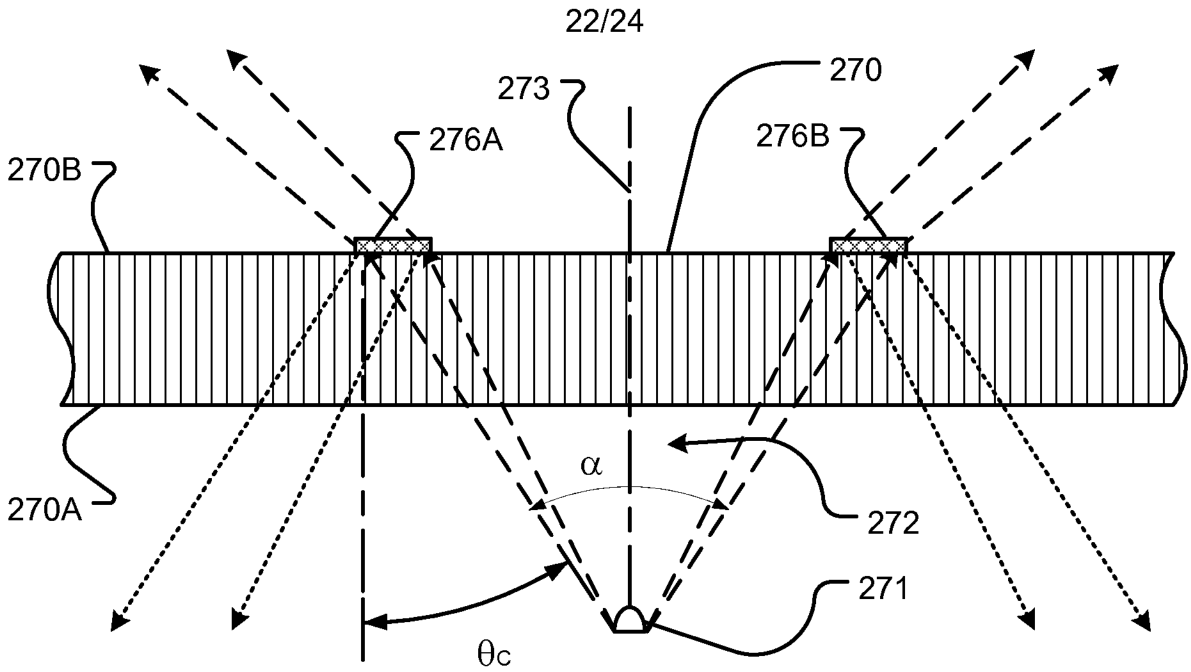

Figure 18A

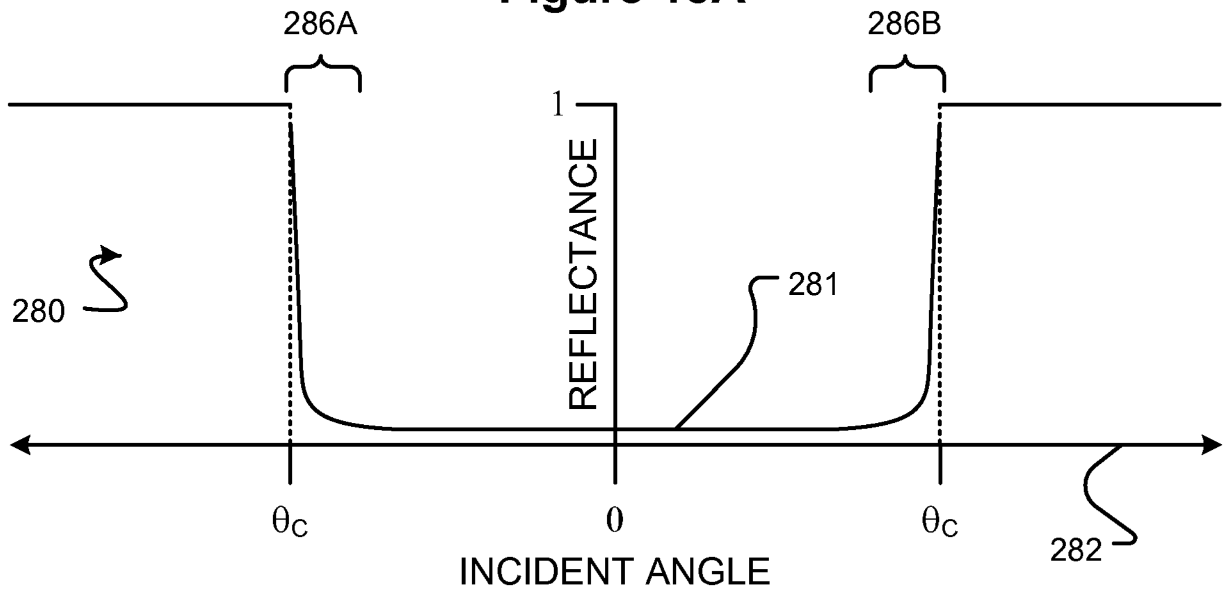

Figure 18B

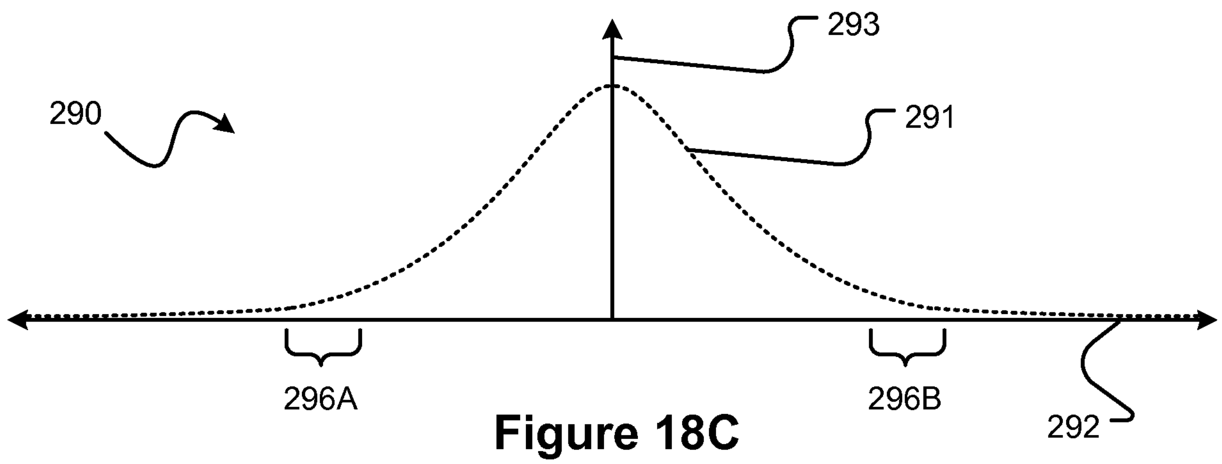

Figure 18C

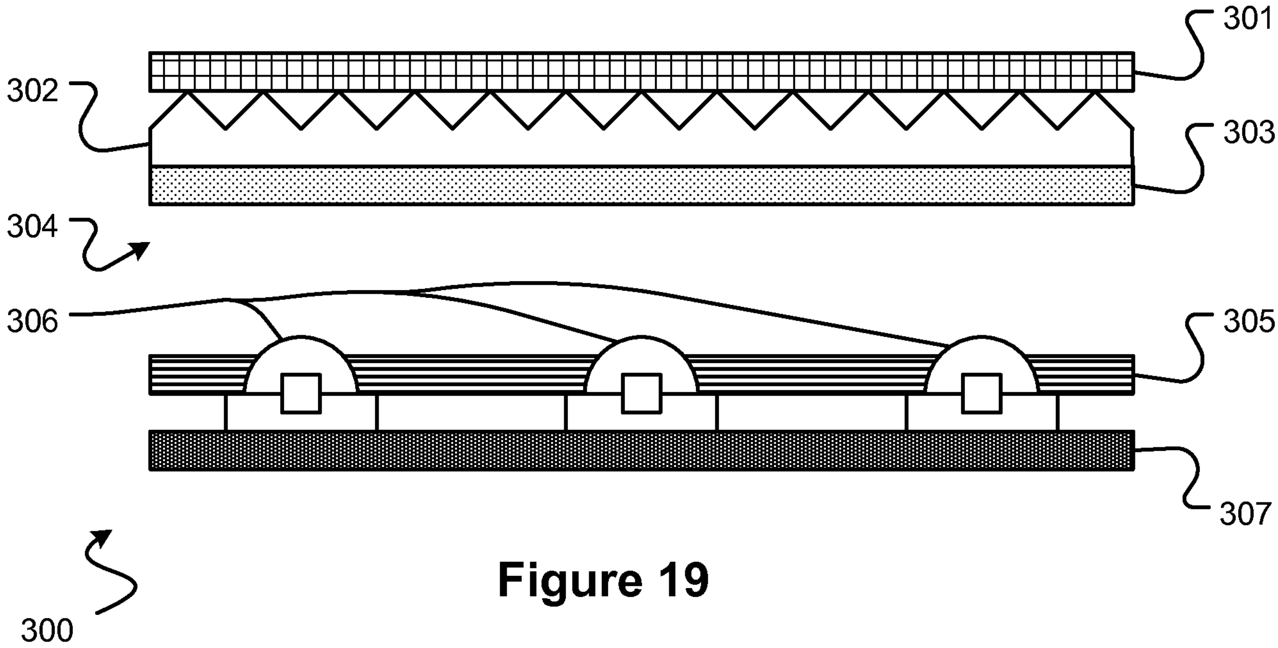

Figure 19

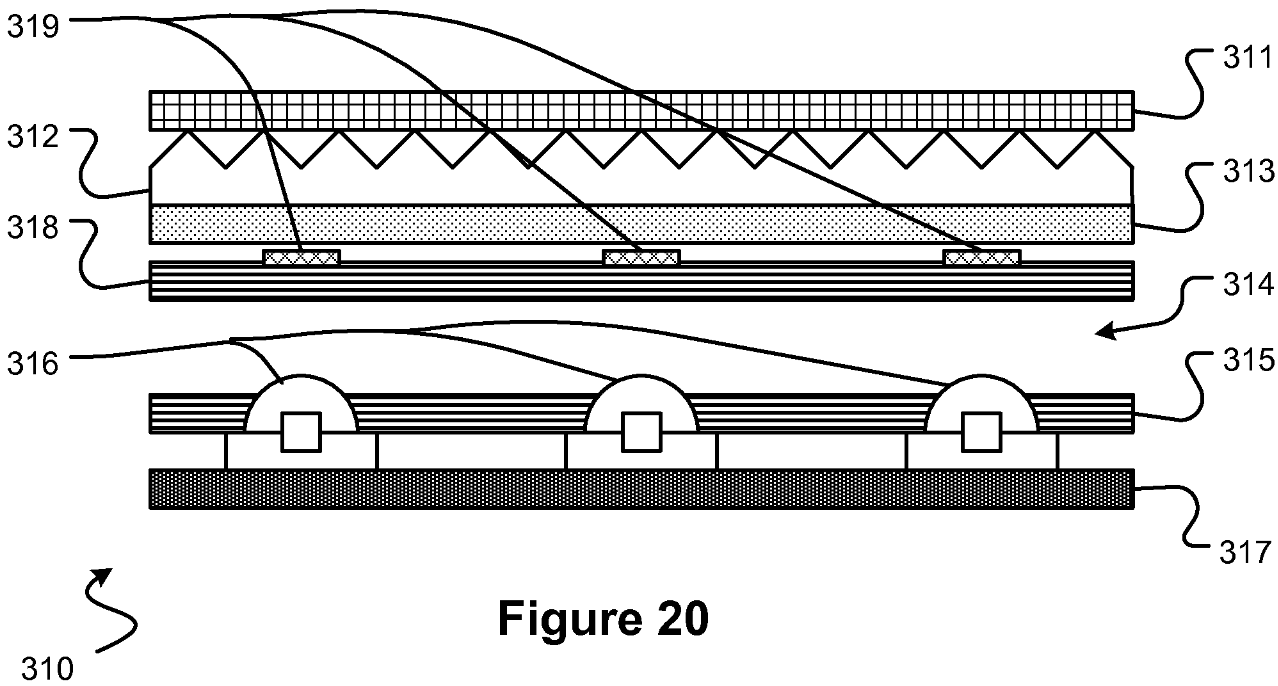

Figure 20

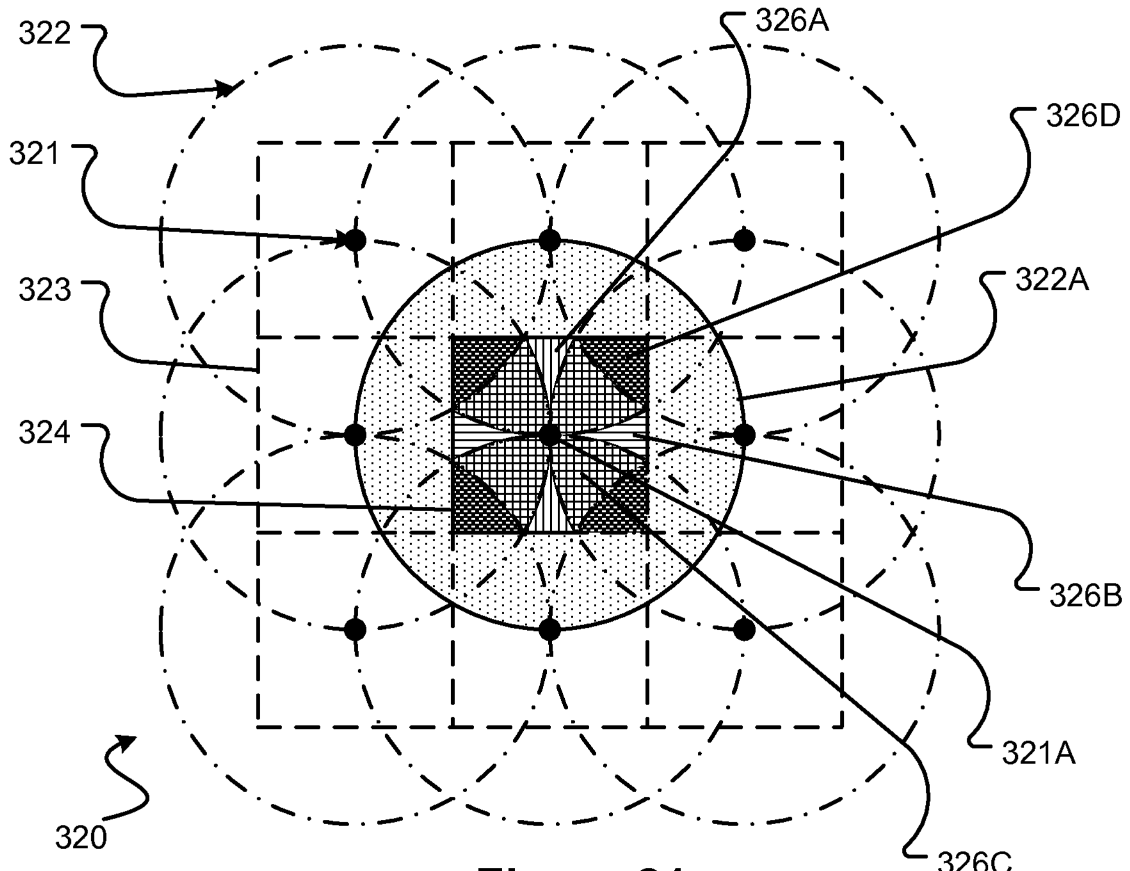

Figure 21

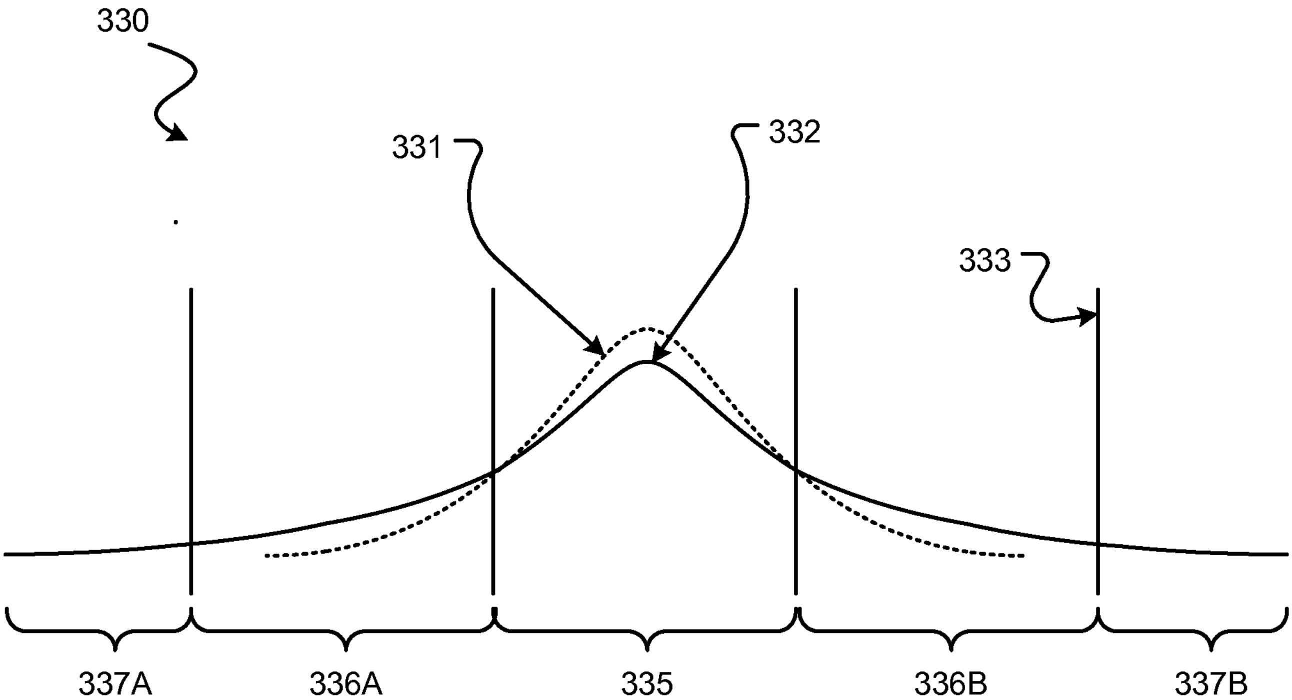

Figure 22