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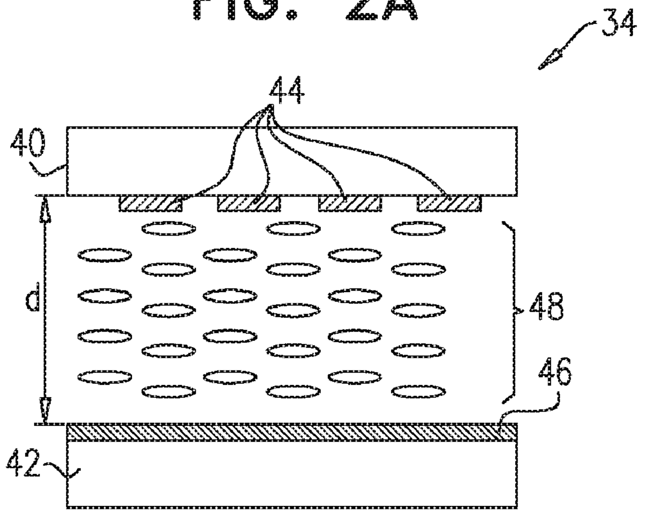
(54) Title: ELECTRICALLY-TUNABLE LENSES AND LENS SYSTEMS

FIG. 2A



(57) Abstract: An optical device (34, 66, 76) includes an electro-optical layer (48), having an effective local index of refraction at any given location within an active area of the electro-optical layer that is determined by a voltage waveform applied across the electro-optical layer at the location. Conductive electrodes (44, 64, 74, 82, 84) extend over opposing first and second sides of the electro-optical layer. The electrodes include an array of excitation electrodes, which extend along respective, mutually-parallel axes in a predefined direction across the first side of the electro- optical layer, and which includes at least first and second electrodes having different, respective widths in a transverse direction, perpendicular to the axes. Control circuitry (38) is coupled to apply respective control voltage waveforms to the excitation electrodes so as to generate a specified phase modulation profile in the electro-optical layer.

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1. An optical device, comprising:

an electro-optical layer, having an effective local index of refraction at any given location within an active area of the electro-optical layer that is determined by a voltage waveform applied across the electro-optical layer at the location;

conductive electrodes extending over opposing first and second sides of the electro-optical layer, the electrodes comprising an array of excitation electrodes, which extend along respective, mutually-parallel axes in a predefined direction across the first side of the electro-optical layer, and which comprises at least first and second electrodes having different, respective widths in a transverse direction, perpendicular to the axes; and

control circuitry, which is coupled to apply respective control voltage waveforms to the excitation electrodes and to modify the control voltages applied to each of the excitation electrodes concurrently and independently so as to generate a specified phase modulation profile in the electro-optical layer.

2. The device according to claim 1, wherein the respective widths of the electrodes differ from one another with a standard variation that is at least 10% of a mean width of all the electrodes.

3. The device according to claim 1 or 2, wherein the respective widths of at least some of the electrodes vary along the respective axes of the electrodes.

4. The device according to any of claims 1-3, wherein the array of excitation electrodes comprises a first array of first excitation electrodes, extending in a first direction across the first side of the electro-optical layer, and

wherein the conductive electrodes comprises a second array of second excitation electrodes, which extend in a second direction, perpendicular to the first direction, across the second side of the electro-optical layer, and which comprises at least third and fourth electrodes having different, respective widths.

5. The device according to any of claims 1-3, wherein the conductive electrodes comprise a common electrode, positioned over the active area on the second side of the electro-optical layer.

6. Apparatus comprising first and second optical devices according to claim 5, wherein the first and second optical devices are arranged in series, and wherein the excitation electrodes in

the second optical device are oriented in a direction orthogonal to the excitation electrodes in the first optical device.

7. The apparatus according to claim 6, wherein the first and second optical devices comprise respective, first and second electro-optical layers that are polarization-dependent and are arranged such that the first optical device modulates light in a first polarization, while the second optical device modulates the light in a second polarization, different from the first polarization, and wherein the apparatus comprises a polarization rotator positioned between the first and second optical devices so as to rotate the light from the first polarization to the second polarization.

8. The device according to any of claims 1-7, wherein the first and second electrodes have respective first and second widths, such that the first width is at least twice the second width, and wherein the control circuitry is configured to apply the respective control voltage waveforms so that the specified phase modulation profile has an abrupt transition that occurs in a vicinity of at least one of the second electrodes.

9. The device according to claim 8, wherein generation of the specified phase modulation profile causes the device to function as a Fresnel lens.

10. The device according to claim 8 or 9, wherein the electrodes comprise parallel stripes of a transparent conductive material having gaps between the stripes of a predefined gap width, and wherein the second width of the second electrodes is no greater than four times the gap width.

11. The device according to any of claims 8-10, wherein the second width of the second electrodes is less than a layer thickness of the electro-optical layer.

12. The device according to any of claims 8-11, wherein the phase modulation profile has multiple abrupt transitions that occur in respective vicinities of corresponding ones of the second electrodes, and

wherein the electro-optical layer is configured to provide a range of phase modulation values that is proportional to a relation between a density of the second electrodes relative to a spacing between the abrupt transitions in the phase modulation function.

13. The device according to any of claims 1-12, wherein the electro-optical layer comprises a liquid crystal.

14. An optical device, comprising:

an electro-optical layer, having an effective local index of refraction at any given location within an active area of the electro-optical layer that is determined by a voltage waveform applied across the electro-optical layer at the location, the electro-optical layer having opposing first and second sides and a layer thickness equal to a distance between the first and second sides;

conductive electrodes extending over the first and second sides of the electro-optical layer, the electrodes comprising an array of excitation electrodes comprising parallel stripes of a transparent conductive material having gaps between the stripes of a gap width that is no greater than 2 μm and is less than the layer thickness of the electro-optical layer; and

control circuitry, which is coupled to apply respective control voltage waveforms to the excitation electrodes so as to generate a specified phase modulation profile in the electro-optical layer.

15. The device according to claim 14, wherein the gap width is less than half the layer thickness.

16. The device according to claim 14 or 15, wherein the electro-optical layer comprises a liquid crystal.

17. An optical device, comprising:

an electro-optical layer, having opposing first and second sides and having an effective local index of refraction at any given location within an active area of the electro-optical layer that is determined by a voltage waveform applied across the electro-optical layer at the location;

a buffer layer comprising a transparent dielectric material having an interior surface adjacent to the first side of the electro-optical layer and an exterior surface opposite the interior surface and a thickness of at least 0.2 μm between the interior and exterior surfaces;

conductive electrodes disposed over the first and second sides of the electro-optical layer and comprising an array of excitation electrodes extending across the exterior surface of the buffer layer, which separates the excitation electrodes from the electro-optical layer; and

control circuitry, which is coupled to apply respective control voltage waveforms to the excitation electrodes so as to generate a specified phase modulation profile in the electro-optical layer.

18. The device according to claim 17, wherein the excitation electrodes comprise parallel stripes of a transparent conductive material having gaps between the stripes of a predefined gap width, and the buffer layer has a buffer layer thickness that is more than one-fourth of the gap width.

19. The device according to claim 17 or 18, wherein the electro-optical layer comprises a liquid crystal.

20. An optical device, comprising:

an electro-optical layer, having an effective local index of refraction at any given location within an active area of the electro-optical layer that is determined by a voltage waveform applied across the electro-optical layer at the location;

a first array of first excitation electrodes, which extend along respective, mutually-parallel first axes in a first direction over the active area on a first side of the electro-optical layer;

a second array of second excitation electrodes, which extend along respective, mutually-parallel second axes in a second direction, orthogonal to the first direction, over the active area on a second side of the electro-optical layer, opposite the first side; and

control circuitry, which is coupled to apply respective control voltage waveforms concurrently to both the first excitation electrodes and the second excitation electrodes s and is configured to concurrently modify the respective control voltage waveforms applied to both the first excitation electrodes and the second excitation electrodes so as to generate a specified phase modulation profile in the electro-optical layer.

21. The device according to claim 20, wherein the phase modulation profile is defined as a function that is separable into first and second component functions, which respectively vary along the first and second axes, and wherein the control voltage waveforms applied to the first and second excitation electrodes are specified in accordance with the first and second component functions, respectively.

22. The device according to claim 21, wherein the first and second component functions are defined in terms of a set of component waveforms that are selected so as to correspond to different, respective phase shifts in the electro-optical layer, such that the phase modulation profile comprises a sum of the respective phase shifts due to the first and second component functions at each location within the active area.

23. The device according to claim 22, wherein the component waveforms have different, respective duty cycles.

24. The device according to claim 22 or 23, wherein the component waveforms are selected so that the sum of the respective phase shifts making up the phase modulation profile is a modular sum with a modulus of $2n\pi$, wherein n is an integer.

25. The device according to claim 24, wherein n has different, respective values for at least some different pairs of the first and second component functions.

26. The device according to any of claims 20-25, wherein the control voltage waveforms are selected so that the phase modulation profile contains abrupt phase transitions, and the device functions as a Fresnel lens.

27. The device according to claim 26, wherein the control circuitry is configured to apply the respective control voltage waveforms with opposite polarities to pairs of mutually-adjacent excitation electrodes in a vicinity of the abrupt phase transitions.

28. The device according to any of claims 20-27, wherein the electro-optical layer comprises a liquid crystal.

29. Optical apparatus, comprising:

a static lens, comprising a transparent material having a curved exterior surface with a specified refractive power and an interior surface containing at least first and second overlapping indentations; and

a dynamic lens, which is contained in the static lens and has a variable phase modulation profile, which modifies the refractive power of the static lens, and which comprises:

an electro-optical layer, having opposing first and second sides and having an effective local index of refraction at any given location within an active area of the electro-optical layer that is determined by a voltage applied across the electro-optical layer at the location;

first and second transparent substrates, which are disposed respectively on the first and second sides of the electro-optical layer and are sized and shaped to fit respectively into the first and second indentations in the static lens, and which comprise electrodes configured to apply voltages across the electro-optical layer; and

control circuitry, which is coupled to apply the voltages to the electrodes so as to generate the modulation profile in the electro-optical layer.

30. The apparatus according to claim 29, wherein the control circuitry comprises electrical connections disposed at an edge of the first transparent substrate, and wherein the interior surface of the static lens contains a groove into which the electrical connections fit.

31. A method for producing an optical device, the method comprising:

providing an electro-optical layer, having an effective local index of refraction at any given location within an active area of the electro-optical layer that is determined by a voltage waveform applied across the electro-optical layer at the location;

positioning conductive electrodes over opposing first and second sides of the electro-optical layer, the electrodes comprising an array of excitation electrodes, which extend along respective, mutually-parallel axes in a predefined direction across the first side of the electro-optical layer, and which comprises at least first and second electrodes having different, respective widths in a transverse direction, perpendicular to the axes; and

coupling control circuitry to apply respective control voltage waveforms to the excitation electrodes and to modify the control voltages applied to each of the excitation electrodes concurrently and independently so as to generate a specified phase modulation profile in the electro-optical layer.

32. The method according to claim 31, wherein the respective widths of the electrodes differ from one another with a standard variation that is at least 10% of a mean width of all the electrodes.

33. The method according to claim 31 or 32, wherein the respective widths of at least some of the electrodes vary along the respective axes of the electrodes.

34. The method according to any of claims 31-33, wherein the array of excitation electrodes comprises a first array of first excitation electrodes, extending in a first direction across the first side of the electro-optical layer, and

wherein positioning the conductive electrodes comprises positioning a second array of second excitation electrodes to extend in a second direction, perpendicular to the first direction, across the second side of the electro-optical layer, and wherein the second array comprises at least third and fourth electrodes having different, respective widths.

35. The method according to any of claims 31-33, wherein the conductive electrodes comprise a common electrode, positioned over the active area on the second side of the electro-optical layer.

36. The method according to claim 35, and comprising arranging in series first and second optical devices made in accordance with the method of claim 35, wherein the excitation electrodes in the second optical device are oriented in a direction orthogonal to the excitation electrodes in the first optical device.

37. The method according to claim 36, wherein the first and second optical devices comprise respective, first and second electro-optical layers that are polarization-dependent and are arranged such that the first optical device modulates light in a first polarization, while the second optical device modulates the light in a second polarization, different from the first polarization, and

wherein the method comprises positioning a polarization rotator between the first and second optical devices to rotate light from the first polarization to the second polarization.

38. The method according to any of claims 31-37, wherein the first and second electrodes have respective first and second widths, such that the first width is at least twice the second width, and wherein coupling the control circuitry comprises applying the respective control voltage waveforms so that the specified phase modulation profile has an abrupt transition that occurs in a vicinity of at least one of the second electrodes.

39. The method according to claim 38, wherein generation of the specified phase modulation profile causes the device to function as a Fresnel lens.

40. The method according to claim 38 or 39, wherein the electrodes comprise parallel stripes of a transparent conductive material having gaps between the stripes of a predefined gap width, and wherein the second width of the second electrodes is no greater than four times the gap width.

41. The method according to any of claims 38-40, wherein the second width of the second electrodes is less than a layer thickness of the electro-optical layer

42. The method according to any of claims 38-41, wherein the phase modulation profile has multiple abrupt transitions that occurs in respective vicinities of corresponding ones of the second electrodes, and

wherein providing the electro-optical layer comprises configuring the electro-optical layer to produce a range of phase modulation values that is proportional to a relation between a density of the second electrodes relative to a spacing between the abrupt transitions in the phase modulation function.

43. The method according to any of claims 31-42, wherein the electro-optical layer comprises a liquid crystal.

44. A method for producing an optical device, the method comprising:

providing an electro-optical layer, having an effective local index of refraction at any given location within an active area of the electro-optical layer that is determined by a voltage waveform applied across the electro-optical layer at the location, the electro-optical layer having opposing first and second sides and a layer thickness equal to a distance between the first and second sides;

positioning conductive electrodes over the first and second sides of the electro-optical layer, the electrodes comprising an array of excitation electrodes comprising parallel stripes of a transparent conductive material having gaps between the stripes of a gap width that is no greater than 2 μm and is less than the layer thickness of the electro-optical layer; and

coupling control circuitry to apply respective control voltage waveforms to the excitation electrodes so as to generate a specified phase modulation profile in the electro-optical layer.

45. The method according to claim 44, wherein the gap width is less than half the layer thickness.

46. The method according to claim 44 or 45, wherein the electro-optical layer comprises a liquid crystal.

47. A method for producing an optical device, the method comprising:

providing an electro-optical layer, having opposing first and second sides and having an effective local index of refraction at any given location within an active area of the electro-optical layer that is determined by a voltage waveform applied across the electro-optical layer at the location;

positioning a buffer layer comprising a transparent dielectric material having a thickness of at least 0.2 μm so that an interior surface of the buffer layer is adjacent to the first side of the electro-optical layer;

positioning conductive electrodes over the first and second sides of the electro-optical layer, the conductive electrodes comprising an array of excitation electrodes extending across an exterior surface of the buffer layer, which separates the excitation electrodes from the electro-optical layer; and

coupling control circuitry to apply respective control voltage waveforms to the excitation electrodes so as to generate a specified phase modulation profile in the electro-optical layer.

48. The method according to claim 47, wherein the excitation electrodes comprise parallel stripes of a transparent conductive material having gaps between the stripes of a predefined gap width, and the buffer layer has a buffer layer thickness that is more than one-fourth of the gap width.

49. The method according to claim 47 or 48, wherein the electro-optical layer comprises a liquid crystal.

50. A method for producing an optical device, the method comprising:

providing an electro-optical layer, having an effective local index of refraction at any given location within an active area of the electro-optical layer that is determined by a voltage waveform applied across the electro-optical layer at the location;

positioning a first array of first excitation electrodes to extend along respective, mutually-parallel first axes in a first direction over the active area on a first side of the electro-optical layer;

positioning a second array of second excitation electrodes to extend along respective, mutually-parallel second axes in a second direction, orthogonal to the first direction, over the active area on a second side of the electro-optical layer, opposite the first side; and

coupling control circuitry to apply respective control voltage waveforms concurrently to both the first excitation electrodes and the second excitation electrodes and to concurrently modify the respective control voltage waveforms applied to both the first excitation electrodes and the second excitation electrodes so as to generate a specified phase modulation profile in the electro-optical layer.

51. The method according to claim 50, wherein the phase modulation profile is defined as a function that is separable into first and second component functions, which respectively vary along the first and second axes, and wherein the control voltage waveforms applied to the first and second excitation electrodes are specified in accordance with the first and second component functions, respectively.

52. The method according to claim 51, wherein the first and second component functions are defined in terms of a set of component waveforms that are selected so as to correspond to different, respective phase shifts in the electro-optical layer, such that the phase modulation profile comprises a sum of the respective phase shifts due to the first and second component functions at each location within the active area.

53. The method according to claim 52, wherein the component waveforms have different, respective duty cycles.

54. The method according to claim 52 or 53, wherein the component waveforms are selected so that the sum of the respective phase shifts making up the phase modulation profile is a modular sum with a modulus of $2n\pi$, wherein n is an integer.

55. The method according to claim 54, wherein n has different, respective values for at least some different pairs of the first and second component functions.

56. The method according to any of claims 50-55, wherein the control voltage waveforms are selected so that the phase modulation profile contains abrupt phase transitions, and the device functions as a Fresnel lens.

57. The method according to claim 56, wherein the control circuitry is configured to apply the respective control voltage waveforms with opposite polarities to pairs of mutually-adjacent excitation electrodes in a vicinity of the abrupt phase transitions.

58. The method according to any of claims 50-57, wherein the electro-optical layer comprises a liquid crystal.

59. A method for producing an optical device, the method comprising:

providing a static lens, comprising a transparent material having a curved exterior surface with a specified refractive power and an interior surface containing at least first and second overlapping indentations; and

embedding a dynamic lens in the static lens, the dynamic lens having a variable phase modulation profile, which modifies the refractive power of the static lens, and comprising:

an electro-optical layer, having opposing first and second sides and having an effective local index of refraction at any given location within an active area of the electro-optical layer that is determined by a voltage applied across the electro-optical layer at the location;

first and second transparent substrates, which are disposed respectively on the first and second sides of the electro-optical layer and are sized and shaped to fit respectively into the first and second indentations in the static lens, and which comprise electrodes configured to apply voltages across the electro-optical layer; and

control circuitry, which is coupled to apply the voltages to the electrodes so as to generate the modulation profile in the electro-optical layer.

60. The method according to claim 59, wherein the control circuitry comprises electrical connections disposed at an edge of the first transparent substrate, and wherein the interior surface of the static lens contains a groove into which the electrical connections fit.

61. An optical device, comprising:

an electro-optical layer, having an effective local index of refraction at any given location within an active area of the electro-optical layer that is determined by a voltage waveform applied across the electro-optical layer at the location;

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conductive electrodes extending over opposing first and second sides of the electro-optical layer, the electrodes comprising an array of excitation electrodes, which extend along respective, mutually-parallel axes in a predefined direction across the first side of the electro-optical layer, while respective center points of the electrodes are displaced transversely by an amount that varies along the respective axes of the electrodes; and

control circuitry, which is coupled to apply respective control voltage waveforms to the excitation electrodes so as to generate a specified phase modulation profile in the electro-optical layer.

62. The device according to claim 61, wherein the array of the electrodes on the first side of the electro-optical layer comprises a first array of first excitation electrodes, extending in a first direction across the first side of the electro-optical layer, and wherein the conductive electrodes comprise a second array of second excitation electrodes, which extend in a second direction, perpendicular to the first direction, across the second side of the electro-optical layer, while respective center points of the second excitation electrodes are displaced transversely along the respective axes thereof.

63. An optical device, comprising:

an electro-optical layer, having an effective local index of refraction at any given location within an active area of the electro-optical layer that is determined by a voltage waveform applied across the electro-optical layer at the location, the electro-optical layer having opposing first and second sides;

conductive electrodes extending over the first and second sides of the electro-optical layer, the electrodes comprising an array of excitation electrodes comprising parallel stripes of a transparent conductive material; and

control circuitry, which is coupled to apply respective control voltage waveforms to the excitation electrodes so as to generate in the electro-optical layer a specified phase modulation profile containing abrupt phase transitions, while applying the respective control voltage waveforms with opposite polarities to pairs of mutually-adjacent excitation electrodes in a vicinity of the abrupt phase transitions.

64. The device according to claim 63, wherein the control voltage waveforms are selected so as to cause the device to function as a Fresnel lens.

65. A method for producing an optical device, the method comprising:

providing an electro-optical layer, having an effective local index of refraction at any given location within an active area of the electro-optical layer that is determined by a voltage waveform applied across the electro-optical layer at the location;

positioning conductive electrodes over opposing first and second sides of the electro-optical layer, the electrodes comprising an array of excitation electrodes, which extend along respective, mutually-parallel axes in a predefined direction across the first side of the electro-optical layer, while respective center points of the electrodes are displaced transversely by an amount that varies along the respective axes of the electrodes; and

coupling control circuitry to apply respective control voltage waveforms to the excitation electrodes so as to generate a specified phase modulation profile in the electro-optical layer.

66. The device according to claim 65, wherein positioning the conductive electrodes comprises positioning on the first side of the electro-optical layer a first array of first excitation electrodes, extending in a first direction across the first side of the electro-optical layer, and positioning a second array of second excitation electrodes, extending in a second direction, perpendicular to the first direction, across the second side of the electro-optical layer, while respective center points of the second excitation electrodes are displaced transversely along the respective axes thereof.

67. A method for producing an optical device, the method comprising:

providing an electro-optical layer, having an effective local index of refraction at any given location within an active area of the electro-optical layer that is determined by a voltage waveform applied across the electro-optical layer at the location;

positioning conductive electrodes over opposing first and second sides of the electro-optical layer, the electrodes comprising an array of excitation electrodes comprising parallel stripes of a transparent conductive material; and

coupling control circuitry to apply respective control voltage waveforms to the excitation electrodes so as to generate in the electro-optical layer a specified phase modulation profile containing abrupt phase transitions, while applying the respective control voltage waveforms with opposite polarities to pairs of mutually-adjacent excitation electrodes in a vicinity of the abrupt phase transitions.

68. The device according to claim 67, wherein the control voltage waveforms are selected so as to cause the device to function as a Fresnel lens.

69. Optical apparatus, comprising:

first and second optical devices, which have respective first and second polarization axes and first and second cylinder axes and are arranged in series such that the first and second polarization axes are mutually non-parallel and the first and second cylinder axes are mutually non-parallel, each of the optical devices comprising:

a polarization-dependent electro-optical layer, having an effective local index of refraction, for light that is polarized along the respective polarization axis and is incident at any given location within an active area of the electro-optical layer, that is determined by a voltage applied across the electro-optical layer at the location; and

conductive electrodes extending over opposing first and second sides of the electro-optical layer, the electrodes comprising an array of excitation electrodes, which is configured to apply respective voltages across the excitation electrodes so as to generate in the electro-optical layer a cylindrical phase modulation profile oriented along the respective cylinder axis; and

a polarization rotator positioned between the first and second optical devices so as to rotate a polarization of light that has passed through the first optical device and is parallel to the first polarization axis, in order to align the polarization of the light with the second polarization axis.

70. The apparatus according to claim 69, wherein the array of excitation electrodes comprises an array of parallel stripes of a transparent, conductive material extending across the first side of the electro-optical layer in a direction parallel to the respective cylinder axis, and wherein the conductive electrodes comprise a common electrode, positioned over the active area on the second side of the electro-optical layer.

71. The apparatus according to claim 69 or 70, wherein the first and second polarization axes are mutually perpendicular and the first and second cylinder axes are mutually perpendicular.

72. A method for producing an optical device, the method comprising:

arranging first and second optical devices, which have respective first and second polarization axes and first and second cylinder axes, in series such that the first and second polarization axes are mutually non-parallel and the first and second cylinder axes are mutually non-parallel, each of the optical devices comprising:

a polarization-dependent electro-optical layer, having an effective local index of refraction, for light that is polarized along the respective polarization axis and is incident

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at any given location within an active area of the electro-optical layer, that is determined by a voltage applied across the electro-optical layer at the location; and

conductive electrodes extending over opposing first and second sides of the electro-optical layer, the electrodes comprising an array of excitation electrodes, which is configured to apply respective voltages across the excitation electrodes so as to generate in the electro-optical layer a cylindrical phase modulation profile oriented along the respective cylinder axis; and

positioning a polarization rotator between the first and second optical devices so as to rotate a polarization of light that has passed through the first optical device and is parallel to the first polarization axis, in order to align the polarization of the light with the second polarization axis.

73. The method according to claim 72, wherein the array of excitation electrodes comprises an array of parallel stripes of a transparent, conductive material extending across the first side of the electro-optical layer in a direction parallel to the respective cylinder axis, and wherein the conductive electrodes comprise a common electrode, positioned over the active area on the second side of the electro-optical layer.

74. The method according to claim 69 or 70, wherein the first and second polarization axes are mutually perpendicular and the first and second cylinder axes are mutually perpendicular.