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**Walker et al.**

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(54) **ELECTRO-OPTICAL MATERIAL-BASED DISPLAY DEVICE HAVING ANALOG PIXEL DRIVERS**

0797182 9/1997 (EP) ..... G09G/3/36  
2177841A \* 1/1987 (GB) .  
WO 94/07177 3/1994 (WO) ..... G02F1/136

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\* cited by examiner

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(57) **ABSTRACT**

The display device operates in response to an information signal and comprises analog drive circuits in a two-dimensional array of rows and columns, an analog sampling circuit that derives the analog samples from the information signal, and a sample distribution circuit. The sample distribution circuit receives the analog samples from the analog sampling circuit and distributes them to the analog drive circuits. The sample distribution circuit includes input gates corresponding to the analog drive circuits, column busses corresponding to the columns of the array, and a row selector having outputs corresponding to the rows of the array. The column busses distribute the analog samples column-wise to the analog drive circuits. The input gates connect the analog selector to the column busses. Each output of the row selector is connected to control the input gates in one of the rows. The row selector sequentially opens the input gates in the rows to select the analog samples on the column busses row-wise. A grey scale is generated by modulating light using an electro-optical material. An analog sample is derived from the information signal, a drive signal is generated in response to the analog sample, and the drive signal is applied to the electro-optical material. The drive signal generated in response to the analog sample includes a sequence of a first temporal portion having a time duration that has a pre-determined relationship to the analog sample, and a second temporal portion that is the temporal complement of the first.

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(51) **Int. Cl.**<sup>7</sup> ..... **G09G 3/36**

(52) **U.S. Cl.** ..... **345/98; 345/100**

(58) **Field of Search** ..... 345/102, 154, 345/8, 82, 87, 98, 100, 90, 92, 96

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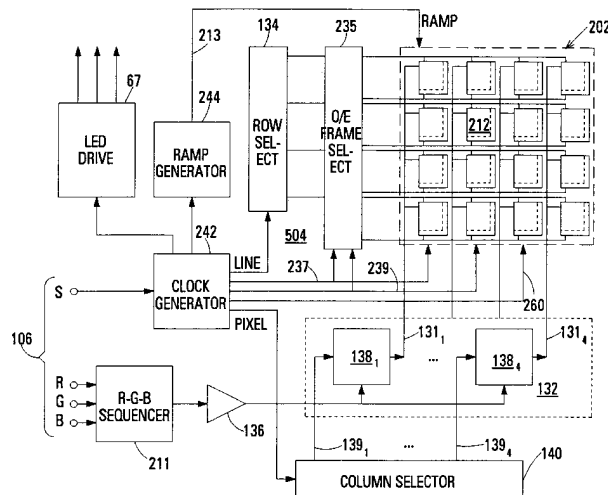
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**21 Claims, 16 Drawing Sheets**



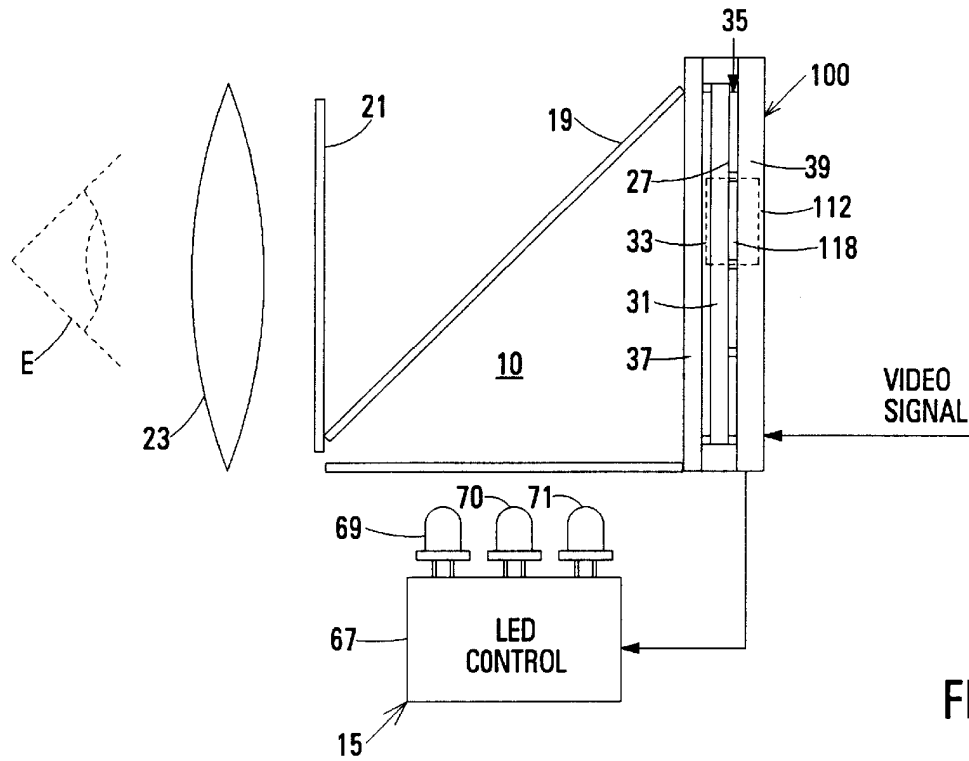


FIG. 1

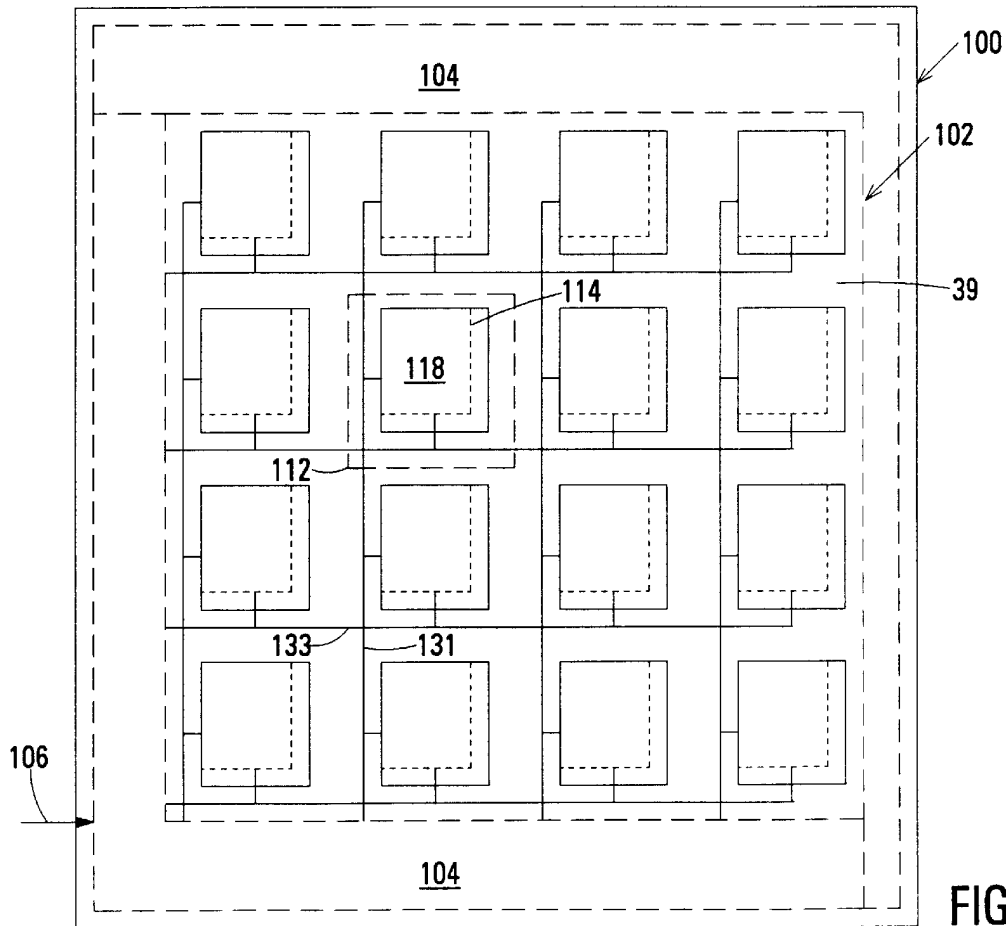


FIG. 2A

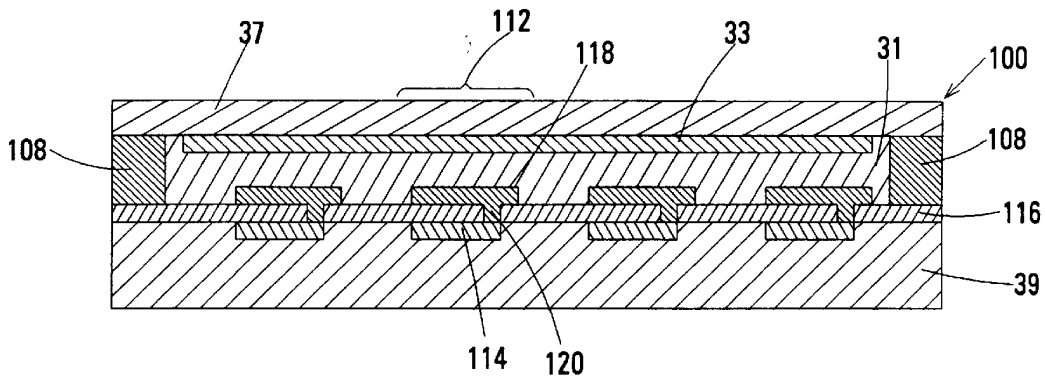


FIG.2B

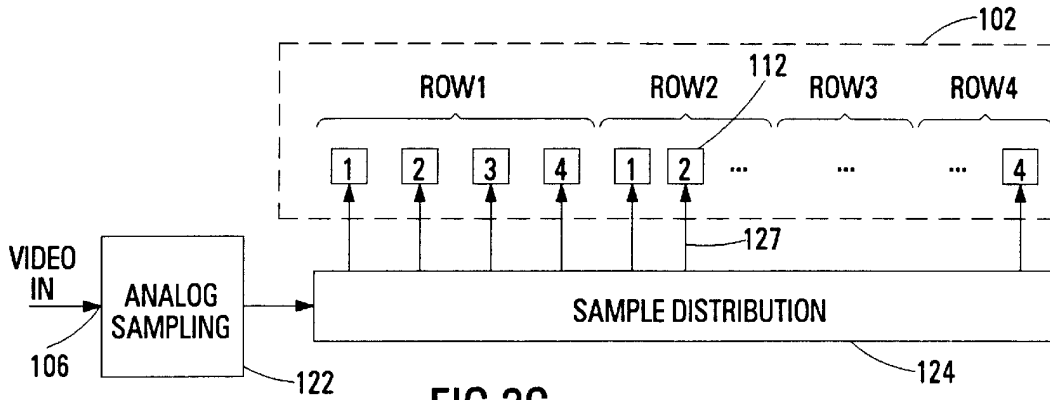


FIG.2C

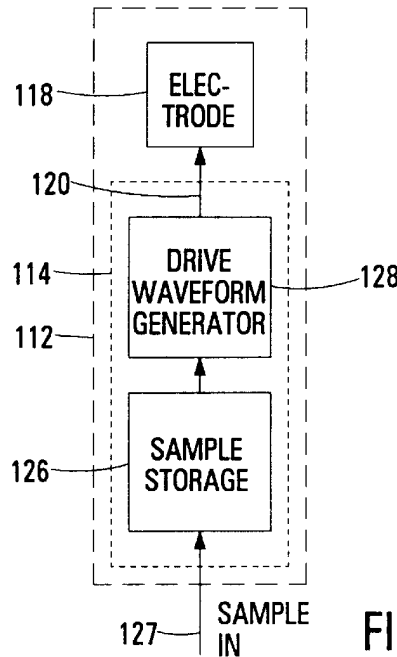
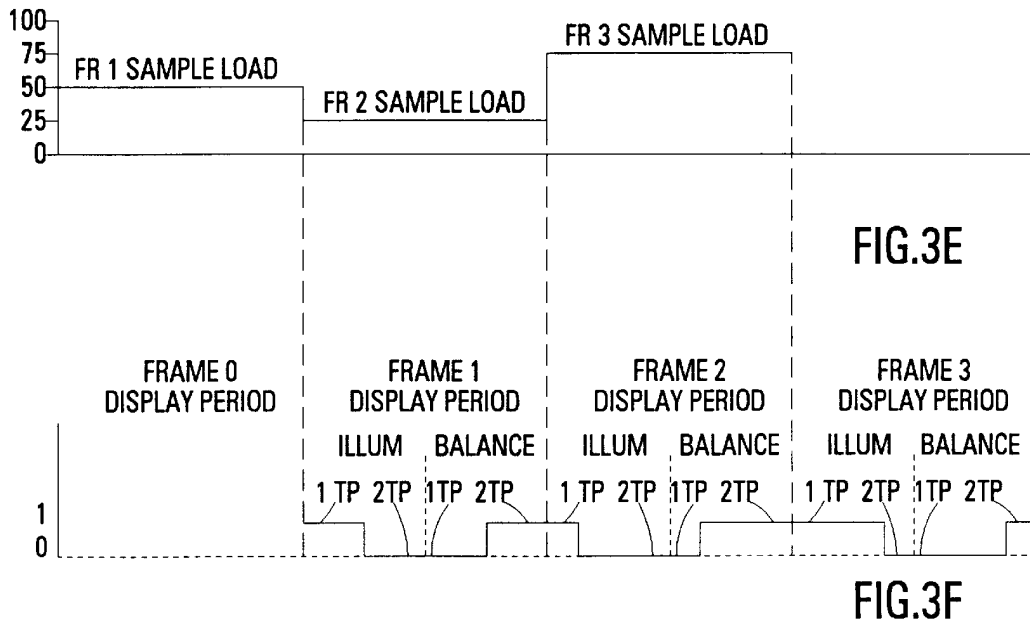
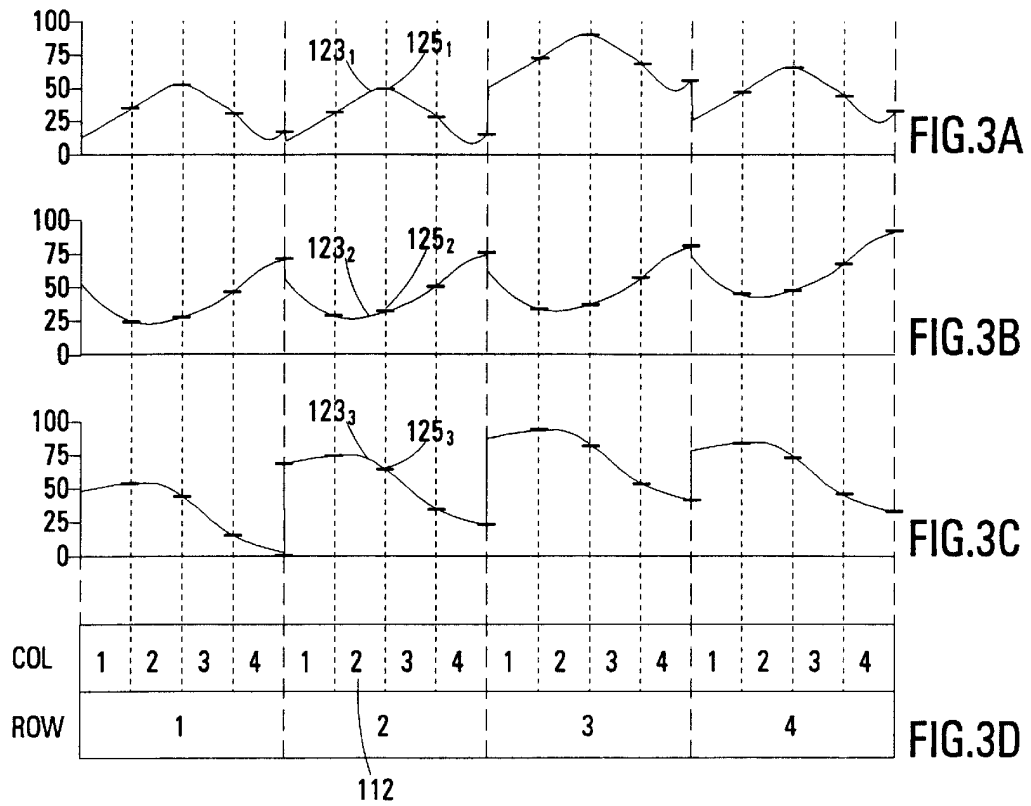


FIG.2D



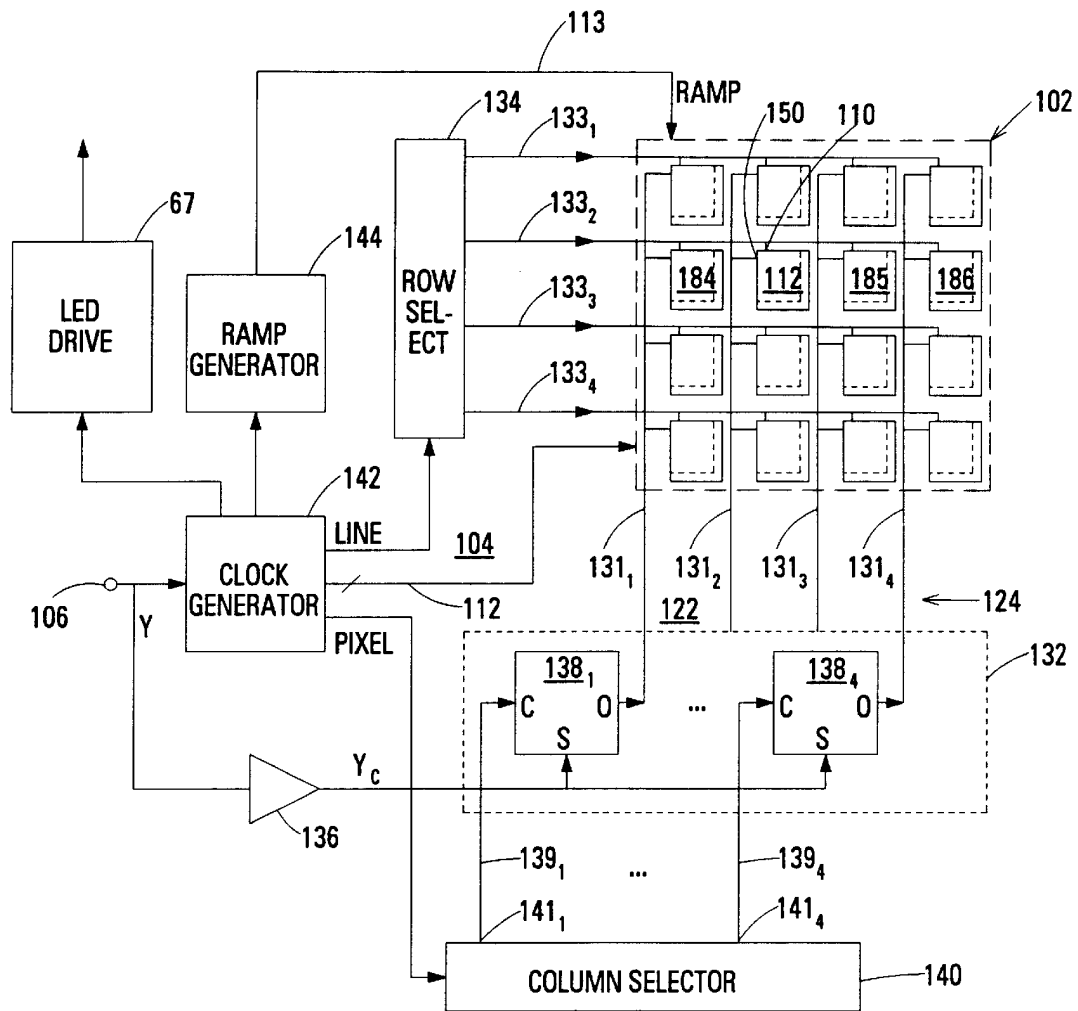


FIG.4A

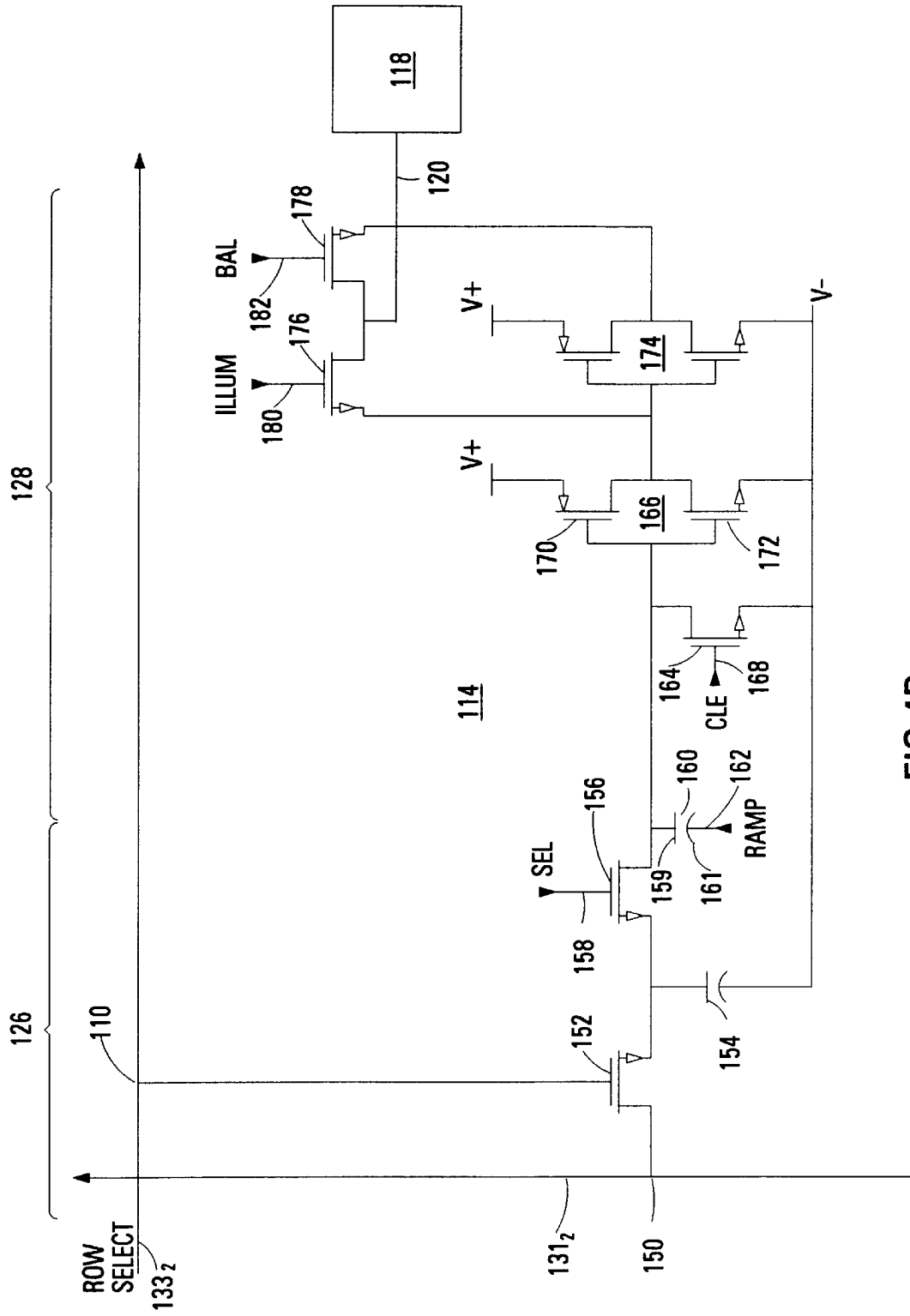
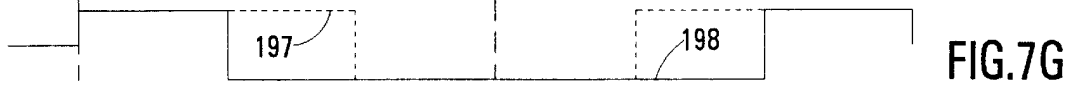
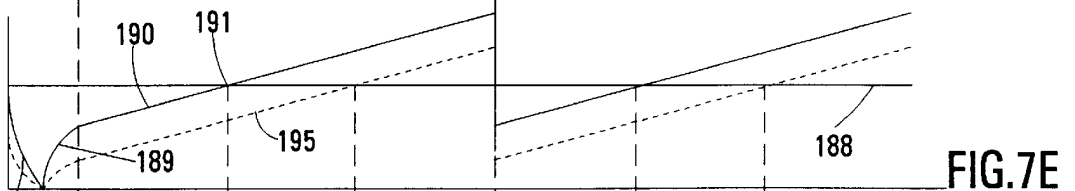
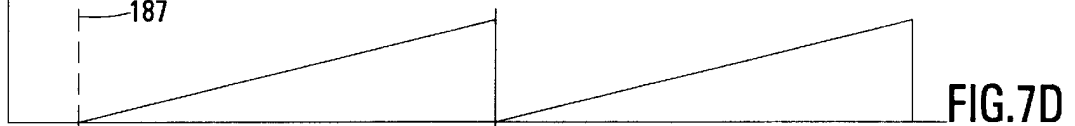
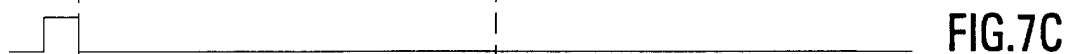
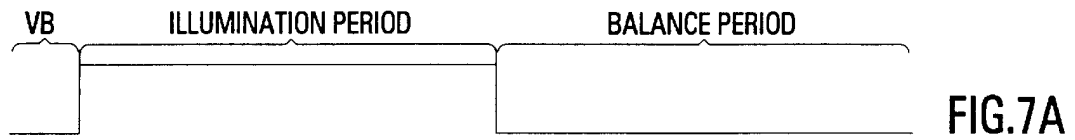
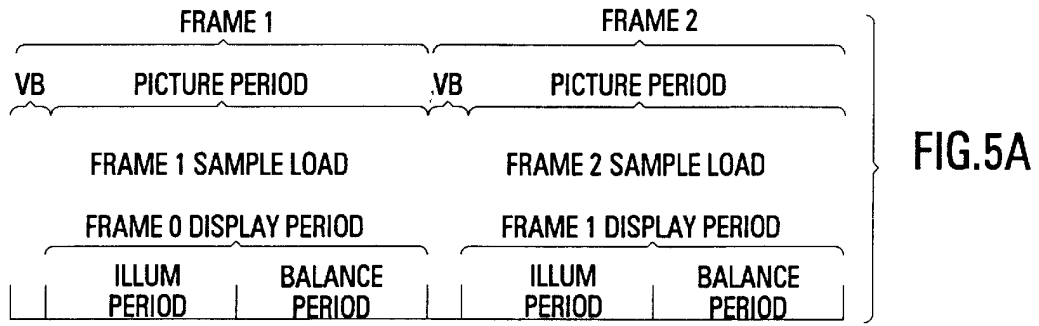
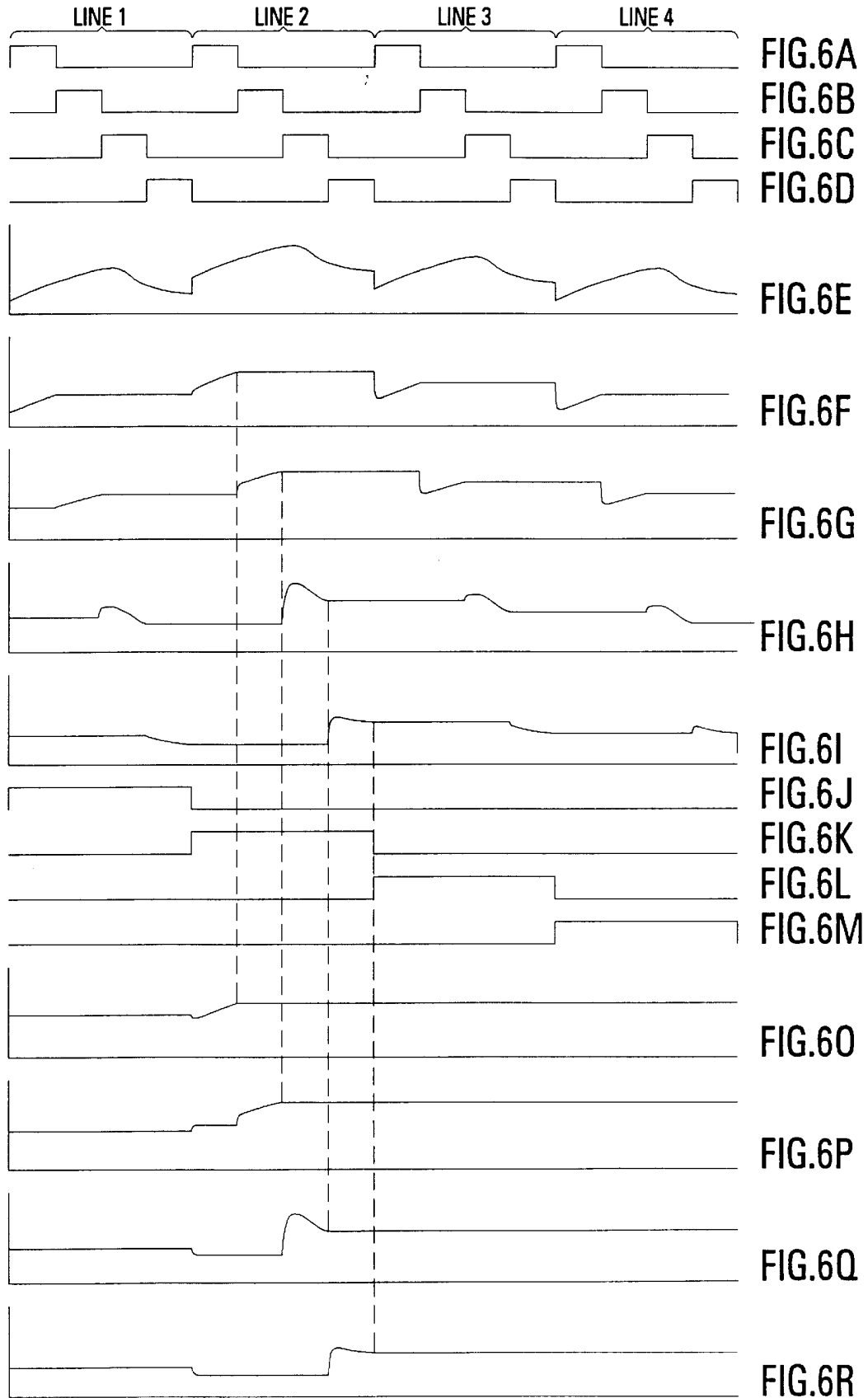


FIG. 4B







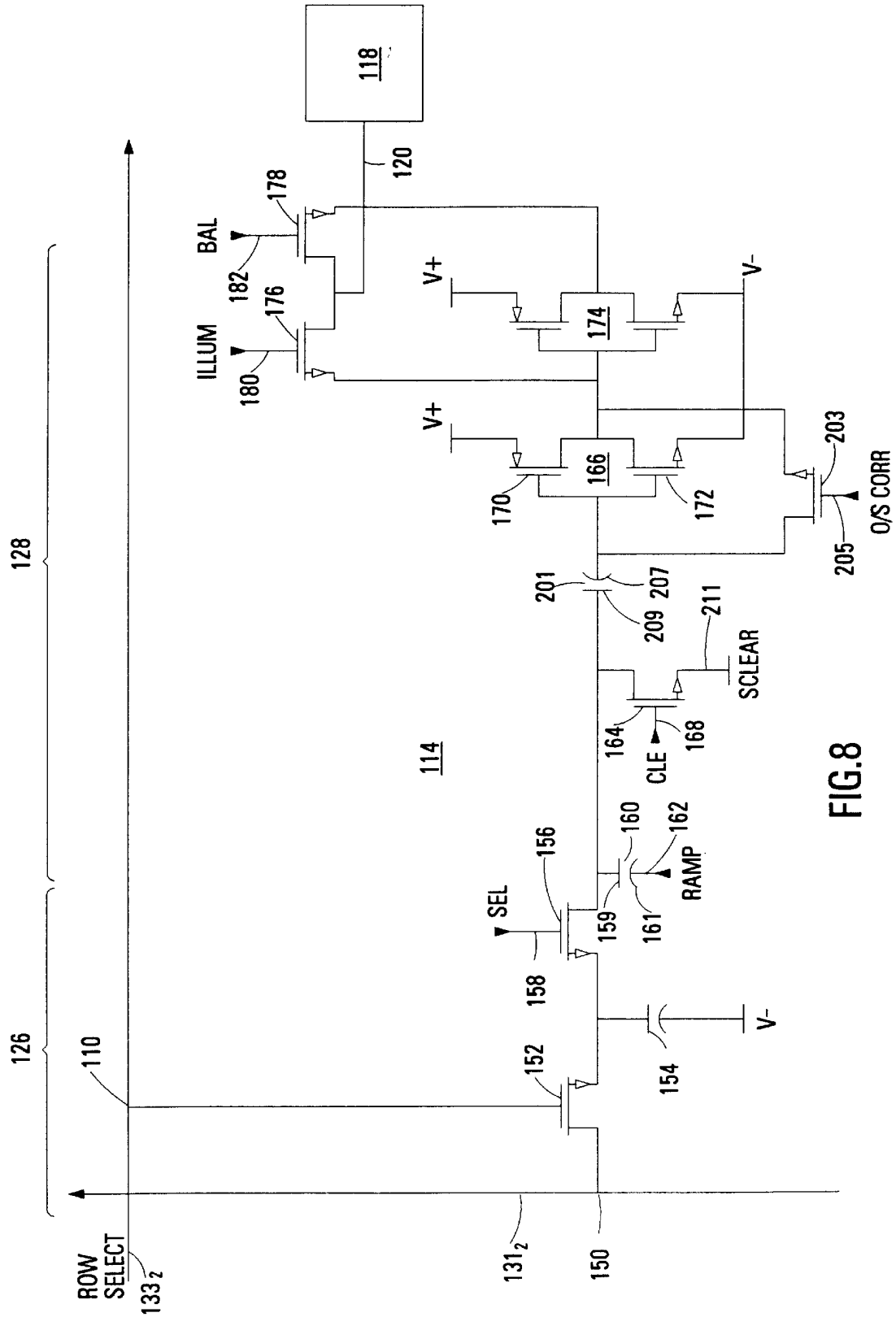


FIG. 8

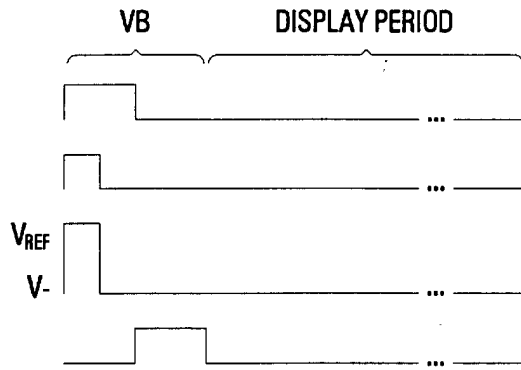


FIG.9A

FIG.9B

FIG.9C

FIG.9D

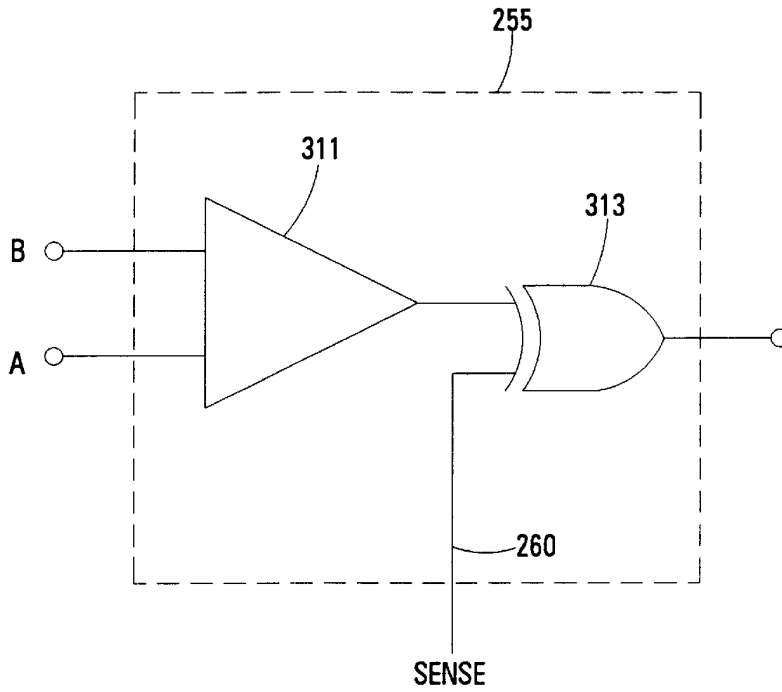


FIG.12

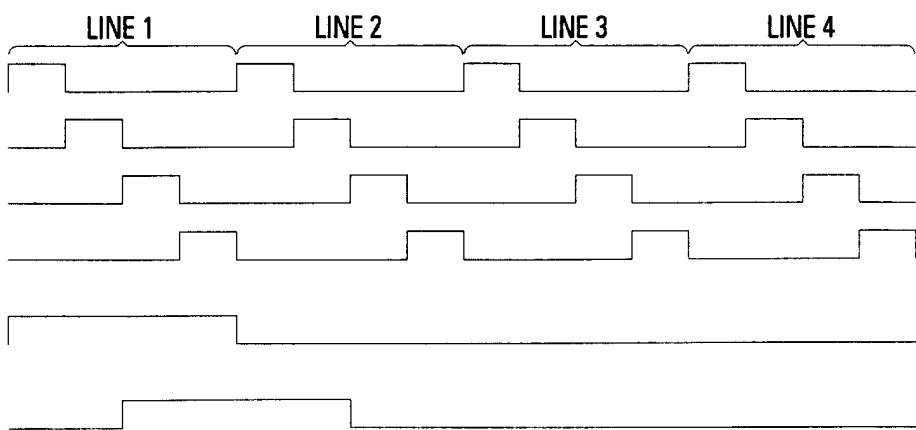


FIG.14A

FIG.14B

FIG.14C

FIG.14D

FIG.14E

FIG.14F

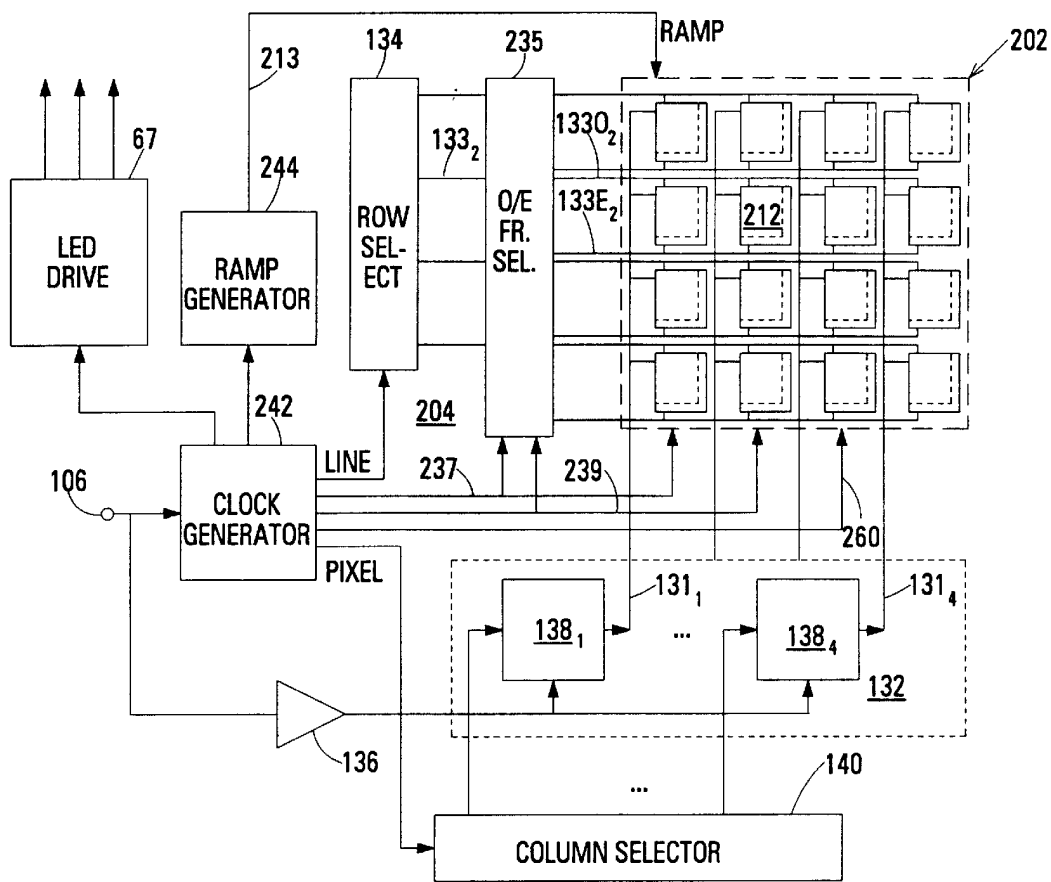


FIG. 10A

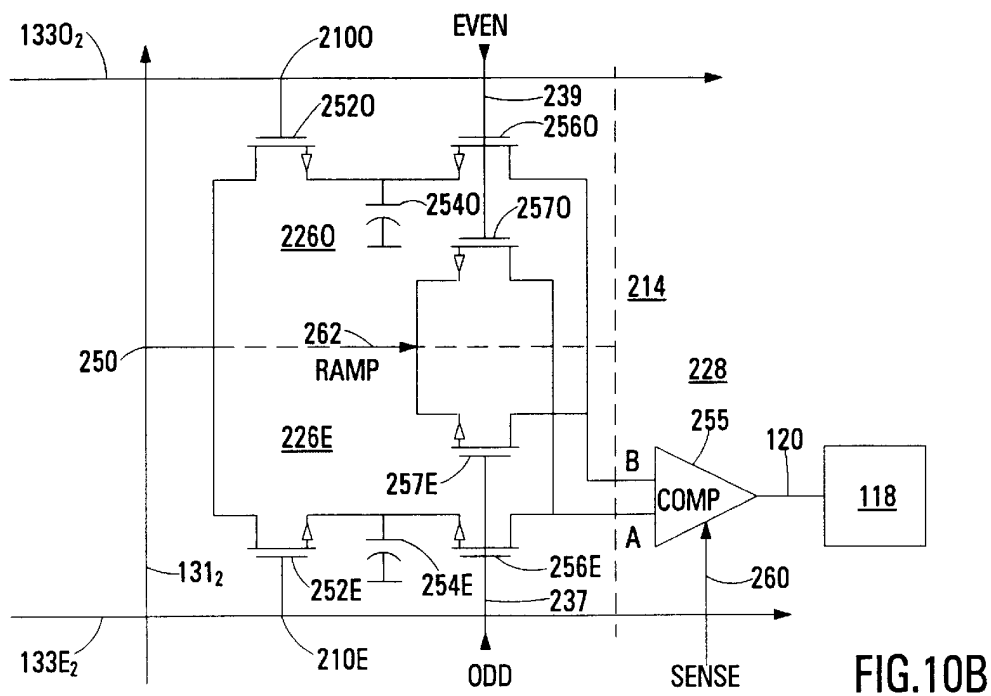


FIG. 10B

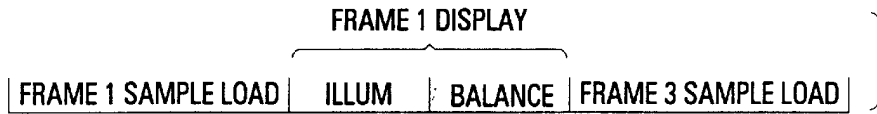


FIG. 11A



FIG. 11B

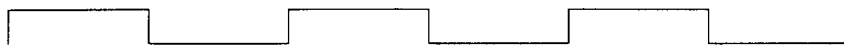


FIG. 11C

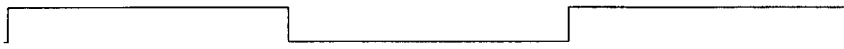


FIG. 11D

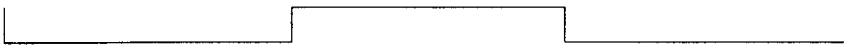


FIG. 11E

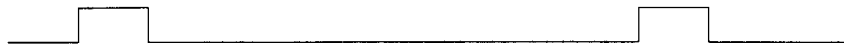


FIG. 11F



FIG. 11G



FIG. 11H

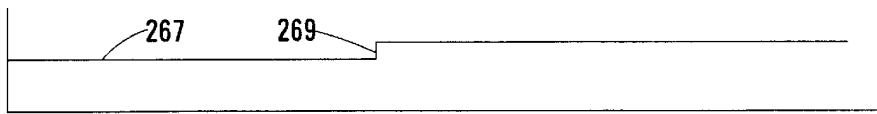


FIG. 11I

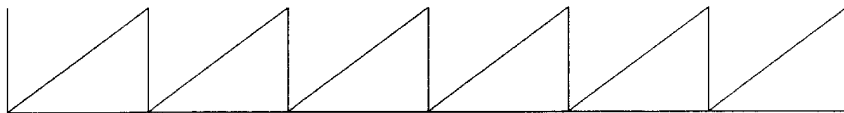


FIG. 11J

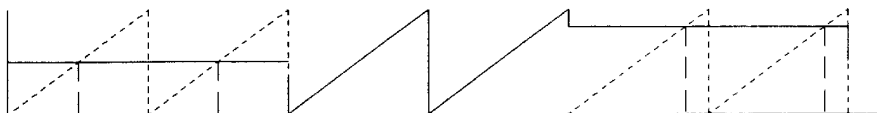


FIG. 11K

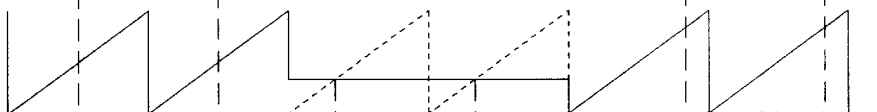


FIG. 11L



FIG. 11M



FIG. 11N

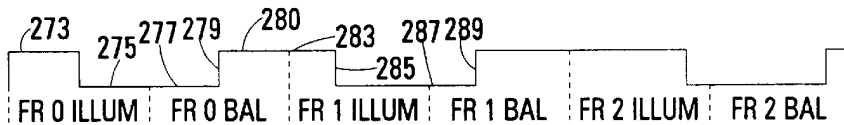


FIG. 11O

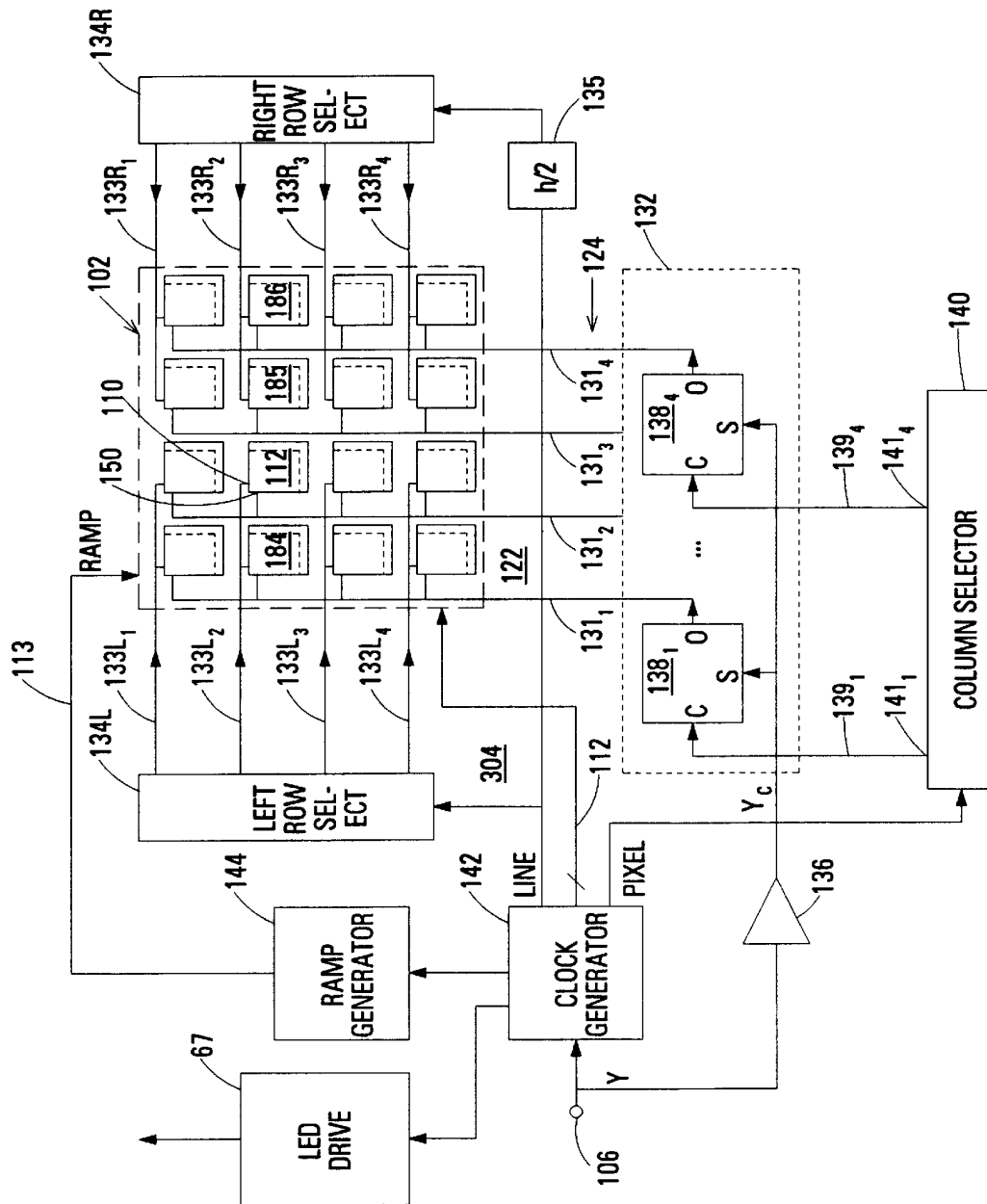


FIG. 13

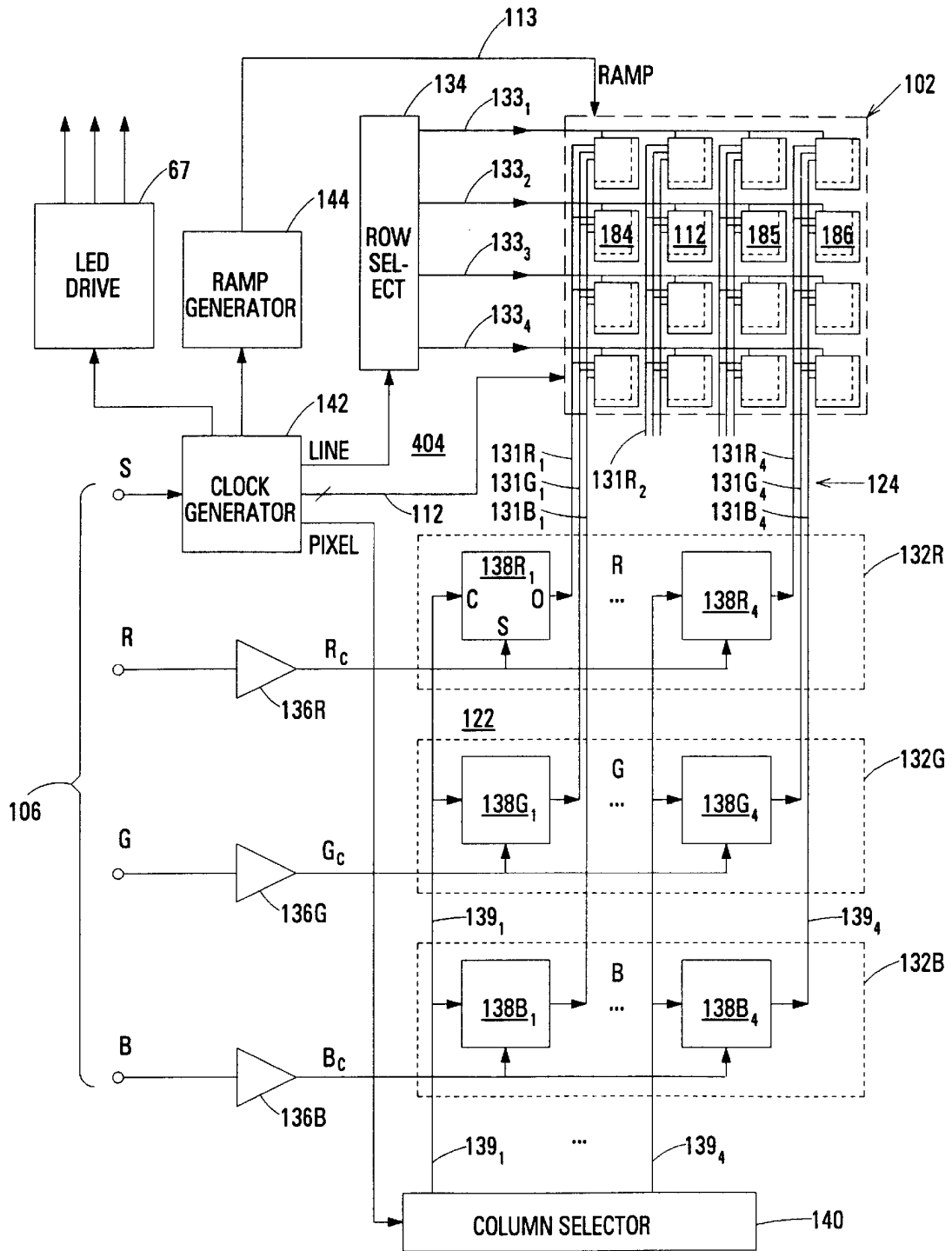


FIG.15A

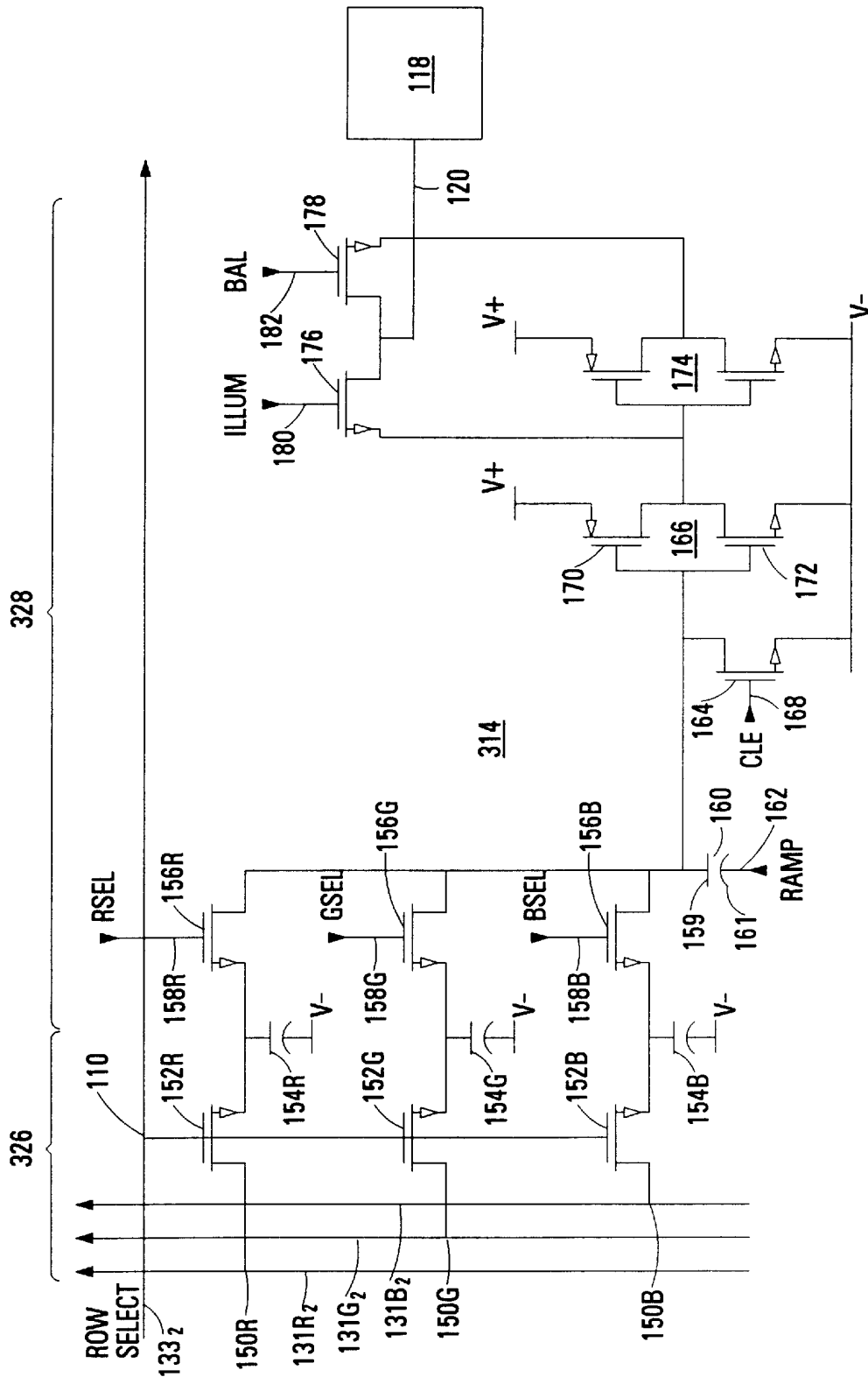


FIG.15B

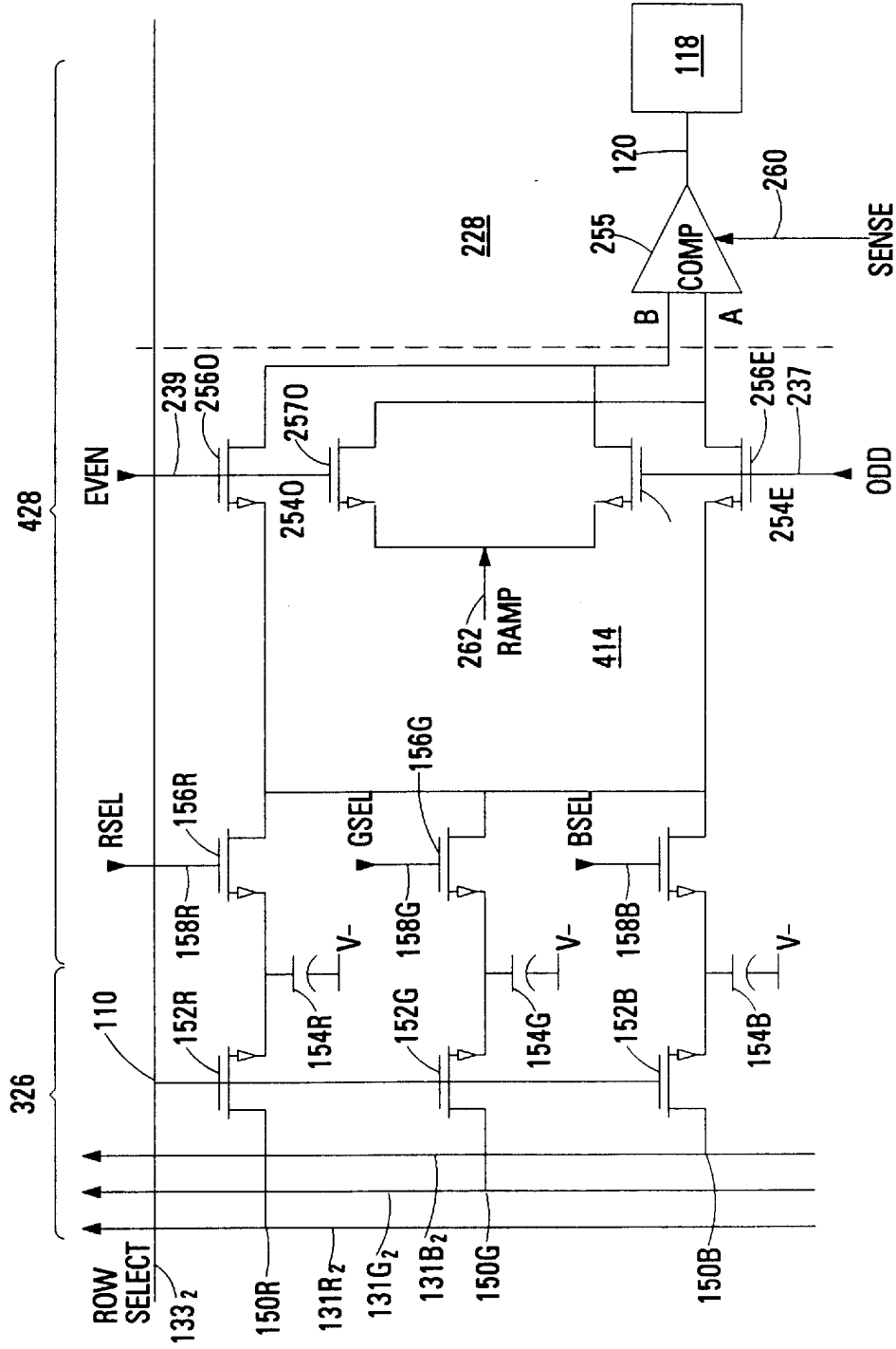


FIG.15C



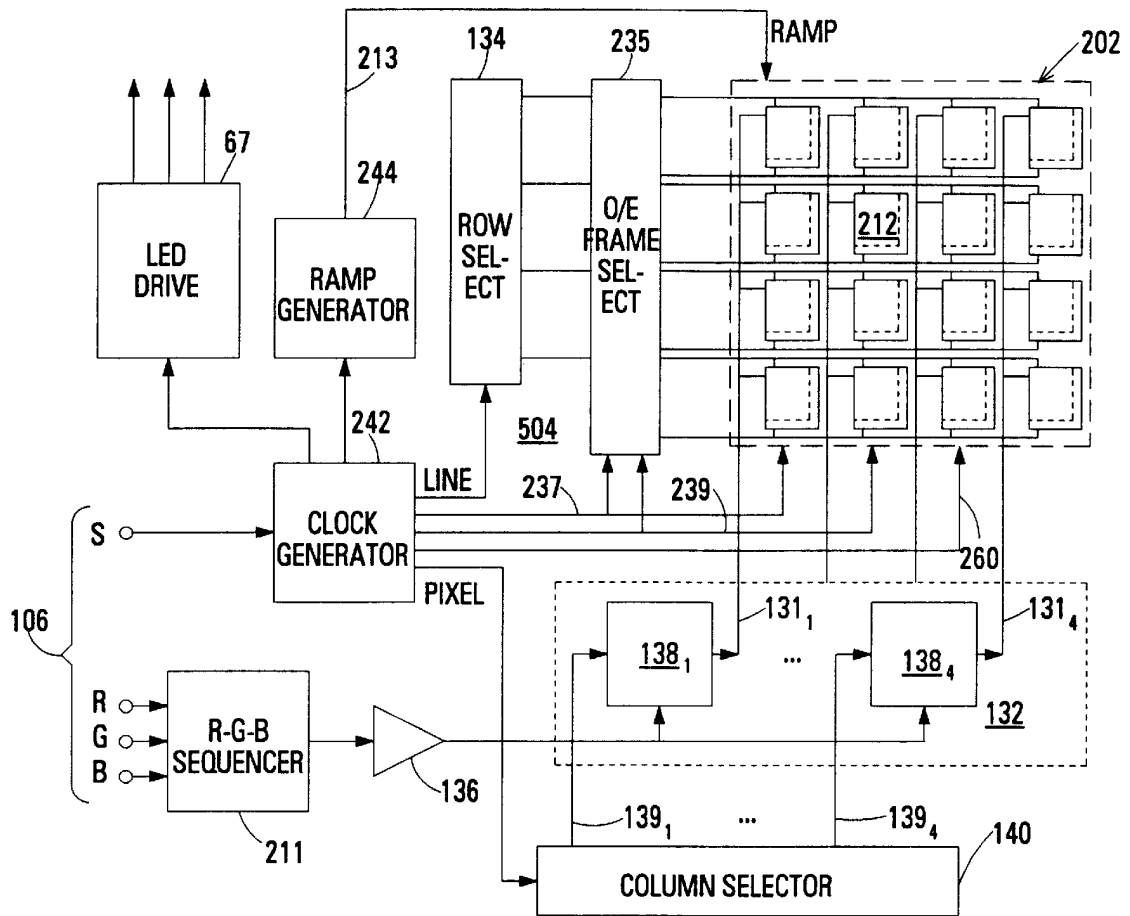


FIG.16

## ELECTRO-OPTICAL MATERIAL-BASED DISPLAY DEVICE HAVING ANALOG PIXEL DRIVERS

### FIELD OF THE INVENTION

The invention relates video and graphics display devices, to analog circuits for driving the picture elements (pixels) of video and graphics display devices, and, in particular, to analog circuits for driving the picture elements of a display device based on an electro-optical material.

### BACKGROUND OF THE INVENTION

A substantial need exists for various types of video and graphics display devices with improved performance and lower cost. For example, a need exists for miniature video and graphics display devices that are small enough to be integrated into a helmet or a pair of glasses so that they can be worn by the user. Such wearable display devices would replace or supplement the conventional displays of computers and other devices. In particular, wearable display devices could be used instead of the conventional displays of laptop and other portable computers. Potentially, wearable display devices can provide greater brightness, better resolution, larger apparent size, greater privacy, substantially less power consumption and longer battery life than conventional active matrix or double-scan liquid crystal-based displays. Other potential applications of wearable display devices are in personal video monitors, in video games and in virtual reality systems.

Miniaturized displays based on cathode-ray tubes or conventional liquid crystal displays have not been successful in meeting the demands of wearable displays for low weight and small size. Of greater promise is a micro display of the type described in U.S. Pat. No. 5,596,451 of Handschy et al., the disclosure of which is incorporated into this disclosure by reference. This type of micro display includes a reflective spatial light modulator that uses a ferroelectric liquid crystal (FLC) material as its light control element.

The spatial light modulator of the FLC-based micro display just described is driven by a digital drive signal. The conventional analog video signal generated by the graphics card of a personal computer, for example, is fed to a converter that converts the analog video signal into a digital bitstream suitable for driving the spatial light modulator. The converter converts the analog video signal into a time domain binary weighted digital drive signal suitable for driving the spatial light modulator. The time durations of the bits of the time domain binary weighted digital drive are binary weighted, so that the duration of the most-significant bits is  $2^{n-1}$  times that of the least-significant bits, where  $n$  is the number of bits representing each sample of the analog video signal. For example, if each sample of the analog video signal is represented by 8 bits, the duration of each most-significant bit is 256 times that of each least-significant bit. Driving the pixels digitally means that the pixel driver must be capable of changing state several times during each frame of the analog video signal. The switching speed must be shorter than the duration of the least-significant bit. This requires that the drive circuitry in each pixel be capable of high-speed operation, which increases the power demand and expense of the micro display system. On the other hand, the long time duration of the most-significant bits of the digital drive signal means that the digital drive signal is static for the majority of the frame period.

Practical embodiments of the micro display referred to above typically locate the converter referred to above exter-

nal of the micro display and connect the converter to the micro display by a high-speed digital link. The converter time multiplexes the digital drive signals for transmission though the digital link as follows: the least-significant bits for of the digital drive signals all the pixels of the spatial light modulator, followed by the next-least-significant bits of the digital drive signals for all the pixels, and so on through the most-significant bits of the digital drive signals for all the pixels. The digital link must be capable of transmitting all the bits representing each frame of the component video signal within the frame period of the component video signal. The digital link, its driver and receiver must be capable of switching at a switching speed shorter than the duration of the least-significant bit, yet remain static for times corresponding to the durations of the most-significant bits.

In addition, the converter requires a large, high-speed buffer memory to convert the parallel, raster-scan order digital signals generated from the analog video signal to a bit-order signal for each color component. This increases the cost and power requirements of the converter.

The digital serial link can be eliminated by locating the converter in the micro display itself, but relocating the converter increases the size, weight and complexity of the micro display. Moreover, miniaturizing the converter to fit it in the micro display can increase the cost of the converter. Finally, relocating the converter does not reduce its overall cost and complexity.

What is needed is a miniature display device that can operate in response to a video signal or graphics data and that does not suffer from the size, weight, complexity and cost disadvantages of the conventional digitally-driven micro display.

Conventional-sized video and graphics displays rely on cathode-ray tubes or full-size liquid crystal displays. The former are bulky, heavy and fragile. The former are also expensive to produce and are very heavy in the larger sizes required to realize the benefits of high-definition video. The latter are expensive to produce in screen sizes comparable with conventional cathode-ray tubes, and have a limited dynamic range and a limited viewing angle. What is also needed is a miniature display device that can form the basis of an full-size video and graphics display that would provide an effective alternative to conventional cathode-ray tubes and liquid crystal displays.

### SUMMARY OF THE INVENTION

The invention provides a display device based on an electro-optical material. The display device operates in response to an information signal and comprises analog drive circuits arranged in a two-dimensional array of rows and columns, an analog sampling circuit that derives the analog samples from the information signal, and a sample distribution circuit. The sample distribution circuit receives the analog samples from the analog sampling circuit and distributes the analog samples to the analog drive circuits. The sample distribution circuit includes input gates corresponding to the analog drive circuits, column busses corresponding to the columns of the array, and a row selector having outputs corresponding to the rows of the array. The column busses perform a column-wise distribution of the analog samples to the analog drive circuits. The analog drive circuits are connected to the column busses by the input gates. Each of the outputs of the row selector is connected to control the input gates in one of the rows. The row selector sequentially opens the input gates in the rows to

perform a row-wise selection of the analog samples on the column busses.

The analog sampling circuit may include a sampling circuit and a column selector. The sampling circuit comprises a row of sample-and-hold circuits. Each of the sample-and-hold circuits corresponds to one of the column busses and comprises an output connected to the one of the column busses, an input connected to receive the information signal, and a column control signal input. The column selector is connected to the column control signal inputs of the sample-and-hold circuits. The column selector generates column control signals for the sample-and-hold circuits at a signal rate related to the information signal. The column control signal for a one of the sample-and-hold circuits is in an opposite state to the column control signals for the remaining ones of the sample-and-hold circuits. The column control signal in the opposite state moves progressively along the row of sample-and-hold circuits at the signal rate.

When the information signal is a color video signal, the analog sampling circuit and sample distribution circuit may both include serial or parallel arrangements to derive and distribute analog samples of the color components of the color video signal to the analog drive circuits.

When the information signal is a video signal composed of lines and frames, the location in each of the lines of the video signal from which the analog sampling circuit derives the analog samples that the sample distribution circuit distributes to each column bus depends on the location of the column bus in the array.

The invention also provides a display device based on an electro-optical material. The display device operates in response to an information signal, and comprises an array of pixels, a sample distribution circuit and a light source. Each of the pixels includes an electrode electrically coupled to the electro-optical material, and an analog drive circuit that includes an output electrically connected to the electrode. The sample distribution circuit distributes an analog sample derived from the information signal to the analog drive circuit of each of the pixels. The analog drive circuit generates a drive signal composed of a sequence of a first temporal portion and a second temporal portion, the first electrical portion having a time duration that has a predetermined relationship to the analog sample, the second temporal portion being a temporal complement of the first temporal portion. The light source illuminates the electro-optical material simultaneously with the analog drive circuit generating the drive signal sequence.

The analog drive circuit may include a sample selection section that stores the analog sample received from the sample distribution circuit, and a drive signal generator that generates the drive signal in response to the analog sample stored in the sample selection section.

The sequence of the first temporal portion and the second temporal portion may be a first sequence of the first temporal portion and the second temporal portion in which the analog drive circuit generates the drive signal in a first electrical state during the first temporal portion and in a second electrical state during the second temporal portion. The analog drive circuit may generate the drive signal additionally composed of a second sequence of the first temporal portion, in which the drive signal is in the second electrical state, and the second temporal portion, in which the drive signal is in the first electrical state. The first temporal portion and the second temporal portion may be in any order in the second sequence. In this case, the light source illuminates the electro-optical material during the first sequence.

The invention also provides a method of generating a grey scale in response to an information signal. The grey scale is generated by modulating light using an electro-optical material. In the method, an analog sample is derived from the information signal, a drive signal is generated in response to the analog sample, and the drive signal is applied to the electro-optical material. The drive signal generated in response to the analog sample includes a sequence of a first temporal portion and a second temporal portion. The first temporal portion has a time duration that has a predetermined relationship to the analog sample, and the second temporal portion is the temporal complement of the first temporal portion.

The method may additionally comprise illuminating the electro-optical material in synchronism with the drive signal.

Generating the drive signal may be subject to an error factor that changes the predetermined relationship between the duration of the first temporal state and the analog sample, and the method may additionally comprise minimizing the visual effect of the error factor on the gray scale. When the information signal includes odd-numbered sequences interleaved with even-numbered sequences, such as in a video signal, minimizing the visual effect of the error factor on the gray scale may include inverting the sense of the error factor when generating the drive signal in response to either the odd-numbered sequences or even-numbered sequences.

#### BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 shows the structure of a display device according to the invention that can be used to perform the method according to the invention.

FIGS. 2A–2D show details of the spatial light modulator of the display device shown in FIG. 1.

FIGS. 3A–3D illustrate how analog samples are derived from the video signal and distributed to the analog drive circuit of each pixel in the pixel array of the spatial light modulator shown in FIGS. 2A–2D.

FIG. 3E shows the analog samples derived from the three frames of the video signal shown in FIGS. 3A–3C stored in the sample selection section of the analog drive circuit of an exemplary pixel of the pixel array.

FIG. 3F shows the drive signals generated by the analog drive circuit in response to the analog samples shown in FIG. 3E.

FIG. 4A is a block diagram showing the pixel array and the sample derivation and distribution circuit of a first embodiment of a monochrome display device according to the invention that can be used to perform the method according to the invention.

FIG. 4B is a schematic diagram of an exemplary analog drive circuit of the first embodiment of the display device according to the invention.

FIGS. 5A–5D are waveform diagrams illustrating the operation of the embodiment of the display device shown in FIG. 4A.

FIGS. 6A–6R are waveform diagrams illustrating the operation of the embodiment of the sample derivation and distribution circuit shown in FIG. 4A.

FIGS. 7A–7G are waveform diagrams illustrating the operation of the embodiment of the analog drive circuit shown in FIG. 4B.

FIG. 8 is a schematic diagram of a variation on the embodiment of the analog drive circuit shown in FIG. 4B that incorporates circuitry that performs the method accord-

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ing to the invention for minimizing variations in the effective offset of the drive signal generator.

FIGS. 9A–9D are waveform diagrams illustrating the operation of the offset minimizing circuitry of the embodiment shown in FIG. 8.

FIG. 10A is a block diagram showing the pixel array and the sample derivation and distribution circuit of a second embodiment of a monochrome display device according to the invention that can be used to perform the method according to the invention.

FIG. 10B is a schematic diagram of an exemplary analog drive circuit of the second embodiment of the display device according to the invention.

FIGS. 11A–11O are waveform diagrams illustrating the operation of the embodiments of the display device, the sample derivation and distribution circuit and the analog drive circuit shown in FIGS. 10A and 10B.

FIG. 12 is a block diagram of an example of a switched-sense comparator suitable for use in the analog drive circuits shown in FIGS. 10B, 15C and 16B.

FIG. 13 is a block diagram showing the pixel array and the sample derivation and distribution circuit of a variation of the second embodiment of the monochrome display device.

FIGS. 14A–14F are waveform diagrams illustrating the operation of the embodiment of the sample derivation and distribution circuit shown in FIG. 13.

FIG. 15A is a block diagram showing the pixel array and the parallel-load sample derivation and distribution circuit of a first embodiment of a color display device according to the invention that can be used to perform the method according to the invention.

FIG. 15B is a schematic diagram of a first type of exemplary analog drive circuit used in the first embodiment of the color display device according to the invention.

FIG. 15C is a schematic diagram of a second type of exemplary analog drive circuit used in the first embodiment of the color display device according to the invention.

FIG. 16 is a block diagram showing the pixel array and the serial-load sample derivation and distribution circuit of a second embodiment of a color display device according to the invention that can be used to perform the method according to the invention.

#### DETAILED DESCRIPTION OF THE INVENTION

FIG. 1 shows the structure of the display device 10 according to the invention that includes the reflective spatial light modulator 100. Other principal components of the display device are the light source 15, the polarizer 17, the beam splitter 19, the analyzer 21 and the eyepiece 23.

The light source 15 is composed of the LED driver 67 that drives the LEDs 69–71. The LEDs are of different colors and are independently driven in a color display device, as will be described below with reference to FIGS. 15A and 16. Fewer or more LEDs, or other light-emitting devices whose output can be rapidly modulated may alternatively be used as the light source 15. As a further alternative, a white light source and a light modulator may be used. The light modulator modulates the amplitude of the light output by the light source and, in a color display device, additionally modulates the color of the light output.

The light source 15 generates light that passes through the polarizer 17. The beam splitter 19 reflects a fraction of the polarized light from the polarizer towards the spatial light

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modulator 100. The reflective electrode 35 located on the surface of the substrate 39 of the spatial light modulator reflects a fraction of the incident polarized light. Depending on the electric field across the layer 31 of electro-optical material (the electro-optical layer), to be described below, the direction of polarization of the reflected light is either unchanged or is rotated through 90°. The reflected light passes to the user's eye E through the beam splitter 19, the analyzer 21 and the eyepiece 23.

The eyepiece 23 focuses the light reflected by the reflective electrode 35 at the user's eye E. The eyepiece is shown as a single convex lens in FIG. 1. A more complex optical arrangement may be used to form a low-aberration image of the desired apparent size at the user's eye.

The direction of polarization of the analyzer 21 is aligned parallel to the direction of polarization of the polarizer 17 so that light whose direction of polarization has not been rotated by the spatial light modulator will pass through the analyzer to the user's eye E, and light whose direction of polarization has been rotated through 90° by the spatial light modulator will not pass through the analyzer. Thus, the analyzer prevents light whose direction of polarization has been rotated by the spatial light modulator from reaching the user's eye. Consequently, the spatial light modulator will appear light or dark to the user depending on the applied electric field. When the spatial light modulator appears light, it will be said to be in its ON state, and when the spatial light modulator appears dark, it will be said to be in its OFF state. The direction of polarization of the analyzer can alternatively be arranged orthogonal to that of the polarizer. In this case, the spatial light modulator operates in the opposite sense to that just described. This enables a positive picture to be obtained by illuminating the spatial light modulator during the balance period, to be described below.

The optical arrangement shown in FIG. 1 may also form the basis of a full-size video or graphics display. The inventors have demonstrated such a full-size color display device with a nominal diagonal dimension of 430 mm. This display device was made by increasing the intensity of the light source 15 and by replacing the eyepiece 23 with magnifying optics that form an image of the reflective electrode 35 on a suitable screen. A single spatial light modulator sequentially illuminated by light of the three primary colors, or parallel spatial light modulators, each illuminated by light of a different primary color, can be used in a full-size color display device.

FIG. 1 additionally shows some details of the spatial light modulator 100. The spatial light modulator is composed of the electro-optical layer 31 sandwiched between the common electrode 33 and the reflective electrode 35. The electrode 33 is transparent and is deposited on the surface of the transparent cover 37. The electrode 35 is located on the surface of the semiconductor substrate 39.

An electro-optical material is a material having an optical property that depends on an applied electric field. For example, in the optical arrangement shown in FIG. 1, the rotation of the direction of polarization of light impinging on the electro-optical layer depends on the direction of an electric field applied to the layer. In other electro-optical materials, rotation of the direction of polarization may depend on the strength of the electric field applied to the layer. The transmissivity of other electro-optical materials may depend on the electric field applied to the layer.

Some electro-optical materials have a bistable characteristic. In such materials, the optical property of the material is set by applying a short-duration electrical pulse. The

material will keep the optical property set by the electrical pulse until the material is reset by applying a short duration optical pulse in the opposite direction. Bistable electro-optical materials have the advantage that the electrical pulses that drive them can be inherently DC balanced, so an additional balance period, to be described below, need not be provided. This provides a larger luminous efficiency compared with electro-optical materials that require a DC balance period.

In the preferred embodiment, the electro-optical material is a ferroelectric liquid crystal material. The direction of the electric field applied between the transparent electrode **33** and the reflective electrode **35** determines whether the direction of polarization of light impinging on the ferroelectric material sandwiched between the electrodes is rotated or not. In other embodiments, a conventional nematic liquid crystal may be used as the electro-optical material. In this case, the strength of the electric field between the electrodes determines whether the direction of polarization is rotated or not.

To enable the display device **10** to display an image instead of merely controlling the passage of light from the light source **15** to the user's eye E, the reflective electrode **35** is divided into a two-dimensional array of pixel electrodes, exemplary ones of which are shown at **118**. In addition, an analog drive circuit according to the invention (**114** in FIG. 2A) that drives the pixel electrode is located in the substrate **39** under each pixel electrode. The analog drive circuit, the pixel electrode and the portions of the electro-optical layer **31** and the common electrode **33** overlaying the pixel electrode collectively constitute a pixel, an exemplary one of which is shown at **112**.

When the electro-optical layer **31** is composed of a ferroelectric material, the direction of the electric field applied between each pixel electrode, such as the pixel electrode **118**, and the common electrode **33** determines whether the direction of polarization of the light reflected by the pixel electrode is rotated through 90° or not, and thus whether the corresponding pixel, such as the pixel **112**, will appear bright or dark to the user. When the pixel appears light, the pixel will be said to be in its ON state, and when the pixel appears dark, the pixel will be said to be in its OFF state.

The optical characteristics of the pixels of the spatial light modulator **100** are binary: light from the light source **15** and reflected by the pixel either passes through the analyzer **21** to the user's eye E or does not pass through the analyzer to the user's eye. To produce a grey scale, the apparent brightness of each pixel is varied by temporally modulating the light that reaches the user's eye. The light is modulated by choosing a basic time period that will be called the illumination period of the spatial light modulator. The spatial light modulator is illuminated through the illumination period, and each pixel is set to its ON state for a first temporal portion of the illumination period, and to its OFF state for a second temporal portion. The second temporal portion constitutes the remainder of the illumination period, and is thus complementary to the first temporal portion. Alternatively, the OFF state may precede the ON state. The fraction of the illumination period constituted by the first temporal portion, during which the pixel is in its ON state, determines the apparent brightness of the pixel.

To maximize the service life of the spatial light modulator, the DC balance of each pixel must be maintained. Since the time-integral of the electric field applied to a conventional (non-bistable) ferroelectric material during the first temporal

portion is rarely equal and opposite to that applied during the second temporal portion, additional measures must be taken to restore the DC balance of the pixel. The DC balance of the pixel is restored by driving the pixel so that the electric field applied to the ferroelectric material of the pixel averages to zero. This is accomplished in practice by driving the pixel electrode so that the first sequence of the first temporal portion and the second temporal portion constituting the illumination period is followed by a second sequence of the first temporal portion and the second temporal portion, the second sequence constituting a balance period. In the first and second temporal portions of the balance period, the state of the drive signal is the same as that during the second and first temporal portions, respectively, of the illumination period. To prevent the balance period following each illumination period from causing the display device **10** to display a uniform, grey image, the light generated by the light source **15** is modulated so that the spatial light modulator **100** is only illuminated during each illumination period and is not illuminated during the following balance period.

The illumination period and the balance period collectively constitute the display period of the spatial light modulator. The display period of a monochrome display may correspond to the frame period or the picture period of the video signal, for example.

As noted above, the drive signal required to drive a bistable electro-optical material during the illumination period can be inherently DC balanced. Consequently, no balance period need be provided, and the duration of the illumination period can be extended from about 50% of the display time to about 100% of the display time.

The principles just described may be extended to enable the spatial light modulator to generate a color image. In this case, the spatial light modulator is driven by the color components of a color video signal, and three display periods are defined for each frame of the color video signal, one for each color component. The light source **15** illuminates the spatial light modulator with light of a different color during the illumination period of each display period. Each pixel is set to its ON state for a fraction of each of the three illumination periods, and to its OFF state for the remainder of the illumination period. The fraction of each of the three illumination periods in which the pixel is in its ON state determines the apparent saturation and hue of the pixel. The display periods of a color display may each correspond to one-third of the frame period of the color video signal, for example. Making the display period the same for the three color components is operationally convenient, but is not essential.

The spatial light modulator **100** will now be described in more detail with reference to FIGS. 2A–2D. Referring first to FIGS. 2A and 2B, the light modulator is composed of the electro-optical layer **31** sandwiched between the transparent cover **37** and the semiconductor substrate **39**. The transparent cover, which may be a thin glass plate, for example, is separated from the substrate by the spacers **108**. The translucent common electrode **33**, which may be a layer of indium tin oxide (ITO), for example, is located on the inside surface of the transparent cover, facing the substrate.

An array **102** of pixels is located on the surface of the substrate **39**. The exemplary pixel is shown at **112**. The drawings throughout this disclosure show pixel arrays with only four pixels in each dimension to simplify the drawings. In a practical embodiment, the pixel array would be composed of, for example, 640×480, 800×600 pixels, 1280×1024 pixels, 2044×1125 pixels, or some other acceptable two-dimensional arrangement of pixels.

For each pixel in the pixel array **102**, an analog drive circuit according to the invention is formed by conventional semiconductor processing on and under the surface of the substrate **39**. The analog drive circuit of the exemplary pixel **112** is shown at **114**. The analog drive circuit is composed of transistors, capacitors and other circuit elements (not shown) interconnected by one or more layers of conductors (not shown). The analog drive circuits of the pixels constituting the pixel array **102** are connected to one another and to pads through which external electrical connections are made by additional layers of conductors (not shown). The surface of the substrate, and the above-mentioned layers of conductors, are covered by the insulating layer **116**. The reflective pixel electrode **118** of the pixel **112** is located on the surface of the insulating layer overlaying the analog drive circuit. The pixel electrode is connected to the output of the analog drive circuit **114** by the conductor **120** which passes through an aperture formed in the insulating layer.

In the pixel **112**, the analog drive circuit **114** generates a drive signal that is applied to the pixel electrode **118**. The drive signal applied to the electrode has a 1 state and a 0 state. The 1 state may be a high voltage state, and the 0 state may be a low voltage state, for example. The state of the drive signal applied to the pixel electrode determines whether or not the portion of the electro-optical layer **31** overlaying the pixel electrode rotates the direction of polarization of light falling on the pixel, as described above. The analog drive circuit sets the apparent brightness of the pixel by applying the drive signal to the pixel electrode in response to an analog sample derived from a video signal. During each above-described illumination period the drive signal starts in one state, corresponding to the ON state of the pixel, for example, and remains there for the first temporal portion. Before the end of the illumination period, the drive signal switches to the other state and remains there for the second temporal portion. The fraction of the illumination period for which the pixel is in its ON state determines the apparent brightness of the pixel. When the video signal is a color video signal, the analog drive circuit sets the apparent saturation and hue of the pixel by applying drive signals that turn the pixel ON for fractions of three consecutive illumination periods that depend on the three color components of the color video signal.

The video signal may be a conventional analog video signal such as is generated by a conventional computer graphics adaptor card, video or television receiver. In the examples to be described below, a conventional analog video signal is shown. However, this is not critical; the video signal may be composed of digital graphics data such as is fed to a computer graphics adaptor or is generated by a digital video or television receiver. In this case, conventional additional circuitry (not shown) is provided to convert the digital graphics data to an analog video signal, or to derive directly from the digital graphics data the analog samples that are distributed to the analog drive circuits of the pixels.

FIG. 2A shows the pixels arranged in the two-dimensional pixel array **102** on the surface of the substrate **39**. The sample derivation and distribution circuit **104** is also formed in the substrate **39**. This circuit distributes analog samples derived from the video signal received via the video input **106** to the pixel array and generates the various timing and control signals required by the pixel array. Signals are distributed from the sample derivation and distribution circuit to the pixels by busses, representative ones of which are shown schematically at **131** and **133**.

FIG. 2C is schematic representation of the electrical arrangement of the spatial light modulator **100**. The analog

sampling circuit **122** receives a video signal via the video input **106** and derives a stream of analog samples from the video signal. The analog samples are distributed to the pixels constituting the pixel array **102** by the sample distribution circuit **124**. Each pixel receives at least one sample of each frame of the video signal. The location in the frame of the video signal whence the sample is derived corresponds to the location of the pixel in the pixel array, as illustrated in FIGS. 3A–3D.

FIGS. 3A–3C respectively show examples of three consecutive frames of the video signal received via the video input **106**. Each frame is shown divided into four lines corresponding to the four rows of the pixel array **102**. Each line is shown divided into four segments, corresponding to the four pixels in each row of the pixel array. The analog sample generated by the analog sampling circuit in response to each segment of the video signal is indicated by a short horizontal line. For example, the analog samples derived from the segments **123<sub>1</sub>**, **123<sub>2</sub>** and **123<sub>3</sub>**, i.e., the second segment of the second line of each frame, are indicated by the horizontal lines **125<sub>1</sub>**, **125<sub>2</sub>** and **125<sub>3</sub>**, respectively.

The row and column numbers of the pixels in the pixel array **102** to which the sample distribution circuit **124** distributes the analog samples are indicated in FIG. 3D. For example, the exemplary pixel **112** is the second pixel in the second row of the pixel array, and so receives the analog samples **125<sub>1</sub>**, **125<sub>2</sub>** and **125<sub>3</sub>** respectively derived from the segments **123<sub>1</sub>**, **123<sub>2</sub>** and **123<sub>3</sub>** of the frames. These segments extend from ¼-way along to ½-way along the second line of each frame of the video signal.

FIG. 2D is a schematic representation of the electrical arrangement of the pixel **112** in the two-dimensional pixel array **102**. The remaining pixels have the same electrical arrangement. The pixel is composed of the analog drive circuit **114**, the output of which is connected to the electrode **118** by the conductor **120**. The analog drive circuit is composed of the sample selection section **126**, and the drive signal generator **128**. The sample selection section has a sample input **127** connected to the sample distribution circuit **124** (FIG. 2C). During each frame of the video signal, the sample selection section receives an analog sample derived from the video signal via the sample input and temporarily stores the sample until the sample is needed by the drive signal generator **128**. FIG. 3E shows the analog samples derived from the three frames of the video signal shown in FIGS. 3A–3C stored in the sample selection section of the pixel **112**.

The drive signal generator **128** receives each analog sample stored in the sample selection section **126** during the picture period of the previous frame and, in response to the sample, generates a drive signal and applies the drive signal to the electrode **118**. The drive signal generator generates the drive signal with a period corresponding to the above-described display period. FIG. 3F shows an example of the drive signal generated by the analog drive circuit **114** in response to the analog samples shown in FIG. 3E. Each of the display periods of the drive signal is composed of an illumination period and a balance period of equal durations. The drive signal generator additionally generates the drive signal in the 1 state for a first temporal portion **1 TP** that constitutes a fraction of each illumination period that is proportional to the voltage level of the corresponding analog sample. This can be seen by comparing the durations of the first temporal portions **1 TP** of illumination periods shown in FIG. 3F with the corresponding voltage levels shown in FIG. 3E.

The drive signal is generated so that it remains in the 0 state for the second temporal portion **2 TP** constituting the

remainder of the illumination period, and also for the first temporal portion 1TP of the balance period. The first temporal portion of the balance period has a duration equal to the first temporal portion of the illumination period in which the drive signal was in the 1 state. Finally, the drive signal changes to the 1 state for the second temporal portion 2 TP constituting the remainder of the balance period. The duration of the first temporal portion of the drive signal is different in each of the three illumination periods, depending on the voltage level of the respective sample. In each following balance period, the drive signal is in the 1 state for the second temporal portion, and is therefore in the 1 state for a time that is complementary to the duration of the 1 state in the illumination period.

In the example shown in FIG. 3F, the display period of each frame begins immediately after the end of the display period of the previous frame. In some embodiments, such as the embodiment to be described below with reference to FIGS. 4A and 4B, the drive waveform is generated intermittently, and a period in which the drive signal is generated in a neutral state is interposed between consecutive display periods.

The waveforms just described are those required to drive an electro-optical material that lacks a bistable characteristics. However, it will be apparent to a person of ordinary skill in the art that circuits, such as those to be described below, for generating such waveforms can easily be adapted to generate the waveforms required to drive a bistable electro-optical material. For example, an analog drive circuit capable of generating the waveforms just described can be adapted to drive a bistable electro-optical material by capacitatively or a.c. coupling the output of the circuit to the pixel electrode.

FIGS. 4A and 4B show a first practical embodiment of the circuitry of the spatial light modulator 100 in more detail. In particular, FIG. 4A shows in more detail the sample derivation and distribution circuit 104 that derives analog samples from the video signal and distributes the samples to the individual pixels. FIG. 4B shows the analog drive circuit of one of the pixels in detail and will be described below. In this embodiment, sample selection circuits that perform the row-wise distribution function of the sample distribution circuit 124 shown in FIG. 2C reside in the analog drive circuits of the pixels. The analog sampling circuit 122 generates a stream of analog samples for each column of the pixel array 102, and the sample selection circuit in each pixel performs the row-wise selection from the analog sample stream.

This embodiment will be described with reference to a monochrome display device based on a highly-simplified 4x4 array of pixels to simplify the drawing and the explanation. A variation that provides a color display device will be described below with reference to FIGS. 15A and 15B.

The analog sampling circuit 122 receives the video signal Y via the video input 106. As will be described in more detail below, the analog drive circuit of each pixel in the pixel array 102 has a sample input and a row select input. For example, the pixel 112 has the sample input 150 and the row select input 110. The analog drive circuit additionally has a ramp input and additional inputs for various timing and control signals (not shown in FIG. 4A). Each analog drive circuit delivers a drive signal to the electrode that overlays it. The sample inputs of all the pixels in each column of the pixel array are connected to a column bus that is in turn connected to a respective output of the analog sampling circuit 132. For example, the sample inputs of the pixels in

the second column, where the exemplary pixel 112 is located, are connected to the column bus 131<sub>2</sub>. The location in each line of the video signal whence the analog samples received by each column of pixels are derived depends on the location of the column in the pixel array, as described above. An analog sample of every line of the video signal is fed to the sample input of each analog drive circuit.

The row select inputs of all the pixels in each row of the pixel array 102 are connected to a row select bus that is driven by a corresponding output of the row selector 134. For example, the row select inputs of the pixels in the second row, where the exemplary pixel 112 is located, are connected to the row select bus 133<sub>2</sub>. An analog drive circuit can accept an analog sample present at its sample input only when its row select input is the 1 state, for example. The row selector sequentially sets the row select busses to the 1 state at the line rate of the video signal. During the first line of each frame of the video signal, the row selector sets the row select bus 133, connected to the first row of pixels to the 1 state, and sets the remaining row select busses to the 0 state. The sampling circuit 132 sequentially feeds analog samples of the first line of the video signal to the column busses in order, starting with the column bus 131<sub>1</sub> of the first column. The column bus of each column feeds the analog samples to all the pixels in the column, but the analog samples are only accepted by the pixels in the first row.

At the end of the first line of the video signal, row selector 134 sets the row select bus 133<sub>1</sub> connected to the first row of pixels to the 0 state, and sets the row select bus 133<sub>2</sub> connected to the second row of pixels to the 1 state. When the sampling circuit 132 sequentially feeds analog samples of the second line of the video signal to the column busses, the analog samples are only accepted by the pixels in the second row of pixels. This process is repeated with the row selector 134 sequentially setting the remaining row select busses 133<sub>3</sub> and 133<sub>4</sub> to the 1 state until each pixel in the pixel array 102 has accepted a different analog sample derived from the frame of the video signal.

The part of the analog sampling circuit 122 that derives analog samples from the video signal and the sample distribution circuit 124 that feeds the analog samples to the sample input of the analog drive circuit of each of the pixels in the pixel array 102 will now be described.

The video signal is fed from the video input 106 to the buffer amplifier 136. In addition to buffering the video signal, the buffer amplifier may additionally change the dynamic range and DC level of the video signal to meet the dynamic range and DC level requirements of the analog drive circuits of the light modulator 100. The video signal Y<sub>C</sub> output by the buffer amplifier is fed to the sampling circuit 132. The buffer amplifier may alternatively be omitted.

The sampling circuit 132 is composed of one sample-and-hold (S/H) circuit for each column of the pixel array 102. To simplify the drawing, the S/H circuits other than the S/H circuits 138<sub>1</sub> and 138<sub>4</sub> have been omitted. Each of the S/H circuits has a signal input S, a control input C and a sample output O. The signal input is connected to receive the video signal Y<sub>C</sub> output by the buffer amplifier 136. The control input C is connected via a control line to a corresponding output of the column selector 140. For example, the control input of the S/H circuit 138<sub>1</sub> is connected via the control line 139<sub>1</sub> to the output 141<sub>1</sub> of the column selector. The sample output O of each S/H circuit is connected to the column bus of the respective column of pixels. For example, the output of the S/H circuit 138<sub>1</sub> is connected to the column bus 131<sub>1</sub>

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connected to sample inputs of the analog drive circuits of all the pixels in the first column.

The column selector **140** receives the clock signal PIXEL from the clock generator **142**. The clock signal PIXEL includes a pixel-rate clock signal and the horizontal sync signal extracted or otherwise derived from the video signal. The clock generator will be described in more detail below. The column selector is composed of a shift register (not shown) having stages equal in number to the number of columns in the pixel array **102**. The outputs of the stages of the shift register are connected via control lines in column order to the control inputs of the sampling circuit **132**. For example, the output **141**<sub>1</sub> of the first stage of the shift register is connected via the control line **139**, to the control input of the S/H circuit **138**, of the sampling circuit.

The trailing edge of the horizontal sync signal or the horizontal blanking signal resets the shift register constituting the column selector **140** so that the first stage, whose output **141**<sub>1</sub> is connected to the control line **139**<sub>1</sub>, is set to its 1 state, and the outputs of all the other stages are set to their 0 states. Then, the clock signal PIXEL progressively shifts the 1 state along the shift register at the pixel rate. As the output of each stage of the shift register changes from 1 to 0, the sample output O of the S/H circuit controlled by the stage is set to a value that represents the level of the video signal connected to the signal input S of the S/H circuit. For example, as the output **141**<sub>1</sub> of the first stage of the shift register changes from 1 to 0, the sample output of the S/H circuit **138**<sub>1</sub> is set to a value that represents the level of the video signal during the preceding pixel period. The sample output of the S/H circuit may be set to a value equal to the instantaneous level of the video signal at the time the control input to the S/H circuit changes state, or the peak, or mean, or RMS level of the video signal during the period in which the control input is in its 1 state. Alternatively, the sample output of the S/H circuit may be set to some other level related to the video signal during the time that the control input is in its 1 state, depending on the sampling characteristics of the S/H circuits.

The structure of the row selector **134** is similar to that of the column selector **140**. The number of stages in the shift register that constitutes the row selector is equal to the number of rows in the pixel array **102**. The row selector receives the clock signal LINE from the clock generator **142**. The clock signal LINE includes a line-rate clock signal, and the vertical sync signal extracted from the video signal. The row selector is reset by the trailing edge of the vertical sync signal and is clocked by the line-rate clock signal. Consequently, the row selector successively activates the rows of pixels at the line rate of the video signal.

The clock generator **142** receives the video signal from the video input **106** and generates the various clock and control signals required by the analog sampling circuit **122**, the analog drive circuits of the spatial light modulator **100**, the ramp generator **144** and the LED driver **67**. Suitable clock generators are known in the art and so the clock generator **142** will not be described in detail here. The clock generator feeds the control signals SEL, CLE, ILLUM and BAL via the bus **112** for distribution to the analog drive circuits in the pixel array **102**.

As part of its clock and control signal generation, the clock generator **142** extracts the vertical and horizontal sync signals from the video signal. If the video signal lacks such sync signals, the clock generator derives sync signals from such alternative indicia of the start of the frames and lines of the video signal as are included in the video signal or are otherwise available.

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The LED driver **67** receives a control signal from the clock generator **142** and drives the LEDs **69-71** (FIG. 1) in response to the control signal to cause the LEDs to illuminate the spatial light modulator **100**. The timing relationship between the drive signal applied to the LEDs and the control signals applied to the spatial light modulator will be described below.

For each frame of the video signal, the ramp generator **144** generates two successive ramp signals, each having a duration equal to the illumination period. For example, the ramp generator generates the first ramp signal in response to the trailing edge of the vertical sync pulse, and generates the second ramp signal in response to the end of the first ramp signal. Although the ramp signals are depicted as having linear slopes in the drawings, the slopes of the ramp signals are preferably non-linear since a non-linear slope provides simple and effective gamma correction. Gamma correction is required to correct for the non-linear perception of the apparent brightness of the pixel by the human eye.

A suitable non-linear ramp signal may be generated using a memory. Values that define the level of the ramp signal at times corresponding to each cycle of a clock signal, such as a clock signal obtained by dividing the pixel clock signal, are stored in the memory. The memory is then clocked with the clock signal, and the successive values read out from the memory are converted to an analog ramp signal. Other techniques for generating a suitable non-linear ramp signal by digital or analog means are known in the art. The ramp generator feeds the ramp signals via the bus **113** to the pixel array **102** for distribution to the analog drive circuits of the pixels in the array.

The ramp signals generated by the ramp generator **144** are shown in FIG. 7D and 11J below as beginning in a low state and increasing towards a high state. However, this is not critical. The ramp signals may begin in a high state and decrease towards a low state. Moreover, the ramp signal may begin in the low state and increase towards the high state during the illumination period and may then decrease towards the low state in the following balance period, or vice versa.

A first embodiment of the analog drive circuit according to the invention of each of the pixels of the pixel array **102** is shown in FIG. 4B. The analog drive circuits will be described with reference to the exemplary analog drive circuit **114** of the exemplary pixel **112** shown in FIG. 4A. This pixel is the second pixel of the second row of the pixel array. The analog drive circuits of the other pixels of the pixel array are identical, but each is connected to a different combination of column bus and row selector bus.

During each frame of the video signal, the analog drive circuit **114** receives an analog sample derived from the video signal, generates a drive signal in response to the analog sample and applies the drive signal to the pixel electrode **118**.

This embodiment of the analog drive circuit **114** can be regarded as being composed of the sample selection section **126** and the drive signal generator **128**. The sample selection section selects the analog sample for the pixel from among the analog samples on the column bus **131**<sub>2</sub> and stores the analog sample. The drive signal generator generates the drive signal and applies the drive signal to the pixel electrode **118**.

The sample selection section **126** will now be described. The sample selection section selects and stores the analog samples of the video signal that are to be displayed by the pixel **112** from the analog samples placed on the column bus



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**131<sub>2</sub>** by the sampling circuit **132**. The sample selection section also feeds the stored analog samples to the drive signal generator **128**.

The sample input **150** of the analog drive circuit **114** is connected to the column bus **131<sub>2</sub>**. Also connected to the sample input is the drain of the sample select transistor **152**. The gate of the sample select transistor is connected via the row select input **110** to the row select bus **133<sub>2</sub>** connected to all the pixels located in the second row of the pixel array. The source of the sample select transistor is connected to one electrode of the sample storage capacitor **154**. The other electrode of the sample storage capacitor is connected to a constant voltage source, e.g., ground.

The node between the sample storage capacitor **154** and the sample select transistor **152** is connected to the source of the sample output transistor **156**. The gate of the sample output transistor is connected to the sample output control signal SEL generated by the clock generator **142** and distributed by the sample output bus **158** to the gates of the sample output transistors of the analog drive circuits of all the pixels constituting the pixel array **102**.

The drive signal generator **128** will now be described. The drain of the sample output transistor **156** is connected to the electrode **159** of the ramp capacitor **160**. The electrode **161** of the ramp capacitor is connected to the RAMP signal generated by the ramp generator **144** (FIG. 4A) and distributed by the ramp bus **162** to the ramp capacitors of the analog drive circuits of all the pixels constituting the pixel array **102**.

The electrode **159** of the ramp capacitor **160** is also connected to the drain of the reset transistor **164** and the input of the inverter **166**. The source of the reset transistor is connected to a constant voltage source, e.g., ground. The gate of the reset transistor is connected to the reset control signal CLE generated by the clock generator **142** and distributed by the reset bus **168** to the gates of the reset transistors of the analog drive circuits of all the pixels constituting the pixel array **102**.

The inverter **166** is composed of the PMOS transistor **170** and the NMOS transistor **172**, the gates of which are connected to one another and to the input of the inverter, the drains of which are connected to one another and to the output of the inverter, and the sources of which are respectively connected to high and low constant voltage levels  $V+$  and  $V-$ . These constant voltage levels may be, for example, the positive power supply and ground, respectively.

The output of the inverter **166** is connected to the input of the inverter **174** and to the source of the illumination selector transistor **176**. The structure of the inverter **174** is identical to the inverter **166** and so will not be described. The output of the inverter **174** is connected to the source of the balance selector transistor **178**. The drains of the selector transistors **176** and **178** are connected to one another and, by the conductor **120**, to the electrode **118**. The gates of the selector transistors **176** and **178** are respectively connected to the ILLUM control signal and the BAL control signal. The ILLUM and BAL control signals are generated by the clock generator **142** and are distributed by the busses **180** and **182**, respectively, to the gates of the selector transistors of the analog drive circuits of all the pixels constituting the pixel array **102**.

The common electrode **33** shown in FIG. 2B is connected to the constant voltage source  $V+/2$  approximately mid-way between the high and low constant-voltage sources.

Operation of the just-described embodiment of the spatial light modulator **100** according to the invention will now be

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described with reference to FIGS. 4A and 4B, and the timing diagrams shown in FIGS. 5A–5D, and 6A–6R and 7A–7G.

FIG. 5A shows the basic operation of the above-described embodiment of the spatial light modulator in which analog samples of frame **1** are loaded during the picture period of frame **1**, and a display operation is performed in response to the analog samples of frame **1** during the picture period of frame **2**. The frames of the video signal are each divided into a vertical blanking period VB and a picture period. During the picture period of frame **1**, an analog sample derived from frame **1** of the video signal is loaded into the sample storage capacitor **154** of the analog drive circuit of each pixel in the pixel array **102**. This process will be described below with reference to FIGS. 6A–6R. Simultaneously, a display operation is performed in response to the analog samples of the previous frame **0**. During the vertical blanking period of frame **2**, the analog sample of frame **1** stored in the sample storage capacitor of each pixel is transferred to the ramp capacitor of the pixel. Then, during the picture period of frame **2**, a display operation is performed in response to the analog sample transferred to the ramp capacitor of each pixel in the pixel array. Simultaneously, an analog sample of frame **2** is loaded into the sample storage capacitor of the pixel.

The waveform of the current supplied to the LEDs **69–71** by the LED driver **67** is schematically shown in FIG. 5B. During each illumination period, the LED driver **67** feeds current to the LEDs **69–71** to cause the LEDs to illuminate the spatial light modulator **100**. During the balance period following the illumination period and the vertical blanking period preceding the illumination period, the LED driver turns the LEDs OFF. During the illumination period, the analog drive circuits of all the pixels constituting the pixel array **102** simultaneously generate the illumination sequence of the drive signal that they apply to their respective pixel electrodes to cause the pixel to modulate the intensity of the light reflected by the pixel. During each balance period, in which the spatial light modulator is not illuminated, the analog drive circuits of all the pixels simultaneously generate the balance sequence of the drive signal. The balance sequence of the drive signal is complementary to the illumination sequence of the drive signal and restores the DC balance of the pixel. The drive signal will be further described below with reference to FIGS. 7A–7G.

The waveforms of the ILLUM and BAL control signals are shown in FIGS. 5C and 5D, respectively. During the vertical blanking period at the beginning of each frame period, the clock generator **142** generates both of these control signals in their 0 state. Accordingly, both the selector transistors **176** and **178** are OFF, and the voltage on the pixel electrode **118** is approximately equal to the voltage on the common electrode **33** (FIG. 2B). The clock generator **142** generates the ILLUM control signal in the 1 state whenever the LED driver **67** supplies current to the LEDs **69–71**. The ILLUM control signal turns the illumination selector transistor **176** ON, which connects the electrode **118** to the output of the inverter **166**. During the following blanking period, the LED driver supplies no current to the LEDs, and the clock generator generates the BAL control signal shown in FIG. 5D in its 1 state. This turns the balance selector transistor **178** ON, which connects the electrode **118** to the output of the inverter **174**.

The process by which an analog sample of the frame of the video signal is loaded into the sample storage capacitor **154** of the analog drive circuit of each pixel in the pixel array **102** will now be described below with reference to FIGS. 4A, 4B and 6A–6R. FIGS. 6A–6D respectively show the

control signal waveforms on the control lines **139<sub>1</sub>–139<sub>4</sub>**, connected to the control inputs of the S/H circuits **138<sub>1</sub>–138<sub>4</sub>**, during the picture period of one frame of the video signal. FIG. 6E shows an example of the waveform of the video signal **Y<sub>C</sub>** fed from the buffer amplifier **136** to the signal inputs of the S/H circuits **138<sub>1</sub>–138<sub>4</sub>**. FIGS. 6F–6I respectively show the sample outputs of the S/H circuits **138<sub>1</sub>–138<sub>4</sub>** fed to the column busses **131<sub>1</sub>–131<sub>4</sub>**, respectively. In particular, FIG. 6G shows the sample waveform on the column bus **131<sub>2</sub>** connected to the sample input **150** of the analog drive circuit **114** of the pixel **112**. Sampling begins when the control signal on the control line **139<sub>2</sub>** goes to its 1 state. When the control signal is in this state the output of the S/H circuit **138<sub>2</sub>**, connected to the column bus **131<sub>2</sub>** follows the waveform of the conditioned video signal shown in FIG. 6E. When the control signal on the control line **139<sub>2</sub>** returns to its 0 state, the S/H circuit **138<sub>2</sub>** holds the level on the column bus **131<sub>2</sub>** at the level of the conditioned video signal at the transition of the control signal. The level on the column bus remains at this level until the next time the control signal on the control line **139<sub>2</sub>** goes to its 1 state ¼-way along the next line of the conditioned video signal.

FIGS. 6J–6M show the waveforms of the control signals on the row select busses **133<sub>1</sub>–133<sub>4</sub>**, respectively. Each of the control signals is shown as being in its 1 state for the duration of one line of the video signal, and is in its 0 state for the rest of the frame. However, the row select control signals may switch to their 1 states at a time later than the start of their respective lines.

FIGS. 6O–6R respectively show the waveforms on the sample storage capacitors of the analog drive circuits of the pixels **184**, **112**, **185** and **186** in the second row of the pixel array **102**. Analog samples of the second line of the video signal are accepted by these pixels. During the second line of the video signal, the control signal on the row select bus **133<sub>2</sub>** connected to the pixel **112** is in the 1 state. The control signal turns the sample select transistor **152** ON, which connects the sample storage capacitor **154** to the sample input **150**. As a result, the voltage on the sample storage capacitor first changes to the voltage on the column bus **131<sub>2</sub>**, then follows the voltage on the column bus, and finally reaches a constant voltage when the output of the S/H circuit driving the column bus goes into its “hold” mode.

In particular, as shown in FIG. 6P, when the control signal on the row select bus **133<sub>2</sub>** changes to its 1 state at the beginning of the second line, the voltage on the sample storage capacitor **154** of the analog drive circuit **114** changes to the level on the column bus **131<sub>2</sub>**. The voltage on the sample storage capacitor then follows the voltage changes, shown in FIG. 6G, on the column bus **131<sub>2</sub>**. These voltage changes occur as a result of the S/H circuit **138<sub>2</sub>** sampling the second quarter of the second line of the conditioned video signal. Finally, the voltage on the sample storage capacitor reaches a constant level corresponding to the level held by the output of the S/H circuit **138<sub>2</sub>** at the end of the second quarter of the second line. The voltage on the sample storage capacitor reaches this condition at the time of the falling edge of the control waveform shown in FIG. 6B.

FIGS. 6O, 6Q and 6R show how the voltages on the sample storage capacitors of the pixels **184–186** in the second row of the array follow the changes in the voltage on the column busses **131<sub>1</sub>**, **131<sub>3</sub>** and **131<sub>4</sub>**, respectively, when the control signal on the row selector bus **133<sub>2</sub>** (shown in FIG. 6K) is in its 1 state, and remain constant during the other three lines of the frame.

At the end of the second line of the video signal, the control signal on the row selector bus **133<sub>2</sub>** changes from the

1 state to the 0 state. In this state, the control signal on the row selector bus turns the sample select transistor **152** OFF, which disconnects the sample storage capacitor **154** from the sample input **150**. As a result, the voltage on the sample storage capacitor remains fixed at the level it had when the control signal on the row selector bus changed state, as shown in FIG. 6P. The voltages on the sample storage capacitors in the pixels **184–186** in the second row of the array also become fixed when the control signal on the row selector bus **133<sub>2</sub>** reverts to the 0 state.

During the other three lines of the video signal, the control signal on the one of the row select busses **133<sub>1</sub>**, **133<sub>3</sub>** and **133<sub>4</sub>** corresponding to the line of the video signal received at the video input changes to the 1 state. As a result, the voltages on the sample storage capacitors of the pixels in the corresponding row of the pixel array follow the voltage levels appearing on the column busses **131<sub>1</sub>–131<sub>4</sub>**. At the end of each line of the video signal, the control signal on the one of the row select busses **133<sub>1</sub>–133<sub>4</sub>** connected to the corresponding row of the pixel array reverts to the 0 state. This causes the voltages stored in the sample storage capacitors of the pixels in the row to remain fixed until the corresponding line of the next frame.

The processes by which the drive signal generator **128** of each analog drive circuit converts the analog sample stored in the sample storage capacitor **154** into a drive signal will now be described with reference to FIGS. 7A–7G and FIG. 4B. The drive signal has a 1 state duration that depends on the value of the analog sample and subsequently restores the DC balance of the pixel. FIGS. 7A–7G show the events that occur during the vertical blanking period and the illumination period and the balance period constituting the frame **1** display period shown in FIG. 5A, but with a different time scale from that of FIGS. 5A–5D.

FIG. 7A schematically shows the waveform of the current through the LEDs **69–71**. During the vertical blanking period prior to the illumination period, no current flows through the LEDs, as shown in FIG. 7A, the output of the ramp generator is in its minimum state, as shown in FIG. 7D, and both the ILLUM and BAL signals are in their 0 states, so both selector transistors **176** and **178** are OFF. Consequently, the voltage on the pixel electrode **118** is approximately equal to that on the common electrode **33** (FIG. 2B). At the start of the vertical blanking period VB, the reset signal shown in FIG. 7B briefly turns the reset transistor **164** ON. The reset transistor discharges the analog sample of frame **0** from the ramp capacitor **160**, as shown at **187** in FIG. 7E. The ramp capacitor is now ready to receive charge from the sample storage capacitor.

After the reset transistor **164** has turned OFF, the output select control signal SEL shown in FIG. 7C switches the sample output transistor **156** ON. This connects the sample storage capacitor **154** in parallel with the ramp capacitor **160**, which is in a discharged state. Charge sharing occurs, and the voltage on the ramp capacitor rapidly increases, as shown at **188** in FIG. 7E. The voltage level to which the voltage on the ramp capacitor rises is proportional to the charge in the sample storage capacitor before it was connected to the ramp capacitor. The output select control signal SEL switches the sample output transistor OFF at or before the end of the vertical blanking period, as shown in FIG. 7C. This isolates the ramp capacitor from the sample storage capacitor.

Notwithstanding the increased voltage on the ramp capacitor as a result of the charge sharing, the voltage on the electrode **159** of the ramp capacitor **160** is below the

threshold voltage of the inverter 166 at the end of the vertical blanking period. The threshold voltage is indicated by the line 189 in FIG. 7E. As a result, the output voltage of the inverter 166 continues in its high state, as shown in FIG. 7F. However, since the pixel electrode 118 is disconnected from the outputs of both inverters 166 and 174, the voltage on the pixel electrode 118 is approximately equal to that applied to the common electrode 33, as shown in FIG. 7G.

The illumination period starts at the end of the vertical blanking period VB. In response to the trailing edge of the vertical sync pulse marking the start of the illumination period, the clock generator 142 causes the LED driver 67 to feed current through the LEDs 69–71 as shown in FIG. 7A, sets the ILLUM control signal to its 1 state, and triggers the ramp generator 144 to start generating the ramp waveform shown in FIG. 7D.

The ILLUM control signal, shown in FIG. 5C, turns the illumination select transistor 176 ON, which connects the electrode 118 to the output of the inverter 166. This sets the voltage on the electrode to the voltage on the output of the inverter 166 shown in FIG. 7F, i.e., to the 1 state shown in FIG. 7G, and marks the start of the first temporal portion of the illumination period. The BAL control signal, shown in FIG. 5D, keeps the balance select transistor OFF.

The ramp signal generated by the ramp generator 144 is applied to the electrode 161 of the ramp capacitor 160. As the first temporal portion progresses, the ramp signal causes the voltage on the electrode 159 of the ramp capacitor to increase in step with the ramp signal, as shown at 190 in FIG. 7D. At the point 191, the voltage on the electrode 159 of the ramp capacitor reaches the threshold voltage of the inverter 166, and the output of the inverter changes to the 0 state, as shown at 192 in FIG. 7F. Since the pixel electrode 118 is connected to the output of the inverter by the illumination select transistor 176, the voltage on the electrode also changes to the low state, as shown in FIG. 7G. This marks the end of the first temporal portion and the beginning of the second temporal portion of the illumination period. The pixel electrode remains in the 0 state for the second temporal portion constituting the remainder of the illumination period shown in FIG. 7A.

At the end of the illumination period, ramp signal resets, as shown in FIG. 7D, and the voltage on the electrode 159 of the ramp capacitor falls quickly to a level below the threshold voltage of the inverter 166. This causes the output of the inverter 166 to revert to its 1 state, as shown at 193 in FIG. 7F. In addition, both the ILLUM control signal and the BAL control signal change state, as shown in FIGS. 5C and 5D, respectively. This turns the illumination selector transistor 176 OFF and the balance selector transistor 178 ON, which transfers the connection to the pixel electrode 118 from the output of the inverter 166 to the output of the inverter 174. The output of the inverter 174 is in the 0 state when the output of the inverter 166 is in the 1 state. Accordingly, during the first temporal portion of the balance period, the pixel electrode remains in the 0 state as shown in FIG. 7G.

When the level of the electrode 159 of the ramp capacitor reaches the threshold voltage 188 of the inverter 166 once more, the outputs of the inverter 166 changes state, as shown at 194 in FIG. 7F. The output of the inverter 174 also changes state, as a result of which the voltage on the pixel electrode 118 changes from the 0 state to the 1 state, as shown in FIG. 7G. This marks the end of the first temporal portion and the beginning of the second temporal portion of the balance period. The voltage on the pixel electrode

remains in the 1 state for the second temporal portion that constitutes the remainder of the balance period shown in FIG. 7A.

The ramp waveform returns to its minimum state at the end of the balance period, and the reset signal shown in FIG. 7B once more turns the reset transistor 164 ON to discharge the analog sample of frame 1. The BAL control signal returns to its 0 state and the ILLUM control signal remains in its 0 state, as shown in FIG. 5C and 5D at the end of the balance period. The change in the state of the BAL control signal isolates the pixel electrode 118 from the inverters once more, as shown in FIG. 7G.

During the balance period, the drive signal has in its 1 state for the second temporal portion that is complementary to the first temporal portion in which the drive signal applied to the pixel electrode was in its 1 state during the illumination period when the spatial light modulator was illuminated. Consequently, the voltage on the pixel electrode 118 is set to the 1 state and to the 0 state for equal portions of the display period so that the DC balance of the pixel is maintained.

The duration of the first temporal portion of the illumination period in which the pixel electrode 118 remains in the 1 state depends on the initial voltage to which the ramp capacitor 160 was charged by charge sharing with the sample storage capacitor 154. The DC level and dynamic range of the video signal  $Y_C$  generated by the buffer amplifier 136, the voltage range of the ramp signal, and the threshold voltage of the inverter 166 are set so that the inverter 166 changes state almost immediately when the voltage of the analog sample stored in the sample storage capacitor corresponds to the maximum of the dynamic range of the video signal. On the other hand, the inverter does not change state until the end of the illumination period when the sample voltage is at the minimum of the dynamic range of the video signal.

The broken lines 196 and 197 in FIGS. 7F and 7G indicate the longer duration of the 1 states of the output of the inverter 166 and the pixel electrode 118, respectively, when the level of the analog sample is lower, as indicated by the broken line 195 in FIG. 7E. The equally-longer duration of the 0 state of the pixel electrode in the following balance period is indicated by the broken line 198 in FIG. 7G.

In the above-described embodiment of the analog drive circuit, and in the embodiments to be described below, the stages that drive the pixel electrode are required to change state only twice per frame of the video signal. As a result, the analog drive circuit has lower power consumption than a digital drive circuit of comparable performance. Moreover, the performance of the display device with analog drive circuits is less dependent on the switching speed of the electro-optical material than a display using digital drive circuits.

In the analog drive circuit just described, the transfer relationship between the duration of the first temporal portion of the drive signal applied to the pixel electrode 118 during the illumination period and the analog sample stored in the sample storage capacitor 154 depends on the threshold voltage of the inverter 166. The threshold voltage is process-dependent, and can differ between wafers, between pixel arrays on the same wafer, and between the analog drive circuits in the same pixel array. With current processing technology, these threshold voltage variations limit the grey-scale resolution of the spatial light modulator 100 to about four bits. Most graphics and video applications require a larger grey-scale resolution than this.

FIG. 8 shows a second embodiment of an analog drive circuit that reduces the effect of threshold voltage variations, and that can therefore provide a greater grey scale resolution. In the embodiment shown in FIG. 8, elements that correspond to those of the embodiment shown in FIG. 4B are indicated by the same reference numerals, and will not be described again here. The sample derivation and distribution circuit that provides analog samples and control signals to the embodiment shown in FIG. 8 is similar to that shown in FIG. 4A, and so will not be described again here.

In the embodiment of the analog drive circuit shown in FIG. 8, the sample selection section 126 is the same as that of the embodiment shown in FIG. 4B. In the drive signal generator 128, the input of the inverter 166 is connected to the electrode 159 of the ramp capacitor 160 by the coupling capacitor 201. The drive signal generator additionally includes the offset correction transistor 203 whose drain and source are connected to the input and output, respectively, of the inverter 166. The gate of the offset correction transistor is connected to the offset correction control signal O/S CORR. The offset correction control signal is generated by the clock generator 142 and is distributed by the bus 205 to the gates of the offset correction transistors of the analog drive circuits of all the pixels constituting the pixel array 102.

Finally, the source of the reset transistor 164 is connected to the reference signal SCLEAR. This reference signal is generated by the clock generator 142 and is distributed by the bus 211 to the sources of the reset transistors of the analog drive circuits of all the pixels constituting the pixel array 102. As shown in FIG. 9C, the reference signal SCLEAR has two states, a high state  $V_{REF}$  equal to the desired threshold voltage of the inverter 166 and a low state close to the low voltage level  $V_-$ . In one practical embodiment, the high state of the reference signal SCLEAR was half-way between high and low voltages  $V_+$  and  $V_-$ .

Operation of the embodiment shown in FIG. 8 is similar to that of the embodiment shown in FIG. 4B. However, at the beginning of the vertical blanking period VB of each frame, the offset correction control signal O/S CORR and the clear control signal CLE are asserted as shown in FIGS. 9A and 9B, respectively. In addition, the reference signal SCLEAR switches to its high state  $V_{REF}$  at the beginning of the vertical blanking period, as shown in FIG. 9C. The offset correction control signal turns ON the offset correction transistor 203, which interconnects the input and output of the inverter 166. Connecting the output of the inverter to its input sets the voltage on the input of the inverter, and the voltage on the electrode 207 of the coupling capacitor 201, precisely to the threshold voltage of the inverter. The clear control signal CLE turns the reset transistor 164 ON. The reset transistor connects the electrode 209 of the coupling capacitor 201 to the reference signal SCLEAR in its high state. The reset transistor and the offset correction transistor together set the voltage across the coupling capacitor 201 to a value equal to the difference between the actual threshold voltage of the inverter and the desired threshold voltage  $V_{REF}$ .

Part-way through the vertical blanking period VB, the control signal O/S CORR is de-asserted, as shown in FIG. 9B. This turns the offset correction transistor 203 OFF, but the voltage across the coupling capacitor 201 remains. Simultaneously, or slightly later, the reference signal SCLEAR switches to its low state  $V_-$ , as shown in FIG. 9C. Since the control signal CLE is still asserted and the reset transistor 164 is still ON, the ramp capacitor 160 discharges to a low voltage state through the reset transistor. After a

time sufficient for the ramp capacitor to discharge fully, the control signal CLE is de-asserted and the reset transistor 164 turns off.

After the reset transistor 164 has turned off, the control signal SEL is asserted, as shown in FIG. 9D. This turns the selector transistor 156 ON. Charge sharing between the sample storage capacitor 154 and the ramp capacitor 160 takes place as described above with reference to FIG. 7E. The control signal SEL is de-asserted before the end of the vertical blanking period VB to isolate the ramp capacitor from the sample storage capacitor.

Operation of the drive signal generating section during the illumination and balance periods constituting the display period is the same as that described above with reference to FIGS. 7E-7G. When the ramp voltage is applied to the electrode 161 of the ramp capacitor, the inverter 166 will change state when the voltage on the electrode 159 of the ramp capacitor reaches a voltage equal to the high state  $V_{REF}$  of the reference signal SCLEAR, irrespective of actual threshold voltage of the inverter 166. The same will be true for the inverters 166 of the analog drive circuits of all the pixels in the pixel array 102. This greater consistency in the effective threshold voltage of the inverter 166 increases the grey scale resolution of this embodiment of the spatial light modulator according to the invention to greater than eight bits.

The embodiment of the analog drive circuit just described with reference to FIG. 8 includes three capacitors. The area of silicon occupied by these capacitors using present-day fabrication techniques represents a majority of the area of each analog drive circuit, and limits the number of pixels that can be provided on a die of a given size. Also, the spatial light modulator is illuminated for a total of one half of the picture period of the video signal. Since the vertical blanking period is about 8% of the frame period, the illumination efficiency is about 46%. It would be advantageous to increase the illumination efficiency of the spatial light modulator to the theoretical maximum of 50% and to reduce the number of capacitors to two per analog drive circuit.

A second embodiment 214 of the analog drive circuit according to the invention will be described next with reference to FIGS. 10A and 10B. This embodiment performs simultaneous sample loading and display operations, enabling an illumination efficiency of 50% to be achieved, while requiring only two capacitors per analog drive circuit. The number of capacitors is reduced by eliminating capacitors from the drive signal generator, and by adopting a solution to the inverter offset problem that does not require an additional capacitor. Consequently, this embodiment can form part of a spatial light modulator having a greater number of pixels on a given die size than the embodiments shown in FIGS. 4B and 8.

FIG. 10A shows the sample derivation and distribution circuit 204 that derives analog samples from the video signal received via the video input 106 and feeds the analog samples to the analog drive circuits of the pixels constituting the pixel array. This circuit additionally generates the control signals that control the analog drive circuits. Elements of the sample derivation and distribution circuit 204 that correspond to the sample derivation and distribution circuit 104 shown in FIG. 4A are indicated by the same reference numerals and will not be described. Elements that are similar are indicated by the same reference numeral with 100 added. The sample derivation and distribution circuit differs from that shown in FIG. 4A mainly in the interposition of the odd/even frame selector 235 between the row selector 134

and the pixel array **202**, and the provision of an odd-frame selection bus and an even-frame selection bus for each row of pixels in the pixel array.

As will be described in more detail below with reference to FIG. **10B**, the analog drive circuit **214** of the exemplary pixel **212** in the pixel array **202** has a sample input, odd-frame and even-frame row select inputs, a ramp input, odd and even sample select inputs, and a comparator sense control input. The analog drive circuit delivers a drive signal to the pixel electrode **218** that overlays it. The remaining pixels constituting the pixel array are similar. The sample inputs of all the pixels in each column of the pixel array are connected to a respective column bus which is connected a respective output of the sampling circuit **132**. For example, the sample inputs of the pixels in the first column of the pixel array are connected to the column bus **131<sub>1</sub>**. The location in each line of the video signal from which the analog sample received by each column of pixels is derived depends on the row position of the column in the pixel array **202**.

The odd-frame row select inputs of all the pixels in each row of the pixel array **202** are connected to a respective odd-frame row select bus, and the even/frame row select inputs of all the pixels in each row of the pixel array are connected to a respective even-frame row select bus. For example, the odd-frame row select inputs of the pixels in the second row of the pixel array in which the pixel **212** is located are connected to the odd-frame row select bus **133O<sub>2</sub>** and the even-frame row select inputs of the pixels in the second row are connected to the even-frame row select bus **133E<sub>2</sub>**.

The odd- and even-frame row select busses are connected to respective outputs of the odd/even frame selector **235**. The odd/even frame selector has one input and two outputs corresponding to each row of the pixel array **202**. A row select bus connects each output of the row selector **134** to a corresponding input of the odd/even frame selector. For example, the row select bus **133<sub>2</sub>** connects the second output of the row selector to the input of the odd/even frame selector corresponding to the outputs connected to the odd- and even frame row select busses **133O<sub>2</sub>** and **133E<sub>2</sub>**. An analog drive circuit can accept an analog sample of the video signal present at its sample input only when one of its row select inputs is the 1 state, for example. At the beginning of each frame of the video signal, the row selector **134** sets the row select bus **133<sub>1</sub>** to the 1 state and sets the remaining row select busses to the 0 state. Consequently, when the analog samples of the first line of each frame of the video signal are received, these analog samples can be received by the pixels in the first row.

The odd/even frame selector **235** is composed of a pair of two-input gates for each row of pixels. The output of one of the gates constituting each pair is connected to the odd-frame select bus **133O<sub>n</sub>** of the row and the output of the other of the gates is connected to the even-frame select bus **133E<sub>n</sub>** of the row, where n is the row number. A first input of each of the gates constituting the pair is connected to the row select bus **133<sub>n</sub>** corresponding to the row of pixels. The second input of one of the gates is connected to the odd-frame control signal received via the odd-frame control bus **237**. The other input of the other of the gates is connected to the even-frame control signal received via the even-frame control bus **239**. The odd-frame and even-frame control signals are generated by the clock generator **242**. The odd-frame control signal is in the 1 state, for example, during odd-numbered frames of the video signal, and is in the 0 state during even-numbered frames. The even-frame control signal is the inverse of the odd-frame control signal.

With the arrangement just described, the odd/even frame selector **235** maintains in the 0 state the odd- and even-frame row select busses of all rows except the row whose row select input is in the 1 state. The states of odd-frame row select bus and the even-frame row select bus of the row whose row select input is in the 1 state follow the state of the odd-frame control signal and the even-frame control signal, respectively. In other words, the odd-frame row select bus is in the 1 state only when the odd-frame control signal is in the 1 state, and the even-frame row select bus is in the 1 state only when the even-frame control signal is in the 1 state. This enables analog samples of the video signal to be fed to the analog drive circuits in a similar way to that described above with reference to FIG. **4B**. However, the odd- and even-frame row select busses cause analog samples of odd frames and even frames of the video signal to be stored in the odd-frame and even-frame sample selection sections, respectively, of the analog drive circuit.

The analog drive circuit **214** will now be described with reference to FIG. **10B**. The analog drive circuit **214** is the analog drive circuit of the exemplary pixel **212** shown in FIG. **10A**. The analog drive circuit can be regarded as being composed of the odd-frame **226O** sample selection section, the even-frame sample selection section **226E** and the drive signal generator **228**. Both sample selection sections are composed of identical circuits whose operations are time multiplexed to maximize the illumination efficiency of the spatial light modulator **100**. One of these duplicate circuits receives an analog sample of the current frame of the video signal at the same time as the drive signal generator generates a drive signal in response to an analog sample of the previous frame stored in the other.

The odd-frame sample selection section **226O** selects an analog sample derived from each odd frame of the video signal and stores the selected analog sample in an odd-frame sample storage capacitor, and the even-frame sample selection section **226E** selects an analog sample derived from each even frame and stores this analog sample in an even-frame storage capacitor. The analog samples stored in the storage capacitors are alternately selected and fed to the drive signal generator **228** which generates a drive signal in response to each analog sample. The drive signal generator sequentially generates drive signals in response to the analog samples derived from consecutive frames of the video signal. Each drive signal generated by the drive signal generator additionally restores the DC balance of the pixel **212**.

The odd-frame sample selection section **226O** of the analog drive circuit **214** of the exemplary pixel **212** will now be described. The even-frame sample selection section **226E** is almost identical and will not be described. Corresponding elements of the odd-frame sample selection section and the even-frame sample selection section are indicated by the same reference numerals with the letters O and E, respectively, added.

The sample input **250** of the analog drive circuit **214** is connected to the column bus **131<sub>2</sub>**. Also connected to the sample input is the drain of the sample select transistor **252O**, the gate of which is connected via the odd row select input **210O** to the odd-frame row select bus **133O<sub>2</sub>**. The source of the sample select transistor is connected to one electrode of the sample storage capacitor **254O**. The other electrode of the sample storage capacitor is connected to a constant voltage level, e.g., ground.

The node between the sample storage capacitor **254O** and the source of the sample select transistor **252O** is also

connected to the source of the sample output transistor **256O**. The drain of the sample output transistor is connected to the B input of the comparator **255**. The gate of the sample output transistor is connected to the control signal EVEN generated by the clock generator **242** and distributed by the even control bus **239** to the gates of the sample output transistors of the odd-frame sections of the analog drive circuits of all the pixels constituting the pixel array **202**. The sample output transistor **256O** is operated by the control signal EVEN because the odd-frame sample selection section **226O** feeds stored analog samples to the drive signal section **228** at the same time as the even-frame sample section and storage section **226E** receives an analog sample from the sample input **250**. For a similar reason, the sample output transistor **256E** of the even-frame sample selection section **226E** is controlled by the control signal ODD distributed by the odd control bus **237**.

The control signal EVEN is also connected to the gate of the ramp signal selector transistor **257O**. The source of the ramp signal selector transistor is connected to the ramp signal RAMP generated by the ramp generator **244** (FIG. **10A**) and distributed by the ramp signal bus **213** to the ramp signal selector transistors of the analog drive circuits of all the pixels constituting the pixel array **202**. The drain of the ramp signal selector transistor **257O** is connected to the A input of the comparator **255**.

The even-frame sample selection section **226E** differs from the odd-frame sample selection section **226O** only in that the drain of the sample output transistor **256E** is connected to the A input of the comparator **255**, the drain of the ramp signal selector transistor **257E** is connected to the B input of the comparator, and the gates of the transistors **256E** and **257E** are connected to the ODD control signal. With this arrangement, analog samples derived from the even fields of the video signal and stored in the sample storage capacitor **254E** are fed to the A input of the comparator and the ramp signal is fed to the B input, whereas analog samples derived from the odd frames and stored in the sample storage capacitor **254O** are fed to the B input of the comparator and the ramp signal is fed to the A input.

The drive signal generator **228** will now be described. The drive signal generator includes the comparator **255**. The comparator **255** is a switched-sense comparator that has detection sense that depends on the state of the comparator sense control signal SENSE generated by the clock generator **242** and distributed by the comparator sense bus **260** to the comparators of all the pixels constituting the pixel array **202**. The comparator sense control signal serves two functions. First, the comparator sense control signal inverts the detection sense of the comparator in the illumination periods of successive frames. This provides the comparator with a constant detection sense with respect to the ramp signal and the analog samples despite the alternation of the connections of the ramp signal and the analog samples to the A and B inputs of the comparator. For odd-frame analog samples, the detection sense of the comparator is conventional, and the output of the comparator in a 1 state or a 0 state, depending on whether the voltage on the A input is greater than, or less than, the voltage on the B input. For even-frame analog samples, the detection sense is inverted and the output of the comparator in a 1 state or a 0 state, depending on whether the voltage on the B input is greater than, or less than, the voltage on the A input. Second, the comparator sense control signal inverts the detection sense of the comparator in the balance period following each illumination period. This enables the comparator to generate the balance portion of the drive signal simply by repeating of the cycle of the ramp signal connected to one of its inputs.

Alternating the inputs of the comparator **255** to which the analog samples and the ramp signal are connected and inverting the detection sense of the comparator reduces the visibility of errors resulting from differences in the input offset voltages of the comparators. The inputs are alternated and the detection sense of the comparator is inverted between consecutive frames. For example, in an odd frame, the input offset may add to the analog sample so that the pixel appears brighter than its nominal brightness. In the following even frame, the input offset adds to the ramp signal, so the pixel appears dimmer than its nominal brightness. The brighter appearance and the dimmer appearance of the pixel average between the two frames, so that the pixel appears at its nominal brightness.

If the input offset voltage of the comparator **255** is small, or the input offset voltages of the comparators of all the analog drive circuits of the pixel array **102** are similar, the analog drive circuit can be simplified. This can be done by eliminating the ramp signal selector transistors **257O** and **257E**, connecting the ramp signal to the A input, for example, of the comparator, and connecting the drains of the sample output transistors **256O** and **256E** to the B input of the comparator. In this case, the waveform of the comparator sense control signal should be changed so that the detection sense of the comparator is normal in the illumination periods and inverted in the balance periods.

The output of the comparator **255** is connected to the pixel electrode **118** by the conductor **120**.

The drive signal generators shown in FIGS. **8** or **15B** may be substituted for the drive signal generator **228** shown in FIG. **10B**.

Operation of the analog drive circuit **214** of the exemplary pixel **212** will now be described with reference to FIGS. **10A**, **10B** and **11A–11O**. The exemplary pixel **212** is located in the second column of the second row of the pixel array **202**. FIGS. **11A–11O** show the waveforms in various parts of the circuit in the course of loading analog samples of three consecutive frames **1**, **2** and **3** of the video signal into the sample selection sections **226O** and **226E** of the circuit, and generating drive signals in response to analog samples of the previous frame **0** and frames **1** and **2**. FIG. **11A** shows the operations sequentially performed by the odd-frame sample and storage section **226O** and the drive signal generator **228** of the analog drive circuit on analog samples of the odd-numbered frames of the video signal. FIG. **11B** shows the operations sequentially performed by the even-frame sample selection storage section **226E** and the drive signal generator **228** on analog samples of the even frames. Frames **1** and **3** are odd frames, and frames **0** and **2** are even frames.

As shown in FIG. **11A**, during the frame **1** sample load period, in which frame **1** is received at the video input **106** (FIG. **10A**), an analog sample of frame **1** is loaded into the odd-frame sample selection section **226O**. The frame **0** display period shown in FIG. **11B** is concurrent with the frame **1** sample load period. During the illumination period of the frame **0** display period, the drive signal generator **228** of the circuit generates a drive signal in response to an analog sample of the previous frame, frame **0**, and the spatial light modulator **100** is illuminated with light generated by the LEDs **69–71**. The drive signal of the LEDs is schematically shown in FIG. **11C**. In the balance period of the frame **0** display period shown in FIG. **11B**, the drive signal generator generates a drive signal that restores the DC balance of the pixel, and the spatial light modulator is not illuminated.

During the frame **2** sample load period shown in FIG. **11B**, in which frame **2** is received at the video input **106**

(FIG. 10A), an analog sample of frame 2 is loaded into the even-frame sample selection section 226E. The frame 1 display period shown in FIG. 11A is concurrent with the frame 2 sample load period. During the illumination period of the frame 1 display period, the drive signal generator 228 generates a drive signal in response to the analog sample of frame 1 stored in the odd sample selection section 226O, and the spatial light modulator 100 is illuminated with light generated by the LEDs 69–71. In the balance period of the frame 1 display period shown in FIG. 11A, the drive signal generator generates a drive signal that restores the DC balance of the pixel, and the spatial light modulator is not illuminated.

Finally, during the frame 3 sample load period shown in FIG. 11A, in which frame 3 is received at the video input 106 (FIG. 10A), an analog sample of frame 3 is loaded into the odd-frame sample selection section 226O. The frame 2 display period shown in FIG. 11B is concurrent with the frame 3 sample load period. During the illumination period of the frame 2 display period, the drive signal generator 228 generates a drive signal in response to the analog sample of frame 2 stored in the even sample selection section 226E, and the spatial light modulator is illuminated with light generated by the LEDs 69–71. In the balance period of the frame 2 display period, the drive signal generator generates a drive signal that restores the DC balance of the pixel, as shown in FIG. 11A, and the spatial light modulator is not illuminated.

FIGS. 11D and 11E show the states of the control signal ODD and the control signal EVEN, respectively. The control signal ODD is in its 1 state during the odd-frame sample load periods, i.e., during the periods that the odd-numbered frames are received at the video input 106, and is in its 0 state during the even-frame sample load periods, i.e., the periods during which the even-numbered frames are received at the video input. The control signals ODD and EVEN are slightly asymmetrical to prevent the transistors controlled by these control signals being ON simultaneously and to prevent charge sharing between the capacitors 254O and 254E as a result.

In the sample load period of each frame of the video signal, an analog sample of the frame is loaded into the analog drive circuit 214 by processes similar to those described above with reference to FIGS. 6A–6R. The analog samples from the odd frames of the video signal are loaded into the odd-frame sample selection section 226O of the analog drive circuit in response to the odd-frame row select signal. FIG. 11F shows the odd-frame row select signal fed via the odd-frame row select bus 133O<sub>2</sub> to the analog drive circuits of the pixels located in the second row of the pixel array 202. The odd-frame row select signal causes the odd-frame sample selection sections of the analog drive circuits of only the pixels located in the second row to accept the analog samples from the column busses 131<sub>1</sub>–131<sub>4</sub>, and corresponds to the row select signal shown in FIG. 6B. However, as can be seen in FIG. 11F, the odd-frame row select signal is only asserted during the sample load periods of the odd frames of the video signal. FIG. 11G shows the even-frame row select signal fed via the even-frame row select bus 133E<sub>2</sub> to the analog drive circuits of the pixels located in the second row of the pixel array 202. The waveform of the even-frame row select signal is the same as that of the odd-frame row select signal shown in FIG. 11F, delayed by one frame period.

Each of the row select control signals is shown in FIGS. 11F and 11G as being in its 1 state for the duration of one line of the video signal, and is in its 0 state until the

corresponding line of the next odd or even frame. However, the row select control signals may switch to their 1 states at a time later than the start of their respective lines.

FIG. 11H shows how the voltage on the odd-frame sample storage capacitor 254O of the analog drive circuit 214 changes during the sample load periods of frames 1–3. Initially, the voltage on the sample storage capacitor corresponds to the analog sample of the twice-previous frame (frame –1, an odd frame) of the video signal, as shown at 261. Then, the odd-frame row select signal shown in FIG. 11F is asserted during the second line of frame 1. This signal causes the sample select transistor 252O to connect the sample storage capacitor 254O to the column bus 131<sub>2</sub>. After a delay corresponding to one pixel, the analog sample corresponding to the second pixel of the second line of the frame 1 is fed to the sample storage capacitor. This causes the voltage on the capacitor to change to the level, as indicated at 263 in FIG. 11H. After a delay corresponding to two more pixels, the odd-frame row select signal is de-asserted, which causes the sample select transistor to disconnect the sample storage capacitor from the column bus. The sample storage capacitor continues to hold a voltage corresponding to the analog sample of frame 1 until the odd-frame row select signal shown in FIG. 11H is next asserted during frame 3. Then, the sample storage capacitor accepts an analog sample of frame 3, as shown at 265 in FIG. 11H.

During the even frame sample load periods, the even-frame row select signal fed via the even-frame row select bus 133E<sub>2</sub> to the analog drive circuits of the pixels located in the second row of the pixel array 202 is asserted, as shown in FIG. 11G. The even-frame row select signal causes the even-frame sample selection sections of the analog drive circuits of only the pixels located in the second row of the pixel array to accept analog samples from the column busses 131<sub>1</sub>–131<sub>4</sub>. FIG. 11I shows how the voltage on the sample storage capacitor 254E of the analog drive circuit 214 changes during frames 1–3. Initially, the voltage on the sample storage capacitor corresponds to the analog sample of the previous frame (frame 0, an even frame) of the video signal, as shown at 267. Then, the even-frame row select signal is asserted during the second line of frame 2, as shown in FIG. 11G. This signal causes the sample select transistor 252E to connect the sample storage capacitor 254E to the column bus 131<sub>2</sub>. After a delay corresponding to one pixel, the analog sample corresponding to the second pixel of the second line of frame 2 is fed to the sample storage capacitor. This causes the voltage on the capacitor to change to one corresponding to the analog sample, as indicated at 269 in FIG. 11I. After a delay corresponding to two more pixels, the even-frame row select signal is de-asserted, which causes the sample select transistor 252E to disconnect the sample storage capacitor from the column bus. The sample storage capacitor continues to hold the voltage corresponding to the analog sample through the rest of the sample load periods of frames 2 and 3 until the even-frame row select signal is next asserted in the next even frame 4 (not shown).

FIGS. 11J–11O show how, in each frame period, the drive signal generator 228 generates the drive signal in response to the analog sample of the previous frame loaded into one of the sample selection sections 226O and 226E during the sample load period of the previous frame. FIG. 11J shows the waveform of the ramp signal RAMP. In the example shown, the ramp signal has a sawtooth waveform and has a period equal to one-half of the frame period. A ramp signal with a linear voltage-time characteristic is shown to simplify the drawings, but a non-linear characteristic is preferred. A

non-linear characteristic enables gamma correction to be performed, as discussed above. The ramp signal is shown in FIG. 11J as beginning in a low state and increasing towards a high state. However, this is not critical. The ramp signal may begin in a high state and decrease towards a low state. Moreover, the ramp signal may begin in the low state and increase towards the high state during the illumination period and may then decrease towards the low state in the following balance period, or vice versa.

FIGS. 11K and 11L respectively show the voltage on the A and B inputs of the comparator 255. In addition, broken lines show the waveforms of the portions of the ramp signal fed to the other input of the comparator. At the start of the frame 0 illumination period shown in FIG. 11B, the control signal ODD shown in FIG. 11D changes to its 1 state. This turns the sample output transistor 256E and the ramp signal selector transistor 257E ON. At the same time, the control signal EVEN changes to its 0 state, as shown in FIG. 11E, and turns the sample output transistor 256O and the ramp signal selector transistor 257O OFF. Consequently, the analog sample of the previous frame 0 stored in the sample storage capacitor 254E of the even sample selection section is connected to the A input of the comparator 255, as shown in FIG. 11K. The ramp signal RAMP is connected to the B input of the comparator, as shown in FIG. 11L. The waveform of the ramp signal is also shown as a broken line in FIG. 11K.

Since the level on the A input of the comparator is initially higher than that of the B input, the nominal output of the comparator is a 1, as shown at 271 in FIG. 11M. The comparator sense control signal SENSE shown in FIG. 11N is in its 1 state, so the detection sense of the comparator is normal and the drive signal connected to the pixel electrode 118 is in the 1 state for the duration of the first temporal portion of the illumination period, as shown at 273 in FIG. 11O.

The ramp signal RAMP increases as the frame 0 illumination period progresses. When the ramp signal slightly exceeds the voltage of the sample storage capacitor 254E, the nominal output state of the comparator 255 and, hence, the state of the pixel electrode 118, change from a 1 to a 0. This marks the end of the first temporal portion of the illumination period. The electrode remains in the 0 state for the second temporal portion shown at 275 in FIG. 11O. The second temporal portion constitutes the remainder of the frame 0 illumination period.

At the beginning of the frame 0 balance period shown in FIG. 11B, the level of the ramp signal RAMP shown in FIG. 11J returns to zero, and the nominal output of the comparator 255 shown in FIG. 11M changes state. However, since the comparator sense control signal SENSE also changes state, as shown in FIG. 11N, the actual output of the comparator remains unchanged. Consequently, the state of the pixel electrode remains unchanged during the first temporal portion of the balance period, as shown at 277 in FIG. 11O.

The ramp signal RAMP once more increases as the frame 0 balance period progresses. When the ramp signal slightly exceeds the voltage of the sample storage capacitor 254E, the nominal output state of the comparator 255 changes from 0 to 1. Since the comparator sense control signal remains unchanged, the state of the pixel electrode also changes from 0 to 1. This marks the end of the first temporal portion of the balance period. The electrode remains in this state during the second temporal portion, as shown at 279 in FIG. 11O, constituting the remainder of the balance period. The spatial light modulator is not illuminated during the balance period.

The states of the drive waveform in the first and second temporal portions of the balance period are opposite to those in the first and second temporal portions, respectively, of the illumination period so that the DC balance of the pixel is restored.

At the start of the frame 1 illumination period, the control signal EVEN shown in FIG. 11E changes to its 1 state. This turns the sample output transistor 256O and the ramp signal selector transistor 257O of the odd-frame sample selection section 226O ON. At the same time, the control signal ODD changes to its 0 state, as shown in FIG. 11D, which turns the sample output transistor 256E and the ramp signal selector transistor 257E of the even-frame sample selection section 226E OFF. Consequently, the sample storage capacitor of the odd sample selection section, in which an analog sample of frame 1 was stored during the frame 1 sample load period, as shown in FIG. 11H, is connected to the B input of the comparator 255, as shown in FIG. 11L. The ramp signal RAMP is connected to the A input of the comparator, as shown in FIG. 11K. The waveform of the ramp signal is also shown as a broken line in FIG. 11L.

Since the level on the B input of the comparator 255 is initially higher than that on the A input, the nominal output of the comparator is 0, as shown at 281 in FIG. 11M. The comparator sense control signal SENSE shown in FIG. 11N is in its 0 state, so the detection sense of the comparator is inverted, and the pixel electrode remains in the 1 state during the first temporal portion of the frame 1 illumination period, as shown at 283 in FIG. 11O.

The ramp signal increases as the frame 1 illumination period progresses. When the ramp signal slightly exceeds the voltage stored in the sample storage capacitor 254E, the nominal output of the comparator changes from 0 to 1 and the state of the pixel electrode changes from 1 to 0, as shown at 285 in FIG. 11O. The electrode remains in this state for the second temporal portion constituting the remainder of the frame 1 illumination period during which the spatial light modulator is illuminated (see FIG. 11C).

At the beginning of the frame 1 balance period, the level of the ramp signal RAMP returns to zero, and the nominal output of the comparator 255 shown in FIG. 11M changes from 1 to 0. The comparator sense control signal SENSE also changes from 0 to 1, so the state of the pixel electrode remains unchanged (and opposite to that during the first temporal portion of the frame 1 illumination period) during the first temporal portion of the balance period, as shown at 287 in FIG. 11O.

The ramp signal increases as the frame 1 balance period progresses. When the ramp signal slightly exceeds the voltage stored in the sample storage capacitor 254O, the nominal output of the comparator 255 shown in FIG. 11M changes from 0 to 1. Since the comparator sense control signal remains unchanged, the state of the pixel electrode also changes from 0 to 1, as shown at 289 in FIG. 11O. The pixel electrode remains in this state for the second temporal portion constituting the remainder of the frame 1 balance period. The spatial light modulator is not illuminated during the frame 1 balance period. The states of the drive waveform in the first and second temporal portions of the balance period are opposite to those in the first and second temporal portions, respectively, of the illumination period so that the DC balance of the pixel is restored.

Operation of the analog drive circuit 214 during the frame 2 illumination and balance periods is the same as during the frame 0 illumination and balance periods, respectively, and will therefore not be described. During the frame 2 illumi-



nation period, the analog drive circuit applies a drive signal to the pixel electrode in response to the analog sample of frame 2. This analog sample was stored in the sample storage capacitor 254E during the frame 2 sample load period.

It can be seen from FIGS. 11K and 11L that the first temporal portion of the illumination period, during which the drive signal applied to the electrode 212 is in the 1 state, depends on the level of the analog sample stored in the respective one of the sample storage capacitors during the previous frame. The analog sample of frame 1 has relatively low level whereas the analog sample of frame 2 has a relatively high level. The fraction of the illumination period constituted by the first temporal portions during the frame 1 illumination period and the frame 2 illumination period, respectively, in response to these analog samples depends on the levels of the analog samples.

FIG. 12 shows an example of a circuit that may be used as the switched-sense sense comparator 255 in the analog drive circuit 214 shown in FIG. 10B.

The comparator 255 is composed of the conventional comparator 311, the output of which is fed to one input of the exclusive-OR (XOR) gate 313. The control signal SENSE is distributed from the clock generator 142 to the analog drive circuits of all the pixels via the bus 260. When the control signal SENSE is in its 1 state, the detection sense of the comparator 255 is the same as that of the conventional comparator 311. When the control signal SENSE is in its 0 state, the detection sense of the comparator 255 is the inverse of that of the conventional comparator 311.

In the embodiments of the spatial light modulator described above, the analog samples are distributed to the pixels by the column busses 131<sub>1</sub>–131<sub>4</sub>. In a practical embodiment, the column busses are long and have substantial capacitance and therefore delay the analog samples transmitted along them. Moreover, comparing FIGS. 6D and 6J–6M shows that the control signal on each of the row select busses 133<sub>1</sub>–133<sub>4</sub> is de-asserted almost at the same time as the last analog sample of each line of the video signal is placed on the column bus 131<sub>4</sub>. This, together with the transmission delay on the column busses causes less than the full analog sample to be loaded into the analog drive circuits of the pixels at the right-hand side of the pixel array. The problem is especially severe in the pixels that are remote from the sampling circuit 132, i.e., the pixels in the upper right of the pixel array in the examples shown in FIGS. 4A and 10A. The problem can be overcome using the embodiment 304 of the sample derivation and distribution circuit shown in FIG. 13. The embodiment shown in FIG. 13 is a variation of the embodiment of the sample derivation and distribution circuit shown in FIG. 4A and uses the analog drive circuit shown in FIG. 4B. The embodiments shown in FIGS. 10A, 15A and 16 can be similarly modified.

In the sample derivation and distribution circuit 304 shown in FIG. 13, the row select busses are broken at the center of the pixel array to form two sets of row select busses 133L<sub>1</sub>–133L<sub>4</sub> and 133R<sub>1</sub>–133R<sub>4</sub>. The left-hand row select busses 133L<sub>1</sub>–133L<sub>4</sub> are connected to the row select inputs of the analog drive circuits of the pixels in the left-hand half of the pixel array (columns 1 and 2 in the example shown) and to the output of the left-hand row selector 134L. The right-hand row select busses 133R<sub>1</sub>–133R<sub>4</sub> are connected to the row select inputs of the analog drive circuits of the pixels in the right-hand half of the pixel array (columns 3 and 4 in the example shown) and to the output of the right-hand row selector 134R. The left-hand and right-hand row selectors

are identical to the row selector 134 described above with reference to FIG. 4A, and so will not be described again here. The clock signal LINE, described above with reference to FIG. 4A, is fed to the clock input of the left-hand row selector 134L, and is also fed via the half-line delay 135 to the right-hand row selector 134R.

Operation of the sample derivation and distribution circuit shown in FIG. 13 will now be described with reference to FIGS. 14A–14F. FIGS. 14A–14D respectively show the control signal waveforms on the control lines 139<sub>1</sub>–139<sub>4</sub> connected to the control inputs of the S/H circuits 138<sub>1</sub>–138<sub>4</sub> during the picture period of one frame of the video signal. An analog sample is placed on the respective column bus 131<sub>1</sub>–131<sub>4</sub> at each falling edge of these waveforms.

Operation of left-hand row selector 134L is identical to that of the row selector 134 described above with reference to FIGS. 6J–6M. As shown in FIG. 14E, the control signal on the row select bus 133L, switches to its 1 state at the beginning of the first line of the video signal, and remains in its 1 state until the end of the first line. However, during the second half of the first line, no sampling is performed by the sample-and-hold circuits 138<sub>1</sub> and 138<sub>2</sub> whose outputs are connected via the column busses 131<sub>1</sub> and 131<sub>2</sub> to the analog drive circuits connected to the row select bus 133L<sub>1</sub>. Accordingly, the analog drive circuits in the first row of the pixel array that are connected to the row select bus 133L<sub>1</sub> have a time corresponding to about one-half of the line period to receive their respective analog samples.

Operation of right-hand row selector 134R is similar to that of the row selector 134 described above with reference to FIGS. 6J–6M, but is delayed by one-half of the line period. As shown in FIG. 14F, the control signal on the row select bus 133R<sub>1</sub>, is in its 0 state during the first half of the first line of the video signal, and changes to its 1 state half-way through the first line period. The change in state takes place prior to the sample-and-hold circuits 138<sub>3</sub> and 138<sub>4</sub> feeding any analog samples of the first line of the video signal onto the column busses 131<sub>3</sub> and 131<sub>4</sub>. Consequently, the analog drive circuits in the first row of the pixel array that are connected to the row select bus 133R<sub>1</sub> are able to receive the analog samples of the first line of the video signal when these analog samples are put on the respective column busses.

The row select bus 133R<sub>1</sub> remains in its 1 state for the remainder of the first line of the video signal, and for the first half of the second line of the video signal, as shown in FIG. 14F. During the first half of the second line, no sampling is performed by the sample-and-hold circuits 138<sub>3</sub> and 138<sub>4</sub> whose outputs are connected via the column busses 131<sub>3</sub> and 131<sub>4</sub> to the analog drive circuits connected to the row select bus 133R<sub>1</sub>. Accordingly, the analog drive circuits in the first row of the pixel array that are connected to the row select bus 133R<sub>1</sub> have a time corresponding to about one-half of the line period to receive their respective analog samples.

The row selectors 134L and 134R operate in a manner similar to that described during the remaining lines 2–4 of the frame of the video signal.

In the example shown, the row select busses are broken symmetrically. However, this is not critical: the row select busses may be broken asymmetrically with an appropriate change to the delay of the delay module 135. For example, the circuit may be configured so that the right row selector 134R controls only the analog drive circuits located near the end of each line that would have insufficient time to receive their analog samples if they were controlled by the left row selector 134L.

In the examples shown in FIGS. 14E and 14F, each output of each row selector is in its 1 state for one line period. However, this is not critical. The control signals on the row select busses 133L<sub>1</sub> and 133R<sub>1</sub> are shown in FIGS. 14E and 14F as switching to their 1 states at the beginning and mid-point, respectively, of line 1. However, the row select control signals may switch to their 1 states at a time later than the beginning and mid-point, respectively, of line 1. Moreover, these control signals are shown as reverting to their 0 states at the end of line 1 and the mid-point of line 2, respectively. However, as long as these control signals remain in their 1 for longer than the longest settling time of the analog drive circuits connected to them, they may revert to their 0 states some time before the end of line 1 and the mid-point of line 2, respectively. The setting time of an analog drive circuit is the time required for an analog sample to transfer fully to the analog drive circuit from the sample-and-hold circuit to which the analog drive circuit is connected.

An example of a color display device based on the embodiment shown in FIGS. 4A and 4B is shown in FIGS. 15A and 15B in which elements corresponding to those in FIGS. 4A and 4B are indicated by the same reference numerals. In the embodiment shown in FIGS. 15A and 15B, the sample selection section 326 of the exemplary analog drive circuit 314 includes three sample storage capacitors 154R, 154G and 154B, one for each color component of the color video signal. The parallel sample derivation and distribution circuit 404 includes three sampling circuits 132R, 132G and 132B, one for each color component of the color video signal. The sampling circuits each take analog samples from one color component of the color video signal and distribute the analog samples to the respective sample storage capacitors through one of three color component-specific column busses for each column in the pixel array 102. The column color component-specific column busses for the first column of the pixel array are 131R<sub>1</sub>, 131G<sub>1</sub> and 131B<sub>1</sub>, for example.

In the drive signal generator 328 of the analog drive circuit 314 shown in FIG. 15B, the sample output transistors 156R, 156G and 156B operate in response to the sequentially-supplied select control signals RSEL, GSEL and BSEL, respectively, to sequentially connect the analog sample stored in the sample storage capacitors 154R, 154G and 154B to the ramp capacitor 160 and the inverter 166. For each frame of the color video signal, the drive signal generator generates three drive signals, one in response to each of the three analog samples. During the illumination period of each of the drive signals, one of the LEDs 69-71 illuminates the spatial light modulator with light of a different color corresponding to the color component from which the analog sample was derived. During the balance period of each of the drive signals, the DC balance of the pixel is restored. In this embodiment, the display period for each color has a duration of one-third of the picture period of one frame of the color video signal.

The drive signal generator 328 shown in FIG. 15B may incorporate the offset correction circuitry shown in FIG. 8.

The preferred embodiment of a color display device uses the parallel sample derivation and distribution circuit 404 shown in FIG. 15A but with the analog drive circuit 414 shown in FIG. 15C. The sample selection section 326 of the analog drive circuit is the same as that of the analog drive circuit 314 shown in FIG. 15B. The drive signal generator 428 of the analog drive circuit 414 incorporates the sample output transistors 156R, 156G and 156B of the drive signal generator 328 shown in FIG. 15B and the input change-over

circuitry and switched-sense comparator 255 of the drive signal generator 228 of the analog drive circuit 214 shown in FIG. 10B. The input change-over circuitry, composed of the transistors 256O, 257O, 256E and 257E and the control signals ODD and EVEN, is disposed between the ramp signal bus 262 and the common node of the sample output transistors 156R, 156G and 156B on one hand and the inputs A and B of the comparator 255 on the other. The sample output transistors operate in response to the sequentially-supplied select control signals RSEL, GSEL and BSEL, respectively, to sequentially connect the analog sample stored in the sample storage capacitors 154R, 154G and 154B to the input of the comparator via the input change-over circuitry.

The input change-over circuitry operates in response to the control signals EVEN and ODD. These control signals change state in antiphase between odd-numbered and even-numbered frames of the video signal. The control signal SENSE changes the detection sense of the comparator to take account of the action of the input change-over circuitry and to invert the sense of the comparator between the illumination period and the balance period of each display period. The input change-over circuitry causes any offset error in the comparator average out in consecutive frames, as described above.

An example of a serial-load sample derivation circuit 504 for use in a color display device based on the embodiment shown in FIGS. 10A and 10B is shown in FIG. 16 in which elements corresponding to the embodiment shown in FIG. 10A are indicated by the same reference numerals. In the embodiment shown in FIG. 16, the analog drive circuits of the pixels is identical to the analog drive circuit 214 shown in FIG. 10B, and will not be described further. In the sample derivation and distribution circuit 504, the RGB sequencer 211 converts the color video signal to a color-sequential video signal in which the three color components of each frame of the color video signal are concatenated as frames of the color-sequential video signal. Depending on the capabilities of the graphics adaptor that generates the color video signal, the RGB sequencer 211 may be simple or more complex.

If the graphics adaptor is capable of generating a color-sequential video signal, the RGB sequencer may be omitted. If the graphics adaptor is a conventional graphics adaptor capable of a frame rate of greater than about 100 Hz, for example, and preferably greater than 180 Hz, the RGB sequencer can be a three-way switch. The switch sequentially selects the red, green and blue color components of consecutive frames of the color video signal as the frames of the color-sequential video signal. The switch selects the red component of a first frame, the green component of the second frame and the blue component of the third frame of the color video signal as the first frame, the second frame and the third frame, respectively, of the color-sequential video signal. The sequence then repeats, i.e., the switch selects the red component of the fourth frame of the color video signal as the fourth frame of the color-sequential video signal.

If the graphics adaptor is not capable of a high frame rate, the RGB sequencer 211 samples each color component of each frame of the color video signal. The samples derived from each color component are temporarily stored, and then are sequentially read out in color component order with a clock speed of three times the original sampling rate. Alternatively, a clock speed equal to the original sampling rate can be used, and two of every three samples not read out. The resulting color-sequential bit stream is then subject

to digital to analog conversion to generate to the color-sequential video signal.

The sampling circuit 132 takes analog samples from the color-sequential video signal at the rate of the rate of the pixel clock generated by the clock generator 242 and feeds the analog samples to the column busses. In a time corresponding to the frame period of the color video signal, each pixel of the pixel array receives a sample derived from each of three consecutive frames of the color-sequential video signal corresponding to the three color components of the frame of the color video signal. After an analog sample of each frame of the color-sequential video signal has been loaded into one of the sample selection sections of the analog drive circuit of each pixel constituting the pixel array 202, the waveform generator of the analog drive circuit generates a drive signal in response to the analog sample. During the illumination period of the display period of the drive signal, one of the LEDs 69-71 illuminates the spatial light modulator with light of a color corresponding to the color component from which the analog sample was derived. In the balance period of the display period, the drive signal restores the DC balance of the pixel. In this embodiment, the display period has a duration equal to the frame period of the color-sequential video signal.

Although the above embodiments have been described with various exemplary logic states, signal states, transistor types and rows and columns, the embodiments can have opposite logic states, signal states, transistor types and rows and columns.

Although this disclosure describes illustrative embodiments of the invention in detail, it is to be understood that the invention is not limited to the precise embodiments described, and that various modifications may be practiced within the scope of the invention defined by the appended claims.

We claim:

1. A display device based on an electro-optical material, the display device operating in response to an information signal, and comprising:

analog drive circuits arranged in a two-dimensional array of rows and columns;

an analog sampling circuit that derives the analog samples from the information signal; and

a sample distribution circuit that receives the analog samples from the analog sampling circuit and distributes the analog samples to the analog drive circuits, the sample distribution circuit including:

input gates corresponding to the drive circuits;

column busses corresponding to the columns of the array through which the analog samples are distributed column-wise to the analog drive circuits, the analog drive circuits being connected to the column busses by the input gates, and

a row selector having outputs corresponding to the rows of the array, each of the outputs being connected to control the input gates in one of the rows, the row selector opening the input gates in the rows sequentially to perform a row-wise selection of the analog samples on the column busses.

2. The display device of claim 1, in which the analog sampling circuit includes:

a sampling circuit comprising a row of sample-and-hold circuits, each of the sample-and-hold circuits corresponding to one of the column busses, each of the sample-and-hold circuits comprising:

an output connected to the one of the column busses,

an input connected to receive the information signal, and

a column control signal input; and

a column selector connected to the column control signal inputs of the sample-and-hold circuits, the column selector generating column control signals for the sample-and-hold circuits at a signal rate related to the information signal, the column control signal for a one of the sample-and-hold circuits being in an opposite state to the column control signals for the remaining ones of the sample-and-hold circuits, the column control signal in the opposite state moving progressively along the row of sample-and-hold circuits at the signal rate.

3. The display device of claim 2, in which:

the information signal is a video signal having a pixel rate and a line rate;

the signal rate of the column control signal generated by the column selector is equal to the pixel rate of the video signal; and

the row selector sequentially opens the input gates in the rows at a rate equal to the line rate of the video signal.

4. The display device of claim 1, in which:

the information signal includes odd-numbered sequences interleaved with even-numbered sequences;

the analog drive circuits include respective odd sections that process ones of the analog samples derived from the odd-numbered sequences and even sections that process ones of the analog samples derived from the even-numbered sequences;

the input gates are odd input gates and connect the odd sections of the analog drive circuits to the column busses;

the sample distribution circuit additionally includes:

even input gates that connect the even sections of the analog drive circuits to the column busses,

an odd-even selector interposed between the row selector and the analog drive circuits and having odd outputs and even outputs, each of the odd outputs and even outputs being connected to control the odd input gates and even input gates, respectively, in one of the rows, the odd input gates being opened when the analog samples on the column busses are derived from the odd-numbered sequences, the even input gates being opened when the analog samples on the column busses are derived from the even-numbered sequences.

5. The display device of claim 4, in which the display device additionally comprises a sequencer that receives a color video signal comprising color components and generates a color-sequential video signal from the color video signal and that provides the color-sequential video signal as the information signal, the color-sequential video signal including the odd-numbered sequences interleaved with the even-numbered sequences, each of the sequences corresponding to a frame of one of the color components of the color video signal.

6. The display device of claim 5, in which the sequencer generates each of the sequences of the color-sequential video signal with a time duration equal to a time duration of the frame of the color video signal.

7. The display device of claim 5, in which the sequencer generates each of the sequences of the color-sequential video signal with a time duration equal to  $1/n$  of a time duration of the frame of the color video signal, where  $n$  is the number of color components in the color video signal.

8. The display device of claim 1, in which:  
the information signal is a color video signal comprising  
n color components;

the analog sampling circuit includes a sampling circuit  
corresponding to each of the color components, each  
sampling circuit receiving one of the color components  
and deriving ones of the analog samples therefrom;

the sample distribution circuit includes:

in each of the analog drive circuits, an input gate  
corresponding to each one of the color components;  
for each of the columns of the array, a column bus  
corresponding to each one of the color components  
through which the analog samples derived from the  
one of the color components are distributed column-  
wise to the analog drive circuits, the analog drive  
circuits being connected to the column busses cor-  
responding to the one of the color components by the  
input gates corresponding to the one of the color  
components, and each of the outputs of the row  
selector is connected to control the input gates in the  
respective one of the rows.

9. The display device of claim 8, in which:

the color video signal includes odd-numbered frames  
interleaved with even-numbered frames;

the analog drive circuits include respective odd sections  
that process ones of the analog samples derived from  
the odd-numbered frames and even sections that pro-  
cess ones of the analog samples derived from the  
even-numbered frames;

the input gates are odd input gates and connect the odd  
sections of the drive circuits to the column busses;

the sample distribution circuit additionally includes:

even input gates that connect the even sections of the  
analog drive circuits to the column busses,  
an odd-even selector circuit interposed between the row  
selector circuit and the drive circuits and having odd  
outputs and even outputs, each of the odd outputs  
and even outputs being connected to control the odd  
input gates and even input gates, respectively, in one  
of the rows, the odd input gates being opened when  
the analog samples on the column busses are derived  
from the odd-numbered frames, the even input gates  
being opened when the analog samples on the col-  
umn busses are derived from the even-numbered  
frames.

10. The display device of claim 1, in which:

the row selector is a first row selector, each of the outputs  
of the first row selector being connected to control a  
first sequence of the input gates in one of the rows of  
the array; and

the sample distribution circuit additionally comprises a  
second row selector having outputs corresponding to  
ones of the rows of the array, each of the outputs being  
connected to control the input gates of a second  
sequence of the input gates in the one of the rows of the  
array, the second row selector and the first row selector  
collectively performing the row-wise selection of the  
analog samples on the column busses.

11. The display device of claim 10, in which:

the first row selector opens the first sequence of the input  
gates for an opening time that extends beyond a settling  
time of the analog samples on the column busses  
connected to the first sequence of the input gates; and  
the second row selector opens the second sequence of the  
input gates for an opening time that extends beyond a

settling time of the analog samples on the column  
busses connected to the second sequence of the input  
gates.

12. The display device of claim 10, in which the first row  
selector and the second row selector operate at a predeter-  
mined timing difference.

13. The display device of claim 1, in which:

the information signal is a video signal composed of lines  
and frames; and

the location in each of the lines of the video signal from  
which the analog sampling circuit derives the analog  
samples that the sample distribution circuit distributes  
to each one of the column busses depends on the  
location of the one of the column busses in the array.

14. A display device based on an electro-optical material,  
the display device operating in response to an information  
signal, the display device comprising:

an array of pixels, each of the pixels including:

an electrode electrically coupled to the electro-optical  
material, and  
an analog drive circuit including an output electrically  
connected to the electrode; and

a sample distribution circuit that distributes an analog  
sample derived from the information signal to the  
analog drive circuit of each of the pixels, in which:

the analog drive circuit generates a drive signal composed  
of a sequence of a first temporal portion and a second  
temporal portion, the first temporal portion having a  
time duration that has a predetermined relationship to  
the analog sample, the second temporal portion being a  
temporal complement of the first temporal portion; and  
is the display device additionally comprises a light  
source that illuminates the electro-optical material  
simultaneously with the analog drive circuit generating  
the drive signal.

15. The display device of claim 14, in which:

the information signal is composed of odd-numbered  
sequences interleaved with even-numbered sequences;  
and

the analog drive circuit includes:

an odd sample selection section that temporarily stores  
the analog sample taken from each of the odd-  
numbered sequences,

an even sample selection section that temporarily stores  
the analog sample taken from each of the even-  
numbered sequences, and

a drive signal generator that, during the even-numbered  
sequences, generates the drive signal in response to  
the analog sample stored in the odd sample selection  
section, and, during the odd-numbered sequences,  
generates the drive signal in response to the analog  
sample stored in the even sample selection section.

16. The display device of claim 14, in which the analog  
drive circuit includes:

a sample selection section that stores the analog sample  
received from the sample distribution circuit; and

a drive signal generator that generates the drive signal in  
response to the analog sample stored in the sample  
selection section.

17. The display device of claim 14, in which:

the sequence of the first temporal portion and the second  
temporal portion is a first sequence of the first temporal  
portion and the second temporal portion;

the analog drive circuit generates the drive signal in a first  
electrical state during the first temporal portion and in

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a second electrical state during the second temporal portion, and generates the drive signal additionally composed of a second sequence of the first temporal portion, in which the drive signal is in the second electrical state, and the second temporal portion, in which the drive signal is in the first electrical state, the first temporal portion and the second temporal portion being in any order in the second sequence; and

the light source illuminates the electro-optical material during the first sequence.

18. The display device of claim 14, in which:  
 the information signal is a color video signal comprising n color components;  
 the sample distribution circuit includes:  
 a sampling circuit corresponding to each one of the color components, the sampling circuit receiving the one of the color components and deriving ones of the analog samples therefrom,  
 for each of the columns of the array, a column bus corresponding to each one of the color components, the column bus being connected to the sampling circuit corresponding to the one of the color components  
 in the analog drive circuit of each of the pixels, an input gate and sample storage section corresponding to each one of the color components, the input gate corresponding to the one of the colors being connected to the column bus corresponding to the one of the colors; and  
 a row selector having outputs corresponding to the rows of the array, each of the outputs being connected to control the input gates of the analog drive circuits in one of the rows, the row selector opening the input gates in the rows sequentially to perform a row-wise selection of the analog samples on the column busses; and  
 the analog drive circuit of each of the pixels includes:  
 a sample storage section corresponding to each one of the color components, the sample storage section corresponding to the one of the color components storing one of the analog samples received from the sample

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distribution circuit, the one of the analog samples being derived from the one of the color components, and  
 a drive signal generator that generates the drive signal in response to the analog sample of each one of the color components stored in the sample selection section corresponding to the one of the color components, the drive signal including n first temporal portions each having a duration that has a predetermined relationship to the analog sample of a different one of the color components, and additionally including n second temporal portions, each of the second temporal portions being temporally complementary to a different one of the first temporal portions.

19. The display device of claim 18, in which the light source illuminates the electro-optical material with light of a color corresponding to the color component in response to which the drive signal generates the drive signal.

20. The display device of claim 18, in which:  
 the color video signal comprises frames;  
 the drive signal generator includes an error factor that changes the predetermined relationship between the duration of the first temporal portion and the analog sample, the error factor having a sense; and  
 the drive signal generator additionally includes means for alternating the sense of the error factor between consecutive frames of the color video signal.

21. The display device of claim 20, in which the drive signal generator includes:  
 an comparator including a first input and a second input and having an invertable comparison sense;  
 a reference signal;  
 means for connecting the analog sample alternately to the first input and the second input and for connecting the reference signal alternately to the second input and the first input during alternate frames of the color video signal; and  
 means for inverting the comparison sense of the comparator during alternate frames of the color video signal.

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