(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(19) World Intellectual Property Organization
International Bureau

(43) International Publication Date
23 February 2012 (23.02.2012)

PCT

(10) International Publication Number
WO 2012/024238 A1

(51) International Patent Classification:
G09G 3/34 (2006.01) ***G02B 26/00*** (2006.01)

(21) International Application Number:
PCT/US2011/047790

(22) International Filing Date:
15 August 2011 (15.08.2011)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:
61/374,569 17 August 2010 (17.08.2010) US

(71) Applicant *(for all designated States except US)*: **QUALCOMM MEMS TECHNOLOGIES, INC.** [US/US]; 5775 Morehouse Drive, San Diego, CA 92121 (US).

(72) Inventors; and
(75) Inventors/Applicants *(for US only)*: **HONG, John, H.** [US/US]; 5775 Morehouse Drive, San Diego, CA 92121 (US). **LEE, Chong, U.** [US/US]; 5775 Morehouse Drive, San Diego, CA 92121 (US).

(74) Agent: ABUMERI, Mark, M.; Knobbe Martens Olson & Bear LLP, 2040 Main Street, Fourteenth Floor, Irvine, CA 92614 (US).

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

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

Published:

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

— *before the expiration of the time limit for amending the claims and to be republished in the event of receipt of amendments (Rule 48.2(h))*

(54) Title: ACTUATION AND CALIBRATION OF A CHARGE NEUTRAL ELECTRODE IN AN INTERFEROMETRIC DISPLAY DEVICE

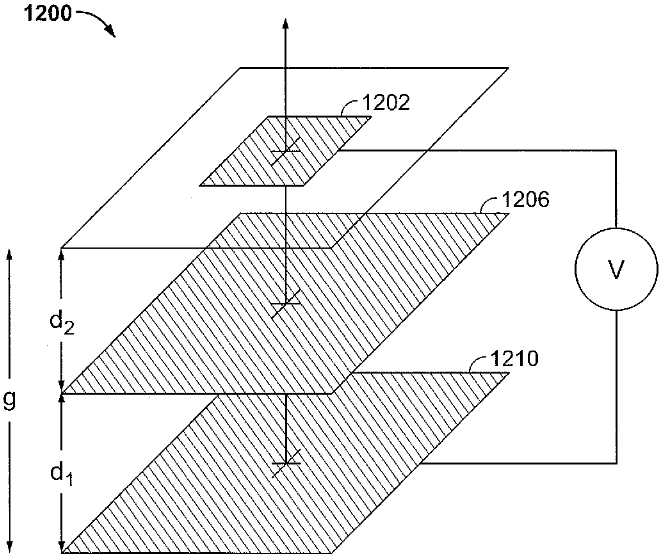


Figure 12

(57) Abstract: This disclosure provides systems, methods, and devices for actuating, charging and calibrating the charge on a movable electrode in interferometric devices. The interferometric device can include a first electrode (1002), a second electrode (1010) spaced apart from the first electrode by a gap, a complementary electrode, at least one electrical contact (2132), and a movable third electrode (1006) disposed between the first electrode and the second electrode. In one implementation, a method of calibrating charge on the movable electrode of the EMS device includes electrically connecting a complementary electrode to the first electrode to form a compound electrode and applying a calibration voltage across the compound electrode and the second electrode to produce a uniform electric field in the gap. Under the electric field the third electrode moves towards the first electrode until it connects with the at least one electrical contact. Once in contact with the electrical contact, an electrical charge on the third electrode can be changed and calibrated when the third electrode is in a second position. When a mechanical restorative force on the third electrode exceeds the electric force of the uniform electric field on the third electrode, the third electrode then moves to a third position.

WO 2012/024238 A1

ACTUATION AND CALIBRATION OF A CHARGE NEUTRAL ELECTRODE IN AN INTERFEROMETRIC DISPLAY DEVICE

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This disclosure claims priority to U.S. Provisional Patent Application No. 61/374,569, filed August 17, 2010, entitled “ELECTROSTATIC ACTUATION AND CALIBRATION OF CHARGE NEUTRAL ELECTRODE,” and assigned to the assignee hereof. The disclosure of the prior application is considered part of, and is incorporated by reference in, this disclosure.

TECHNICAL FIELD

[0002] This disclosure relates to actuation of electrodes in electromechanical systems.

DESCRIPTION OF THE RELATED TECHNOLOGY

[0003] Electromechanical systems (EMS) include devices having electrical and mechanical elements, actuators, transducers, sensors, optical components (e.g., mirrors) and electronics. Electromechanical systems can be manufactured at a variety of scales including, but not limited to, microscales and nanoscales. For example, microelectromechanical systems (MEMS) devices can include structures having sizes ranging from about a micron to hundreds of microns or more. Nanoelectromechanical systems (NEMS) devices can include structures having sizes smaller than a micron including, for example, sizes smaller than several hundred nanometers. Electromechanical elements may be created using deposition, etching, lithography, and/or other micromachining processes that etch away parts of substrates and/or deposited material layers, or that add layers to form electrical and electromechanical devices.

[0004] One type of electromechanical systems device is called an interferometric modulator (IMOD). As used herein, the term interferometric modulator or interferometric light modulator refers to a device that selectively absorbs and/or reflects light using the principles of optical interference. In some implementations, an interferometric modulator may include a pair of conductive plates, one or both of which may be transparent and/or reflective, wholly or in part, and capable of relative motion upon application of an appropriate electrical signal. In an implementation, one plate may include a stationary layer deposited on a substrate and the other plate may include a reflective membrane separated from the stationary layer by an air gap. The position of one plate in relation to another can change the optical interference of light incident on the interferometric modulator. Interferometric modulator devices have a wide range of applications, and are anticipated to be used in improving existing products and creating new products, especially those with display capabilities.

[0005] Some interferometric modulators include bi-stable display elements having two states: a relaxed state and an actuated state. In contrast, analog interferometric modulators can reflect a range of colors. For example, in one implementation of an analog interferometric modulator, a single interferometric modulator can reflect a red color, a green color, a blue color, a black color, and a white color. In some implementations, an analog modulator can reflect any color within a given range of wavelengths.

SUMMARY

[0006] The systems, methods and devices of the disclosure each have several innovative aspects, no single one of which is solely responsible for the desirable attributes disclosed herein.

[0007] One innovative aspect of the subject matter described in this disclosure can be implemented in a device for modulating light that includes a display element. The display element includes a first electrode and a second electrode spaced apart from the first electrode by a gap. The display element also includes a movable third electrode disposed between the first electrode and the second electrode and at least one electrical contact. The first electrode and the second electrode are configured to produce an electric field therebetween capable of moving the movable third electrode when the movable third electrode is electrically isolated and charge neutral when a voltage is applied across the first electrode and the second electrode. The third electrode is configured to move within the gap between an electrically isolated first position, an electrically connected second position, and an electrically isolated third position. The third electrode is in electrical communication with the at least one electrical contact at the electrically connected second position. The electrical contact is configured to change an electrical charge on the third electrode when the third electrode is in the electrically connected second position. The third electrode is also configured to move to the third position after the electrical charge on the third electrode has been changed.

[0008] Another implementation is a device for modulating light including a display element. The device includes means for producing a non-uniform electric field. The device also includes a movable electrode disposed between a first electrode and a second electrode forming a gap therebetween, the movable electrode being configured to move within the gap between an electrically isolated first position, a second position, and an electrically isolated third position. The device also includes means for changing an electrical charge on the movable electrode when the movable electrode is in the second position.

[0009] Yet another implementation includes a method of actuating a device for modulating light. The method includes applying a charging actuation voltage across a first electrode and a second electrode to produce an electric field in a gap between the first electrode and second electrode in order to move an electrically isolated, charge-neutral third electrode, positioned in the gap, towards the first electrode from a first position to a second position. The method also includes electrically connecting the third electrode with an electrical contact when the third electrode is in the second position. The method further includes changing an electrical charge on the third electrode when the third electrode is in the second position until a mechanical restorative force on the third electrode exceeds an electric force of the electric field on the third electrode.

[0010] Another implementation is a method of calibrating an analog interferometric modulator in a display. The method includes applying a calibration voltage across a first electrode and a second electrode to produce an electric field in a gap between the first electrode and the second electrode to move a third electrode, positioned in the gap, towards the first electrode from an electrically isolated first position to an electrically connected second position, the third electrode being subject to a mechanical restorative force. The method further includes electrically connecting the third electrode to one or more conductive posts electrically connected to the first electrode, to change an electric charge on the third electrode when the third electrode is in the second position, until a mechanical restorative force on the third electrode exceeds an electric field force on the third electrode such that the third electrode moves to an electrically isolated third position, the third position being farther away from the first electrode than the second position. In some implementations, the first electrode includes an upper electrode and a complementary electrode aligned laterally relative to the upper electrode and the method also includes electrically connecting the complementary electrode to the upper electrode to form a compound electrode. The calibration voltage can then be applied across the compound electrode and the second electrode.

[0011] Yet another implementation is device for modulating light that includes a display element. The display element includes a first electrode and a second electrode spaced apart from the first electrode by a gap, the first electrode and the second electrode configured to produce a non-uniform electric field therebetween when an actuation voltage is applied across the first electrode and the second electrode during an actuation procedure. The display element further includes a complementary electrode aligned laterally relative to the first electrode, the complementary electrode configured to be electrically isolated from the first electrode during the actuation procedure and electrically connected to the first electrode to form a compound electrode during a calibration procedure, the compound electrode and the second electrode configured to produce a uniform electric field therebetween when a calibration voltage is applied across the compound electrode and the second electrode during the calibration procedure. The display element also includes at least one electrical contact disposed on the complementary electrode and a movable third electrode disposed between the first electrode and the second electrode, the third electrode being configured to move within the gap between an electrically isolated first position, a second position in electrical communication with the at least one electrical contact, and an electrically isolated third position. The electrical contact is configured to change an electrical charge on the third electrode when the third electrode is in the second position, and the third electrode is configured to move to the third position after the electrical charge on the third electrode has been changed.

[0012] Still a further implementation includes a device for modulating light that includes a display element. The display element includes means for producing a non-uniform electric field and means for producing a uniform electric field. The display element further includes a movable electrode disposed between a first electrode and a second electrode forming a gap therebetween, the movable electrode being configured to move within the gap between an electrically isolated first position, a second position, and an electrically isolated third position. The display element also includes means for changing an electrical charge on the movable electrode when the movable electrode is in the second position. In some implementations, the means for producing a non-uniform electric field includes the first electrode and the second electrode. The first electrode and the second electrode have different surface areas. In some implementations, the means for producing a uniform electric field includes the first electrode and the second electrode, where the first electrode includes an upper electrode electrically connected to a complementary electrode aligned laterally relative to the upper electrode.

[0013] Details of one or more implementations of the subject matter described in this specification are set forth in the accompanying drawings and the description below. Other features, aspects, and advantages will become apparent from the description, the drawings, and the claims. Note that the relative dimensions of the following figures may not be drawn to scale.

BRIEF DESCRIPTION OF THE DRAWINGS

[0014] Figure 1 shows an example of an isometric view depicting two adjacent pixels in a series of pixels of an interferometric modulator (IMOD) display device.

[0015] Figure 2 shows an example of a system block diagram illustrating an electronic device incorporating a 3x3 interferometric modulator display.

[0016] Figure 3 shows an example of a diagram illustrating movable reflective layer position versus applied voltage for the interferometric modulator of Figure 1.

[0017] Figure 4 shows an example of a table illustrating various states of an interferometric modulator when various common and segment voltages are applied.

[0018] Figure 5A shows an example of a diagram illustrating a frame of display data in the 3x3 interferometric modulator display of Figure 2.

[0019] Figure 5B shows an example of a timing diagram for common and segment signals that may be used to write the frame of display data illustrated in Figure 5A.

[0020] Figure 6A shows an example of a partial cross-section of the interferometric modulator display of Figure 1.

[0021] Figures 6B–6E show examples of cross-sections of varying implementations of interferometric modulators.

[0022] Figure 7 shows an example of a flow diagram illustrating a manufacturing process for an interferometric modulator.

[0023] Figures 8A–8E show examples of cross-sectional schematic illustrations of various stages in a method of making an interferometric modulator.

[0024] Figure 9 shows an example of a flowchart illustrating one method for actuating and calibrating a charge neutral electrode of an analog interferometric modulator.

[0025] Figure 10 shows an example of a cross-section of an interferometric modulator having a three layer or electrode design.

[0026] Figure 11A shows an example of a cross-section of another analog interferometric modulator with a control circuit.

[0027] Figure 11B shows an example of a schematic of charge pump circuitry to place a charge on an electrode of an interferometric modulator.

[0028] Figure 12 shows an example of a perspective view of an analog interferometric modulator which includes a middle electrode that can be moved between two charged electrodes.

[0029] Figure 13 shows an example of an equivalent circuit of the analog interferometric modulator shown in Figure 12.

[0030] Figure 14 shows an example of a graph illustrating how the net upward electric force acting on the middle electrode of the analog interferometric modulator of Figure 12 varies with the distance between an upper electrode and the middle electrode.

[0031] Figure 15A shows an example of a cross-sectional schematic of an analog interferometric modulator which includes a middle electrode that can be moved between two charged electrodes.

[0032] Figure 15B shows an example of the analog interferometric modulator of Figure 15A after a compound electrode has been formed.

[0033] Figure 16 shows an example of a schematic characterizing the analog interferometric modulator configuration shown in Figure 15A as an equivalent circuit.

[0034] Figure 17 shows an example of a graph illustrating the magnitude of the net upward force acting on the middle electrodes in the analog interferometric modulators of Figures 12 and 15A.

[0035] Figure 18 shows an example of a plan view of a complementary electrode and an upper electrode shown in Figure 15A.

[0036] Figure 19 shows an example of a plan view of another electrode configuration.

[0037] Figure 20 shows an example of a plan view of yet another electrode configuration.

[0038] Figure 21 shows an example of a cross-section of yet another analog interferometric modulator which includes a middle electrode that can be moved between two charged electrodes.

[0039] Figure 22 shows an example of a flowchart illustrating one method for providing charge onto the middle electrode of the analog interferometric modulator of Figure 21.

[0040] Figure 23 shows an example of a cross-section of the analog interferometric modulator of Figure 21 illustrating the middle electrode in a second position.

[0041] Figure 24 shows an example of a cross-sectional schematic of still a further analog interferometric modulator which includes a middle electrode that can be moved between two charged electrodes.

[0042] Figure 25 shows an example of a cross-sectional schematic of the analog interferometric modulator of Figure 24 illustrating the middle electrode in a second position.

[0043] Figure 26 shows an example of a cross-sectional schematic of an analog interferometric modulator which includes a middle electrode that can be calibrated.

[0044] Figure 27 shows an example of a cross-sectional schematic of the analog interferometric modulator of Figure 26 illustrating the middle electrode in a first position.

[0045] Figure 28 shows an example of a cross-sectional schematic of the analog interferometric modulator of Figure 26 after the middle electrode is actuated toward a second position.

[0046] Figure 29 shows an example of a cross-sectional schematic of the analog interferometric modulator of Figure 26 illustrating the middle electrode in the second position.

[0047] Figure 30 shows an example of a cross-sectional schematic of the analog interferometric modulator of Figure 26 illustrating the middle electrode in a third position.

[0048] Figure 31 shows an example of a flowchart illustrating one method for calibrating charge on the middle electrode of the analog interferometric modulator of Figure 26.

[0049] Figure 32 shows an example of a cross-sectional schematic of the analog interferometric modulator of Figure 26 illustrating the middle electrode in the second position during a calibration procedure.

[0050] Figure 33 shows an example of a cross-sectional schematic of the analog interferometric modulator of Figure 26 illustrating the middle electrode in the third position following a calibration procedure.

[0051] Figure 33A shows an example of a cross-sectional schematic of an analog interferometric modulator having a middle electrode with a calibrated charge that is related to the stiffness of springs supporting the middle electrode.

[0052] Figure 34 shows an example of a cross-sectional schematic of yet another analog interferometric modulator which includes a middle electrode that can be calibrated.

[0053] Figure 35 shows an example of a cross-sectional schematic of the analog interferometric modulator of Figure 34 illustrating the middle electrode in a first position.

[0054] Figure 36 shows an example of a cross-sectional schematic of the analog interferometric modulator of Figure 34 after the middle electrode is actuated toward a second position.

[0055] Figure 37 shows an example of a cross-sectional schematic of the analog interferometric modulator of Figure 34 illustrating the middle electrode in the second position.

[0056] Figure 38 shows an example of a cross-sectional schematic of the analog interferometric modulator of Figure 34 illustrating the middle electrode in a third position.

[0057] Figure 39 shows an example of a flowchart illustrating one method of calibrating charge on the middle electrode of the analog interferometric modulator of Figure 34.

[0058] Figure 40 shows an example of a cross-sectional schematic of the analog interferometric modulator of Figure 34 illustrating the middle electrode in the second position during a calibration procedure.

[0059] Figure 41 shows an example of a cross-sectional schematic of the analog interferometric modulator of Figure 34 illustrating the middle electrode in the third position following a calibration procedure.

[0060] Figures 42A and 42B show examples of system block diagrams illustrating a display device that includes a plurality of interferometric modulators.

[0061] Like reference numbers and designations in the various drawings indicate like elements.

DETAILED DESCRIPTION

[0062] The following detailed description is directed to certain implementations for the purposes of describing the innovative aspects. However, the teachings herein can be applied in a multitude of different ways. The described implementations may be implemented in any device that is configured to display an image, whether in motion (e.g., video) or stationary (e.g., still image), and whether textual, graphical or pictorial. More particularly, it is contemplated that the implementations may be implemented in or associated with a variety of electronic devices such as, but not limited to, mobile telephones, multimedia Internet enabled cellular telephones, mobile television receivers, wireless devices, smartphones, bluetooth devices, personal data assistants (PDAs), wireless electronic mail receivers, hand-held or portable computers, netbooks, notebooks, smartbooks, tablets, printers, copiers, scanners, facsimile devices, GPS receivers/navigators, cameras, MP3 players, camcorders, game consoles, wrist watches, clocks, calculators, television monitors, flat panel displays, electronic reading devices (e-readers), computer monitors, auto displays (e.g., odometer display, etc.), cockpit controls and/or displays, camera view displays (e.g., display of a rear view camera in a vehicle), electronic photographs, electronic billboards or signs, projectors, architectural structures, microwaves, refrigerators, stereo systems, cassette recorders or players, DVD players, CD players, VCRs, radios, portable memory chips, washers, dryers, washer/dryers, parking meters, packaging (for example electromechanical systems (EMS), MEMS and non-MEMS applications), aesthetic structures (for example, display of images on a piece of jewelry) and a variety of electromechanical systems devices. The teachings herein also can be used in non-display applications such as, but not limited to, electronic switching devices, radio frequency filters, sensors, accelerometers, gyroscopes, motion-sensing devices, magnetometers, inertial components for consumer electronics, parts of consumer electronics products, varactors, liquid crystal devices, electrophoretic devices, drive schemes, manufacturing processes, and electronic test equipment. Thus, the teachings are not intended to be limited to the implementations depicted solely in the Figures, but instead have wide applicability as will be readily apparent to a person having ordinary skill in the art.

[0063] Methods and devices to actuate, charge, and calibrate movable electrodes in analog interferometric modulators are described herein. For example, various methods and devices are provided to actuate a charge-neutral, electrically isolated electrode ("middle electrode") disposed in a gap between two charged electrodes such that the charge-neutral electrode is actuated and moves toward one of the charged electrodes. In one implementation, at least two charged electrodes are configured to produce an electric field therebetween capable of moving the electrically isolated, charge neutral middle electrode when a voltage V is applied across the charged electrodes. In such implementations, there can be at least two charged electrodes having different dimensions and/or surface areas. The middle electrode can be disposed between such electrodes. In another implementation, the charge-neutral, electrically isolated middle electrode is actuated by applying an electric field between charged electrodes having different surface areas, where a complementary electrode is aligned laterally relative to one of the charged electrodes.

[0064] Methods and devices to provide charge onto movable electrodes in analog interferometric modulators are also described herein. For example, various methods and devices can provide a charge to a charge-neutral, electrically isolated middle electrode after it has been actuated or moved toward a charged electrode. In one implementation, charge is placed on the middle electrode when the middle electrode moves toward a charged electrode and makes direct electrical contact with conductive posts on the charged electrode. The middle electrode develops a net charge until the electric force acting on the middle electrode is overcome by the opposing mechanical spring force acting on the middle electrode. The middle electrode then moves away from the charged electrode, breaking electrical contact and electrically isolating the charge that has been placed on the middle electrode. In another implementation, the middle electrode is inductively charged when the middle electrode moves toward a charged electrode and electrically contacts conductive posts on a complementary electrode aligned laterally relative to the charged electrode, where the complementary electrode is electrically isolated from the charged electrode and connected to electrical ground.

[0065] Methods and devices to calibrate the charge that is provided to a movable electrode in an analog interferometric modulator are also described herein. In one implementation using a “switch” configuration, one or more switches are closed to electrically connect a complementary electrode and a charged electrode to form a compound electrode. A calibration voltage is applied between the compound electrode and the opposing charged electrode, causing the charged middle electrode to move toward the compound electrode and to change its charge by, for example, electrically contacting at least one conductive structure (for example conductive posts) on the compound electrode. In one implementation, the electrical contact causes charge on the middle electrode to change until the electric force acting on the middle electrode is overcome by the opposing mechanical spring force acting on the middle electrode. The middle electrode then moves away from the compound electrode, breaking electrical contact and electrically isolating the charge that remains onto the middle electrode. Upon release, the amount of charge on the middle electrode is related to the mechanical spring force acting on the middle electrode. The structure that holds the middle electrode and provides the mechanical spring force can be, for example, springs of various configurations or the structure of the middle electrode itself that opposes deformation of the electrode. For clarity of disclosure, structure that provides a mechanical spring force on the middle electrode is referred to herein as a “spring” whether such force is provided by the electrode material itself or a structure connected to the middle electrode.

[0066] Another implementation uses a “switchless” configuration to calibrate charge that has been placed on a movable electrode. A calibration voltage is applied between two charged electrodes having different surface areas. The charged middle electrode moves toward the charged electrode having the smaller surface area and electrically contacts conductive posts electrically connected to the charged electrode. The electrical contact causes charge on the middle electrode to change until the electric force acting on the middle electrode is overcome by the opposing mechanical spring force acting on the middle electrode. The middle electrode then moves away from the charged electrode, breaking electrical contact and electrically isolating the charge that remains on the middle electrode. Upon release, the amount of charge on the middle electrode is related to the stiffness of the springs holding the middle electrode.

[0067] Particular implementations of the subject matter described in this disclosure can be implemented to realize one or more of the following potential advantages. A three-terminal electromechanical device (for example, an interferometric modulator) can include a movable middle electrode disposed in a gap between two electrodes, for example, an upper electrode and a lower electrode. Implementations of the devices and methods described herein can move an electrically isolated middle electrode having net zero charge, so that the middle electrode contacts the upper (or lower) electrode. The middle electrode can become charged through this contact, solving drawbacks associated with typical three-terminal devices. Devices and methods are disclosed to charge the middle electrode once it contacts the upper (or lower) electrode. Once charge is provided to the middle electrode, the middle electrode can then be released from the contacting electrode, which isolates charge on the electrode. The charge on the middle electrode can then be calibrated to account for the particular mechanical spring force acting on the middle electrode. Methods and systems for calibrating a charge placed onto the middle electrode are described, for example, with reference to Figures 31–33 and 39–41. Calibrating each of the middle electrodes across an array of three-terminal devices with a desired amount of charge can allow for movement of all of the middle electrodes to the same location upon application of the same voltage across all of the devices. Following calibration, the plurality of calibrated modulators in the array can be in an operationally ready state. Additionally, the actuation, charging, and calibration procedures described herein can be repeated where useful and adjusted to account for variances in the rate of charge leakage from the middle electrodes over the lifetime of the device.

[0068] An example of a suitable EMS or MEMS device, to which the described implementations may apply, is a reflective display device. Reflective display devices can incorporate interferometric modulators (IMODs) to selectively absorb and/or reflect light incident thereon using principles of optical interference. IMODs can include an absorber, a reflector that is movable with respect to the absorber, and an optical resonant cavity defined between the absorber and the reflector. The reflector can be moved to two or more different positions, which can change the size of the optical resonant cavity and thereby affect the reflectance of the interferometric modulator. The reflectance spectrums of IMODs can create fairly broad spectral bands which can be shifted across the visible wavelengths to generate different colors. The position of the spectral band can be adjusted by changing the thickness of the optical resonant cavity, i.e., by changing the position of the reflector.

[0069] Figure 1 shows an example of an isometric view depicting two adjacent pixels in a series of pixels of an interferometric modulator (IMOD) display device. The IMOD display device includes one or more interferometric MEMS display elements. In these devices, the pixels of the MEMS display elements can be in either a bright or dark state. In the bright ("relaxed," "open" or "on") state, the display element reflects a large portion of incident visible light, e.g., to a user. Conversely, in the dark ("actuated," "closed" or "off") state, the display element reflects little incident visible light. In some implementations, the light reflectance properties of the on and off states may be reversed. MEMS pixels can be configured to reflect predominantly at particular wavelengths allowing for a color display in addition to black and white.

[0070] The IMOD display device can include a row/column array of IMODs. Each IMOD can include a pair of reflective layers, i.e., a movable reflective layer and a fixed partially reflective layer, positioned at a variable and controllable distance from each other to form an air gap (also referred to as an optical gap or cavity). The movable reflective layer may be moved between at least two positions. In a first position, i.e., a relaxed position, the movable reflective layer can be positioned at a relatively large distance from the fixed partially reflective layer. In a second position, i.e., an actuated position, the movable reflective layer can be positioned more closely to the partially reflective layer. Incident light that reflects from the two layers can interfere constructively or destructively depending on the position of the movable reflective layer, producing either an overall reflective or non-reflective state for each pixel. In some implementations, the IMOD may be in a reflective state when unactuated, reflecting light within the visible spectrum, and may be in a dark state when unactuated, absorbing and/or destructively interfering light within the visible range. In some other implementations, however, an IMOD may be in a dark state when unactuated, and in a reflective state when actuated. In some implementations, the introduction of an applied voltage can drive the pixels to change states. In some other implementations, an applied charge can drive the pixels to change states.

[0071] The depicted portion of the pixel array in Figure 1 includes two adjacent interferometric modulators **12**. In the IMOD 12 on the left (as illustrated), a movable reflective layer **14** is illustrated in a relaxed position at a predetermined distance from an optical stack **16**, which includes a partially reflective layer. The voltage V_0 applied across the IMOD 12 on the left is insufficient to cause actuation of the movable reflective layer **14**. In the IMOD 12 on the right, the movable reflective layer **14** is illustrated in an actuated position near or adjacent the optical stack **16**. The voltage V_{bias}

applied across the IMOD 12 on the right is sufficient to maintain the movable reflective layer **14** in the actuated position.

[0072] In Figure 1, the reflective properties of pixels **12** are generally illustrated with arrows **13** indicating light incident upon the pixels **12**, and light **15** reflecting from the pixel **12** on the left. Although not illustrated in detail, it will be understood by a person having ordinary skill in the art that most of the light **13** incident upon the pixels **12** will be transmitted through the transparent substrate **20**, toward the optical stack **16**. A portion of the light incident upon the optical stack **16** will be transmitted through the partially reflective layer of the optical stack **16**, and a portion will be reflected back through the transparent substrate **20**. The portion of light **13** that is transmitted through the optical stack **16** will be reflected at the movable reflective layer **14**, back toward (and through) the transparent substrate **20**. Interference (constructive or destructive) between the light reflected from the partially reflective layer of the optical stack **16** and the light reflected from the movable reflective layer **14** will determine the wavelength(s) of light **15** reflected from the pixel **12**.

[0073] The optical stack **16** can include a single layer or several layers. The layer(s) can include one or more of an electrode layer, a partially reflective and partially transmissive layer and a transparent dielectric layer. In some implementations, the optical stack **16** is electrically conductive, partially transparent and partially reflective, and may be fabricated, for example, by depositing one or more of the above layers onto a transparent substrate **20**. The electrode layer can be formed from a variety of materials, for example various metals, for example indium tin oxide (ITO). The partially reflective layer can be formed from a variety of materials that are partially reflective, for example various metals, e.g., chromium (Cr), semiconductors, and dielectrics. The partially reflective layer can be formed of one or more layers of materials, and each of the layers can be formed of a single material or a combination of materials. In some implementations, the optical stack **16** can include a single semi-transparent thickness of metal or semiconductor which serves as both an optical absorber and electrical conductor, while different, electrically more conductive layers or portions (e.g., of the optical stack **16** or of other structures of the IMOD) can serve to bus signals between IMOD pixels.

The optical stack **16** also can include one or more insulating or dielectric layers covering one or more conductive layers or an electrically conductive/optically absorptive layer.

[0074] In some implementations, the layer(s) of the optical stack **16** can be patterned into parallel strips, and may form row electrodes in a display device as described further below. As will be understood by one having ordinary skill in the art, the term "patterned" is used herein to refer to masking as well as etching processes. In some implementations, a highly conductive and reflective material, for example aluminum (Al), may be used for the movable reflective layer **14**, and these strips may form column electrodes in a display device. The movable reflective layer **14** may be formed as a series of parallel strips of a deposited metal layer or layers (orthogonal to the row electrodes of the optical stack **16**) to form columns deposited on top of posts **18** and an intervening sacrificial material deposited between the posts **18**. When the sacrificial material is etched away, a defined gap **19**, or optical cavity, can be formed between the movable reflective layer **14** and the optical stack **16**. In some implementations, the spacing between posts **18** may be approximately 1–1000 um, while the gap **19** may be less than 10,000 Angstroms (Å).

[0075] In some implementations, each pixel of the IMOD, whether in the actuated or relaxed state, is essentially a capacitor formed by the fixed and moving reflective layers. When no voltage is applied, the movable reflective layer **14** remains in a mechanically relaxed state, as illustrated by the pixel **12** on the left in Figure 1, with the gap **19** between the movable reflective layer **14** and optical stack **16**. However, when a potential difference, a voltage, is applied to at least one of a selected row and column, the capacitor formed at the intersection of the row and column electrodes at the corresponding pixel becomes charged, and electrostatic forces pull the electrodes together. If the applied voltage exceeds a threshold, the movable reflective layer **14** can deform and move near or against the optical stack **16**. A dielectric layer (not shown) within the optical stack **16** may prevent shorting and control the separation distance between the layers **14** and **16**, as illustrated by the actuated pixel **12** on the right in Figure 1. The behavior is the same regardless of the polarity of the applied potential difference. Though a series of pixels in an array may be referred to in some instances as "rows" or "columns," a person having ordinary skill in the art will readily understand that referring to one direction as a “row” and another as a “column” is arbitrary. Restated, in some orientations, the rows can be considered columns, and the columns considered to be rows. Furthermore, the display elements may be evenly arranged in orthogonal rows and columns (an “array”), or arranged in non-linear configurations, for example, having certain positional offsets with respect to one another (a “mosaic”). The terms “array” and “mosaic” may refer to either configuration. Thus, although the display is referred to as including an “array” or “mosaic,” the elements themselves need not be arranged orthogonally to one another, or disposed in an even distribution, in any instance, but may include arrangements having asymmetric shapes and unevenly distributed elements.

[0076] Figure 2 shows an example of a system block diagram illustrating an electronic device incorporating a 3x3 interferometric modulator display. The electronic device includes a processor **21** that may be configured to execute one or more software modules. In addition to executing an operating system, the processor **21** may be configured to execute one or more software applications, including a web browser, a telephone application, an email program, or any other software application.

[0077] The processor **21** can be configured to communicate with an array driver **22**. The array driver **22** can include a row driver circuit **24** and a column driver circuit **26** that provide signals to, e.g., a display array or panel **30**. The cross section of the IMOD display device illustrated in Figure 1 is shown by the lines 1–1 in Figure 2. Although Figure 2 illustrates a 3x3 array of IMODs for the sake of clarity, the display array **30** may contain a very large number of IMODs, and may have a different number of IMODs in rows than in columns, and vice versa.

[0078] Figure 3 shows an example of a diagram illustrating movable reflective layer position versus applied voltage for the interferometric modulator of Figure 1. For MEMS interferometric modulators, the row/column (i.e., common/segment) write procedure may take advantage of a hysteresis property of these devices as illustrated in Figure 3. An interferometric modulator may use, in one example implementation, about a 10-volt potential difference to cause the movable reflective layer, or mirror, to change from the relaxed state to the actuated state. When the voltage is reduced from that value, the movable reflective layer maintains its state as the voltage drops back below, in this example, 10 volts, however, the movable reflective layer does not relax completely until the voltage drops below 2 volts. Thus, a range of voltage, approximately 3 to 7 volts, in this example, as shown in Figure 3, exists where there is a window of applied voltage within which the device is stable in either the relaxed or actuated state. This is referred to herein as the "hysteresis window" or "stability window." For a display array **30** having the hysteresis characteristics of Figure 3, the row/column write procedure can be designed to address one or more rows at a time, such that during the addressing of a given row, pixels in the addressed row that are to be actuated are exposed to a voltage difference of about, in this example, 10 volts, and pixels that are to be relaxed are exposed to a voltage difference of near zero volts. After addressing, the pixels can be exposed to a steady state or bias voltage difference of approximately 5 volts in this example, such that they remain in the previous strobing state. In this example, after being addressed, each pixel sees a potential difference within the "stability window" of about 3–7 volts. This hysteresis property feature enables the pixel design, for example that illustrated in Figure 1, to remain stable in either an actuated or relaxed pre-existing state under the same applied voltage conditions. Since each IMOD pixel, whether in the actuated or relaxed state, is essentially a capacitor formed by the fixed and moving reflective layers, this stable state can be held at a steady voltage within the hysteresis window without substantially consuming or losing power. Moreover, essentially little or no current flows into the IMOD pixel if the applied voltage potential remains substantially fixed.

[0079] In some implementations, a frame of an image may be created by applying data signals in the form of "segment" voltages along the set of column electrodes, in accordance with the desired change (if any) to the state of the pixels in a given row. Each row of the array can be addressed in turn, such that the frame is written one row at a time. To write the desired data to the pixels in a first row, segment voltages corresponding to the desired state of the pixels in the first row can be applied on the column electrodes, and a first row pulse in the form of a specific "common" voltage or signal can be applied to the first row electrode. The set of segment voltages can then be changed to correspond to the desired change (if any) to the state of the pixels in the second row, and a second common voltage can be applied to the second row electrode. In some implementations, the pixels in the first row are unaffected by the change in the segment voltages applied along the column electrodes, and remain in the state they were set to during the first common voltage row pulse. This process may be repeated for the entire series of rows, or alternatively, columns, in a sequential fashion to produce the image frame. The frames can be refreshed and/or updated with new image data by continually repeating this process at some desired number of frames per second.

[0080] The combination of segment and common signals applied across each pixel (that is, the potential difference across each pixel) determines the resulting state of each pixel. Figure 4 shows an example of a table illustrating various states of an interferometric modulator when various common and segment voltages are applied. As will be understood by one having ordinary skill in the art, the "segment" voltages can be applied to either the column electrodes or the row electrodes, and the "common" voltages can be applied to the other of the column electrodes or the row electrodes.

[0081] As illustrated in Figure 4 (as well as in the timing diagram shown in Figure 5B), when a release voltage VC_{REL} is applied along a common line, all interferometric modulator elements along the common line will be placed in a relaxed state, alternatively referred to as a released or unactuated state, regardless of the voltage applied along the segment lines, i.e., high segment voltage VS_H and low segment voltage VS_L. In particular, when the release voltage VC_{REL} is applied along a common line, the potential voltage across the modulator pixels (alternatively referred to as a pixel voltage) is within the relaxation window (see Figure 3, also referred to as a release window) both when the high segment voltage VS_H and the low segment voltage VS_L are applied along the corresponding segment line for that pixel.

[0082] When a hold voltage is applied on a common line, for example a high hold voltage VC_{HOLD_H} or a low hold voltage VC_{HOLD_L}, the state of the interferometric modulator will remain constant. For example, a relaxed IMOD will remain in a relaxed position, and an actuated IMOD will remain in an actuated position. The hold voltages can be selected such that the pixel voltage will remain within a stability window both when the high segment voltage VS_H and the low segment voltage VS_L are applied along the corresponding segment line. Thus, the segment voltage swing, i.e., the difference between the high VS_H and low segment voltage VS_L, is less than the width of either the positive or the negative stability window.

[0083] When an addressing, or actuation, voltage is applied on a common line, for example a high addressing voltage VC_{ADD_H} or a low addressing voltage VC_{ADD_L}, data can be selectively written to the modulators along that line by application of segment voltages along the respective segment lines. The segment voltages may be selected such that actuation is dependent upon the segment voltage applied. When an addressing voltage is applied along a common line, application of one segment voltage will result in a pixel voltage within a stability window, causing the pixel to remain unactuated. In contrast, application of the other segment voltage will result in a pixel voltage beyond the stability window, resulting in actuation of the pixel. The particular segment voltage which causes actuation can vary depending upon which addressing voltage is used. In some implementations, when the high addressing voltage VC_{ADD_H} is applied along the common line, application of the high segment voltage VS_H can cause a modulator to remain in its current position, while application of the low segment voltage VS_L can cause actuation of the modulator. As a corollary, the effect of the segment voltages can be the opposite when a low addressing voltage VC_{ADD_L} is applied, with high segment voltage VS_H causing actuation of the modulator, and low segment voltage VS_L having no effect (i.e., remaining stable) on the state of the modulator.

[0084] In some implementations, hold voltages, address voltages, and segment voltages may be used which produce the same polarity potential difference across the modulators. In some other implementations, signals can be used which alternate the polarity of the potential difference of the modulators from time to time. Alternation of the polarity across the modulators (that is, alternation of the polarity of write procedures) may reduce or inhibit charge accumulation which could occur after repeated write operations of a single polarity.

[0085] Figure 5A shows an example of a diagram illustrating a frame of display data in the 3x3 interferometric modulator display of Figure 2. Figure 5B shows an example of a timing diagram for common and segment signals that may be used to write the frame of display data illustrated in Figure 5A. The signals can be applied to a 3x3 array, similar to the array of Figure 2, which will ultimately result in the line time 60e display arrangement illustrated in Figure 5A. The actuated modulators in Figure 5A are in a dark-state, i.e., where a substantial portion of the reflected light is outside of the visible spectrum so as to result in a dark appearance to, for example, a viewer. Prior to writing the frame illustrated in Figure 5A, the pixels can be in any state, but the write procedure illustrated in the timing diagram of Figure 5B presumes that each modulator has been released and resides in an unactuated state before the first line time 60a.

[0086] During the first line time 60a: a release voltage **70** is applied on common line 1; the voltage applied on common line 2 begins at a high hold voltage **72** and moves to a release voltage **70**; and a low hold voltage **76** is applied along common line 3. Thus, the modulators (common 1, segment 1), (1,2) and (1,3) along common line 1 remain in a relaxed, or unactuated, state for the duration of the first line time 60a, the modulators (2,1), (2,2) and (2,3) along common line 2 will move to a relaxed state, and the modulators (3,1), (3,2) and (3,3) along common line 3 will remain in their previous state. With reference to Figure 4, the segment voltages applied along segment lines 1, 2 and 3 will have no effect on the state of the interferometric modulators, as none of common lines 1, 2 or 3 are being exposed to voltage levels causing actuation during line time 60a (i.e., VC_{REL} – relax and VC_{HOLD_L} – stable).

[0087] During the second line time 60b, the voltage on common line 1 moves to a high hold voltage **72**, and all modulators along common line 1 remain in a relaxed state regardless of the segment voltage applied because no addressing, or actuation, voltage was applied on the common line 1. The modulators along common line 2 remain in a relaxed state due to the application of the release voltage **70**, and the modulators (3,1), (3,2) and (3,3) along common line 3 will relax when the voltage along common line 3 moves to a release voltage **70**.

[0088] During the third line time 60c, common line 1 is addressed by applying a high address voltage **74** on common line 1. Because a low segment voltage **64** is applied along segment lines 1 and 2 during the application of this address voltage, the pixel voltage across modulators (1,1) and (1,2) is greater than the high end of the positive stability window (i.e., the voltage differential exceeded a predefined threshold) of the modulators, and the modulators (1,1) and (1,2) are actuated. Conversely, because a high segment voltage **62** is applied along segment line 3, the pixel voltage across modulator (1,3) is less than that of modulators (1,1) and (1,2), and remains within the positive stability window of the modulator; modulator (1,3) thus remains relaxed. Also during line time 60c, the voltage along common line 2 decreases to a low hold voltage **76**, and the voltage along common line 3 remains at a release voltage **70**, leaving the modulators along common lines 2 and 3 in a relaxed position.

[0089] During the fourth line time 60d, the voltage on common line 1 returns to a high hold voltage **72**, leaving the modulators along common line 1 in their respective addressed states. The voltage on common line 2 is decreased to a low address voltage **78**. Because a high segment voltage **62** is applied along segment line 2, the pixel voltage across modulator (2,2) is below the lower end of the negative stability window of the modulator, causing the modulator (2,2) to actuate. Conversely, because a low segment voltage **64** is applied along segment lines 1 and 3, the modulators (2,1) and (2,3) remain in a relaxed position. The voltage on common line 3 increases to a high hold voltage **72**, leaving the modulators along common line 3 in a relaxed state.

[0090] Finally, during the fifth line time 60e, the voltage on common line 1 remains at high hold voltage **72**, and the voltage on common line 2 remains at a low hold voltage **76**, leaving the modulators along common lines 1 and 2 in their respective addressed states. The voltage on common line 3 increases to a high address voltage **74** to address the modulators along common line 3. As a low segment voltage **64** is applied on segment lines 2 and 3, the modulators (3,2) and (3,3) actuate, while the high segment voltage **62** applied along segment line 1 causes modulator (3,1) to remain in a relaxed position. Thus, at the end of the fifth line time 60e, the 3x3 pixel array is in the state shown in Figure 5A, and will remain in that state as long as the hold voltages are applied along the common lines, regardless of variations in the segment voltage which may occur when modulators along other common lines (not shown) are being addressed.

[0091] In the timing diagram of Figure 5B, a given write procedure (i.e., line times 60a–60e) can include the use of either high hold and address voltages, or low hold and address voltages. Once the write procedure has been completed for a given common line (and the common voltage is set to the hold voltage having the same polarity as the actuation voltage), the pixel voltage remains within a given stability window, and does not pass through the relaxation window until a release voltage is applied on that common line. Furthermore, as each modulator is released as part of the write procedure prior to addressing the modulator, the actuation time of a modulator, rather than the release time, may determine the line time. Specifically, in implementations in which the release time of a modulator is greater than the actuation time, the release voltage may be applied for longer than a single line time, as depicted in Figure 5B. In some other implementations, voltages applied along common lines or segment lines may vary to account for variations in the actuation and release voltages of different modulators, for example modulators of different colors.

[0092] The details of the structure of interferometric modulators that operate in accordance with the principles set forth above may vary widely. For example, Figures 6A–6E show examples of cross-sections of varying implementations of interferometric modulators, including the movable reflective layer **14** and its supporting structures. Figure 6A shows an example of a partial cross-section of the interferometric modulator display of Figure 1, where a strip of metal material, i.e., the movable reflective layer **14** is deposited on supports **18** extending orthogonally from the substrate **20**. In Figure 6B, the movable reflective layer **14** of each IMOD is generally square or rectangular in shape and attached to supports at or near the corners, on tethers **32**. In Figure 6C, the movable reflective layer **14** is generally square or rectangular in shape and suspended from a deformable layer **34**, which may include a flexible metal. The deformable layer **34** can connect, directly or indirectly, to the substrate **20** around the perimeter of the movable reflective layer **14**. These connections are herein referred to as support posts. The implementation shown in Figure 6C has additional benefits deriving from the decoupling of the optical functions of the movable reflective layer **14** from its mechanical functions, which are carried out by the deformable layer **34**. This decoupling allows the structural design and materials used for the reflective layer **14** and those used for the deformable layer **34** to be optimized independently of one another.

[0093] Figure 6D shows another example of an IMOD, where the movable reflective layer **14** includes a reflective sub-layer **14a**. The movable reflective layer **14** rests on a support structure, for example support posts **18**. The support posts **18** provide separation of the movable reflective layer **14** from the lower stationary electrode (i.e., part of the optical stack **16** in the illustrated IMOD) so that a gap **19** is formed between the movable reflective layer **14** and the optical stack **16**, for example when the movable reflective layer **14** is in a relaxed position. The movable reflective layer **14** also can include a conductive layer **14c**, which may be configured to serve as an electrode, and a support layer **14b**. In this example, the conductive layer **14c** is disposed on one side of the support layer **14b**, distal from the substrate **20**, and the reflective sub-layer **14a** is disposed on the other side of the support layer **14b**, proximal to the substrate **20**. In some implementations, the reflective sub-layer **14a** can be conductive and can be disposed between the support layer **14b** and the optical stack **16**. The support layer **14b** can include one or more layers of a dielectric material, for example, silicon oxynitride (SiON) or silicon dioxide (SiO_2). In some implementations, the support layer **14b** can be a stack of layers, for example a SiO_2/SiON/SiO_2 tri-layer stack. Either or both of the reflective sub-layer **14a** and the conductive layer **14c** can include, e.g., an aluminum (Al) alloy with about 0.5% copper (Cu), or another reflective metallic material. Employing conductive layers **14a**, **14c** above and below the dielectric support layer **14b** can balance stresses and provide enhanced conduction. In some implementations, the reflective sub-layer **14a** and the conductive layer **14c** can be formed of different materials for a variety of design purposes, for example achieving specific stress profiles within the movable reflective layer **14**.

[0094] As illustrated in Figure 6D, some implementations also can include a black mask structure **23**. The black mask structure **23** can be formed in optically inactive regions (e.g., between pixels or under posts **18**) to absorb ambient or stray light. The black mask structure **23** also can improve the optical properties of a display device by inhibiting light from being reflected from or transmitted through inactive portions of the display, thereby increasing the contrast ratio. Additionally, the black mask structure **23** can be conductive and be configured to function as an electrical bussing layer. In some implementations, the row electrodes can be connected to the black mask structure **23** to reduce the resistance of the connected row electrode. The black mask structure **23** can be formed using a variety of methods, including deposition and patterning techniques. The black mask structure **23** can include one or more layers. For example, in some implementations, the black mask structure **23** includes a molybdenum-chromium (MoCr) layer that serves as an optical absorber, a layer, and an aluminum alloy that serves as a reflector and a bussing layer, with a thickness in the range of about 30–80 Å, 500–1000 Å, and 500–6000 Å, respectively. The one or more layers can be patterned using a variety of techniques, including photolithography and dry etching, including, for example, carbon tetrafluoride (CF_4) and/or oxygen (O_2) for the MoCr and SiO_2 layers and chlorine (Cl_2) and/or boron trichloride (BCl_3) for the aluminum alloy layer. In some implementations, the black mask **23** can be an etalon or interferometric stack structure. In such interferometric stack black mask structures **23**, the conductive absorbers can be used to transmit or bus signals between lower, stationary electrodes in the optical stack **16** of each row or column. In some implementations, a spacer layer **35** can serve to generally electrically isolate the absorber layer **16a** from the conductive layers in the black mask **23**.

[0095] Figure 6E shows another example of an IMOD, where the movable reflective layer **14** is self supporting. In contrast with Figure 6D, the implementation of Figure 6E does not include support posts **18**. Instead, the movable reflective layer **14** contacts the underlying optical stack **16** at multiple locations, and the curvature of the movable reflective layer **14** provides sufficient support that the movable reflective layer **14** returns to the unactuated position of Figure 6E when the voltage across the interferometric modulator is insufficient to cause actuation. The optical stack **16**, which may contain a plurality of several different layers, is shown here for clarity including an optical absorber **16a**, and a dielectric **16b**. In some implementations, the optical absorber **16a** may serve both as a fixed electrode and as a partially reflective layer.

[0096] In implementations such as those shown in Figures 6A–6E, the IMODs function as direct-view devices, in which images are viewed from the front side of the transparent substrate **20**, i.e., the side opposite to that upon which the modulator is formed. In these implementations, the back portions of the device (that is, any portion of the display device behind the movable reflective layer **14**, including, for example, the deformable layer **34** illustrated in Figure 6C) can be configured and operated upon without impacting or negatively affecting the image quality of the display device, because the reflective layer **14** optically shields those portions of the device. For example, in some implementations a bus structure (not illustrated) can be included behind the movable reflective layer **14** which provides the ability to separate the optical properties of the modulator from the electromechanical properties of the modulator, for example voltage addressing and the movements that result from such addressing.

Additionally, the implementations of Figures 6A–6E can simplify processing, for example patterning.

[0097] Figure 7 shows an example of a flow diagram illustrating a manufacturing process 80 for an interferometric modulator, and Figures 8A–8E show examples of cross-sectional schematic illustrations of corresponding stages of such a manufacturing process **80**. In some implementations, the manufacturing process **80** can be implemented to manufacture an electromechanical systems device, for example interferometric modulators of the general type illustrated in Figures 1 and 6. The manufacture of an electromechanical systems device can also include other blocks not shown in Figure 7. With reference to Figures 1, 6 and 7, the process **80** begins at block **82** with the formation of the optical stack **16** over the substrate **20**. Figure 8A illustrates such an optical stack **16** formed over the substrate **20**. The substrate **20** may be a transparent substrate, for example glass or plastic, it may be flexible or relatively stiff and unbending, and may have been subjected to prior preparation processes, e.g., cleaning, to facilitate efficient formation of the optical stack **16**. As discussed above, the optical stack **16** can be electrically conductive, partially transparent and partially reflective and may be fabricated, for example, by depositing one or more layers having the desired properties onto the transparent substrate **20**. In Figure 8A, the optical stack **16** includes a multilayer structure having sub-layers **16a** and **16b**, although more or fewer sub-layers may be included in some other implementations. In some implementations, one of the sub-layers **16a** and **16b** can be configured with both optically absorptive and electrically conductive properties, for example the combined conductor/absorber sub-layer **16a**. Additionally, one or more of the sub-layers **16a** and **16b** can be patterned into parallel strips, and may form row electrodes in a display device. Such patterning can be performed by a masking and etching process or another suitable process known in the art. In some implementations, one of the sub-layers **16a** and **16b** can be an insulating or dielectric layer, for example sub-layer **16b** that is deposited over one or more metal layers (e.g., one or more reflective and/or conductive layers). In addition, the optical stack **16** can be patterned into individual and parallel strips that form the rows of the display. It is noted that Figures 8A–8E may not be drawn to scale. For example, in some implementations, one of the sub-layers of the optical stack, the optically absorptive layer, may be very thin, although sub-layers 16a and 16b are shown somewhat thick in Figures 8A–8E.

[0098] The process **80** continues at block **84** with the formation of a sacrificial layer **25** over the optical stack **16**. The sacrificial layer **25** is later removed (e.g., at block **90**) to form the cavity **19** and thus the sacrificial layer **25** is not shown in the resulting interferometric modulators **12** illustrated in Figure 1. Figure 8B illustrates a partially fabricated device including a sacrificial layer **25** formed over the optical stack **16**. The formation of the sacrificial layer **25** over the optical stack **16** may include deposition of a xenon difluoride (XeF_2)-etchable material, for example molybdenum (Mo) or amorphous silicon (a-Si), in a thickness selected to provide, after subsequent removal, a gap or cavity **19** (see also Figures 1 and 8E) having a desired size. Deposition of the sacrificial material may be carried out using deposition techniques, for example physical vapor deposition (PVD, e.g., sputtering), plasma-enhanced chemical vapor deposition (PECVD), thermal chemical vapor deposition (thermal CVD), or spin-coating.

[0099] The process **80** continues at block **86** with the formation of a support structure, for example post **18**, illustrated in Figures 1, 6 and 8C. The formation of the post **18** may include patterning the sacrificial layer **25** to form a support structure aperture, then depositing a material (for example, a polymer or an inorganic material, for example, silicon oxide) into the aperture to form the post **18**, using a deposition method, for example PVD, PECVD, thermal CVD, or spin-coating. In some implementations, the support structure aperture formed in the sacrificial layer can extend through both the sacrificial layer **25** and the optical stack **16** to the underlying substrate **20**, so that the lower end of the post **18** contacts the substrate **20** as illustrated in Figure 6A. Alternatively, as depicted in Figure 8C, the aperture formed in the sacrificial layer **25** can extend through the sacrificial layer **25**, but not through the optical stack **16**. For example, Figure 8E illustrates the lower ends of the support posts **18** in contact with an upper surface of the optical stack **16**. The post **18**, or other support structures, may be formed by depositing a layer of support structure material over the sacrificial layer **25** and patterning portions of the support structure material located away from apertures in the sacrificial layer **25**. The support structures may be located within the apertures, as illustrated in Figure 8C, but also can, at least partially, extend over a portion of the sacrificial layer **25**. As noted above, the patterning of the sacrificial layer **25** and/or the support posts **18** can be performed by a patterning and etching process, but also may be performed by alternative etching methods.

[0100] The process **80** continues at block **88** with the formation of a movable reflective layer or membrane, for example the movable reflective layer **14** illustrated in Figures 1, 6 and 8D. The movable reflective layer **14** may be formed by employing one or more deposition steps including, for example, reflective layer (e.g., aluminum, aluminum alloy, or other reflective layer) deposition, along with one or more patterning, masking, and/or etching steps. The movable reflective layer **14** can be electrically conductive, and referred to as an electrically conductive layer. In some implementations, the movable reflective layer **14** may include a plurality of sub-layers **14a**, **14b**, and **14c** as shown in Figure 8D. In some implementations, one or more of the sub-layers, for example sub-layers **14a** and **14c**, may include highly reflective sub-layers selected for their optical properties, and another sub-layer **14b** may include a mechanical sub-layer selected for its mechanical properties. Since the sacrificial layer **25** is still present in the partially fabricated interferometric modulator formed at block **88**, the movable reflective layer **14** is typically not movable at this stage. A partially fabricated IMOD that contains a sacrificial layer **25** also may be referred to herein as an "unreleased" IMOD. As described above in connection with Figure 1, the movable reflective layer **14** can be patterned into individual and parallel strips that form the columns of the display.

[0101] The process **80** continues at block **90** with the formation of a cavity, for example cavity **19** illustrated in Figures 1, 6 and 8E. The cavity **19** may be formed by exposing the sacrificial material **25** (deposited at block **84**) to an etchant. For example, an etchable sacrificial material, for example Mo or amorphous Si may be removed by dry chemical etching, for example, by exposing the sacrificial layer **25** to a gaseous or vaporous etchant, for example vapors derived from solid XeF_2, for a period of time that is effective to remove the desired amount of material, typically selectively removed relative to the structures surrounding the cavity **19**. Other etching methods, e.g. wet etching and/or plasma etching, also may be used. Since the sacrificial layer **25** is removed during block **90**, the movable reflective layer **14** is typically movable after this stage. After removal of the sacrificial material **25**, the resulting fully or partially fabricated IMOD may be referred to herein as a “released” IMOD.

[0102] The interferometric modulators described above are bi-stable display elements having two states: a relaxed state and an actuated state. The following description relates to analog interferometric modulators. For example, in one implementation of an analog interferometric modulator, a single interferometric modulator can reflect a red color, a green color, a blue color, a black color, and a white color. In some implementations, an analog interferometric modulator can reflect any color within a range of wavelengths of light depending upon an applied voltage. Further, the optical stack of the analog interferometric modulator may differ from the bi-stable display elements described above. These differences may produce different optical results. For example, in some implementations of the bi-stable elements described above, the closed (actuated) state gives the bi-stable element a dark (for example black) reflective state. In some implementations, the analog interferometric modulator reflects white light when the electrodes are in a position analogous to the closed state of the bi-stable element.

[0103] A three-terminal electromechanical device (for example, an interferometric modulator) can include a movable middle electrode disposed in a gap between an upper and a lower electrode. In one approach, a three-terminal device can use a switch or a series capacitor to provide charge onto the middle electrode. Then, a voltage may be applied across the upper and lower electrodes, and the charged middle electrode can interact with the resulting electric field produced between the upper and lower electrodes. As a result, the charged middle electrode can be moved or displaced based upon the electric field produced by the applied voltage. However, using switches and capacitors to provide charge onto the middle electrode in this manner can lead to parasitic loading of the middle electrode. While it can be useful to provide charge onto a charge-neutral middle electrode that is not electrically connected to any external circuits and, thus, is electrically isolated, a charge-neutral middle electrode would ordinarily not respond to the applied electric field between the upper and lower electrodes. Accordingly, devices and methods for moving an electrically isolated middle electrode with net zero charge, so that it contacts an electrical contact (or electrode) thereby imparting a charge to the middle electrode, can be useful. Devices and methods to release a middle electrode after it receives charge can also be useful.

[0104] Figure 9 shows an example of a flowchart illustrating one method for actuating and calibrating a charge neutral electrode of an analog interferometric modulator. The method **900** begins at block **951** in which an electrically isolated, charge neutral middle electrode is provided. The electrically isolated middle electrode can be charge neutral, for example, before being charged and/or calibrated, when a device is first powered on, or after the charge has been depleted as a result of leakage or a purposeful charge dissipation procedure. The method continues at block **952** in which the middle electrode is actuated, moving the middle electrode towards another electrode using an electrical force. Devices and methods to actuate the middle electrode when it is charge neutral are described below, for example, with reference to Figures 12–20. The method **900** continues at block **953** in which charge is provided to the middle electrode. Figures 21–25 describe some general implementations of systems and methods for placing charge on such a middle electrode. Specifically, device and methods for charging the middle electrode by contact with an upper electrode are described with reference to Figures 21–23, and devices and method for charging the middle electrode by contact with an isolated, grounded complimentary electrode are described with reference to Figures 22 and 24–25. In some implementations, the charge-neutral middle electrode may be charged using a switch configuration, as described with reference to Figures 26–30, while in other implementations, the middle electrode may be charged using a switchless configuration, as described with reference to Figures 34–38.

[0105] The method **900** includes block **954** in which the charge placed on the middle electrode is calibrated to account for the particular mechanical spring force acting on the middle electrode. Certain devices and methods for calibrating the charge using a switch configuration are described with reference to Figures 31–33. Additionally, some implementations of devices and methods for calibrating the charge using a switchless configuration are described with reference to Figures 39–41. Calibrating each of the middle electrodes across an array of three-terminal devices with a desired amount of charge can allow for reliable movement of all of the middle electrodes to the same location upon application of a selected voltage across all of the devices. This can help improve the accuracy of the color displayed in an analog interferometric modulator display.

[0106] The method **900** continues at block **955** in which a display including an array of analog interferometric modulators having calibrated middle electrodes is operated. In some aspects, operating the display includes actuating or moving the middle electrodes to various locations in the gap formed by the upper electrode **1002** and lower electrode **1010** (see Figure 10) to display an image. The location of the middle electrode helps to determine the reflected displayed color of an analog interferometric modulator pixel. The method **900** optionally continues at block **956** in which blocks **952–955** are repeated. In some implementations, before returning to block **952**, the middle electrode is rendered charge neutral. In some implementations, the middle electrode retains some charge when it is actuated at block **952**.

[0107] Figure 10 shows an example of a cross-section of an analog interferometric modulator **1000** having a three layer or electrode design. The modulator **1000** includes an upper or first electrode **1002**. In one implementation, electrode **1002** is a plate made of metal. The upper electrode **1002** may be stiffened using a stiffening layer **1003**. In one implementation, the stiffening layer **1003** is a dielectric. The stiffening layer **1003** may be used to keep the upper electrode **1002** rigid and substantially flat. The modulator **900** also includes a lower or second electrode **1010**, and a middle or third electrode **1006**, which can also include metal. The three electrodes are electrically insulated by insulating posts **1004**. The insulating posts **1004** also serve to hold middle electrode **1006** between electrodes **1002** and **1010** in an equilibrium position when no electric forces are present. The middle electrode **1006** has a stiffening layer **1008** disposed thereon. In one implementation, the stiffening layer **1008** includes silicon oxynitride.

[0108] The middle electrode **1006** is configured to move in the area or gap between upper electrode **1002** and lower electrode **1010**. The stiffening layer **1008** helps to keep a portion of the middle electrode **1006** relatively rigid and flat as it moves between electrodes **1002** and **1010**. In one implementation, the stiffening layer **1008** is disposed on the central portion of the middle electrode **1006**. In this implementation, the side portions of the middle electrode **1006** are able to bend as the middle electrode **1006**

moves. In Figure 10, middle electrode **1006** is shown in an equilibrium position where the electrode is substantially flat. As the middle electrode **1006** moves away from this equilibrium position, the side portions of the middle electrode **1006** will deform or bend. The side portions of the middle electrode **1006** implement an elastic spring force that applies a force to move the middle electrode **1006** back to the equilibrium position (see, for example, springs **2634** in Figures 26–33 and springs 3434 in Figures 34–41).

[0109] The middle electrode **1006** also serves as a mirror to reflect light entering the structure through substrate **1012**. In some implementations, substrate **1012** is made of glass. In one implementation, the lower electrode **1010** is an absorbing chromium or chromium-containing layer. To remain at least partially transparent, the absorbing layer can be made relatively thin, as described above. The lower electrode **1010** has a passivation layer **1014** (now specifically shown as a separate layer) disposed thereon. In one implementation, the passivation layer **1014** is a thin dielectric layer. In another implementation, the upper electrode **1002** has a passivation layer disposed thereon. In some implementations, the passivation layer is a thin dielectric layer.

[0110] Figure 11A shows an example of a cross-section of an analog interferometric modulator **1100** with a control circuit **1120**. The analog interferometric modulator **1100** may be modulator **1000** or other similar design of analog interferometric modulator. Modulator **1100** includes an upper electrode **1102**, a middle electrode **1106**, and a lower electrode **1110**. The modulator **1100** further includes insulating posts **1104** that insulate electrodes **1102**, **1106**, and **1110** from other structures. The modulator **1100** further includes resistive elements **1116** disposed on the upper electrode **1102**. The upper electrode **1102** has a stiffening layer **1103** disposed thereon. In one implementation, the upper electrode **1102** is a metal and the stiffening layer **1103** is a dielectric. The modulator **1100** also includes a thin dielectric passivation layer **1114** disposed on the lower electrode **1110** such that the dielectric passivation layer **1114** is disposed between the lower electrode **1110** and the middle electrode **1106**. The lower electrode **1110** is disposed on a substrate **1112**. Resistive elements **1116** provide a separator between upper electrode **1102** and middle electrode **1106**. When middle electrode **1106** is moved toward upper electrode **1102**, resistive elements **1116** prevent the middle electrode **1106** from coming into contact with the upper electrode **1102**. In one implementation, middle electrode **1106** includes an insulating layer (not shown) disposed on the bottom portion of the middle electrode **1106**.

[0111] The analog interferometric modulator **1100** also includes a control circuit **1120**. The control circuit **1120** is configured to apply a voltage across the upper electrode **1102** and the lower electrode **1110**. A charge pump circuit **1118** is configured to selectively apply a charge to the middle electrode **1106**. Using the control voltage **1120** and the charge pump circuit **1118**, actuation of the middle electrode **1106** is achieved. The charge pump circuit **1118** is used to provide the middle electrode **1106** with an electric charge. The charged middle electrode **1106** then interacts with the electric field created by control circuit **1120** between upper electrode **1102** and the lower electrode **1110**. The interaction of the charged middle electrode **1106** and the electric field causes the middle electrode **1106** to move between electrodes **1102** and **1110**.

[0112] One example of charge injection circuitry which can be implemented as a charge pump circuit **1118** to place an accurate quantity of charge onto IMOD is illustrated in the schematics of Figure 11B. In these schematics, the IMOD is depicted as variable capacitor. The Reset IMOD (left-side) schematic illustrates an example circuit configuration for resetting an IMOD. In this configuration, a switch S3 is closed shorting the IMOD to dissipate the charge on the IMOD. Switches S1and S2 are "open" isolating a voltage source V_{in} and a capacitor C_{in} from each other and from the IMOD. The Pre-charge C_{in} (center) schematic illustrates an example circuit configuration where switch S1 is closed connecting the voltage source V_{in} to the capacitor C_{in}, charging the capacitor C_{in}. The switch S2 is "open" isolating the capacitor C_{in} from the IMOD, and switch S3 is open so that the IMOD is no longer shorted. In the Sample and Transfer Charge onto IMOD (right-side) schematic, switch S1 is open, isolating the voltage source V_{in} from the rest of the circuitry, and switch S2 is closed, connecting capacitor C_{in} to the virtual ground input of the op-amp which remains connected to the IMOD terminal 1 (left terminal). The op-amp output is connected in feedback to terminal 2 of the IMOD. This is a well-known switched capacitor circuit that accurately transfers charge from the input capacitor C_{in} to the capacitor in the feedback path, in this case, the IMOD. Other approaches resulting in incomplete charge transfer can be implemented using switches without an op-amp.

[0113] The middle electrode **1106** can be moved to various positions between electrodes **1102** and **1110** by varying the voltage applied by the control circuit **1120**. For example, a positive voltage V_c applied by control circuit **1120** causes the lower electrode **1110** to be driven to a positive potential with respect to the upper electrode **1102**, which repels the middle electrode **1106** if and when it is positively charged. Accordingly, a positive voltage V_c causes middle electrode **1106** to move toward upper electrode **1102**. Application of a negative voltage V_c by control circuit **1120** causes the lower electrode **1110** to be driven to a negative potential with respect to the upper electrode **1102**, which attracts the middle electrode **1106** when it is positively charged. Accordingly a negative voltage V_c causes middle electrode **1106** to move toward lower electrode **1110**.

[0114] A switch **1122** can be used to selectively connect or disconnect the middle electrode **1106** from the charge pump circuit **1118**. Other methods known in the art besides a switch may be used to selectively connect or disconnect the middle electrode **1106** from the charge pump circuit **1118**, for example, a thin film semiconductor, a fuse, an anti fuse, etc.

[0115] The analog interferometric modulator **1100** may be configured such that the middle electrode **1106** responds in linear proportion to a voltage driven across upper electrode **1102** and lower electrode **1110**. Accordingly, there is a linear relationship between the voltage used to control the movement of the middle electrode **1006** and the position of the middle electrode **1106** between electrodes **1102** and **1110**.

[0116] Using a switch **1122** to provide charge to the middle electrode **1106** can cause parasitic loading of the middle electrode **1106**. For example, if the middle electrode **1106** is not completely isolated electrically, a stored charge Q on the middle electrode **1106** may vary as its position between electrodes **1102** and **1110**. This variation in Q can affect the response of the middle electrode **1106** to a charge. When middle electrode **1106** is not completely isolated electrically, there are parasitic capacitances attached from it to each of the upper electrode **1102** and the lower electrode **1110**. In addition, a portion of the stored charge Q may leak from the middle electrode **1106** through the switch **1122** over time.

[0117] Various systems and methods can be used to account for the parasitic capacitances, for example those described in U.S. Patent No. 7,990,604, issued August 2, 2011, titled “Analog Interferometric Modulator.” For example, modulator **1100** may be configured to account for the parasitic capacitances by including a capacitor connected in series with middle electrode **1106** and in parallel with parasitic capacitances **1140** and **1142**. It would therefore be advantageous to provide charge, then isolate the charge, on the middle electrode **1106** without an electrical connection from the middle electrode **1106** to a switch or series capacitor. Such an electrically isolated electrode can reduce parasitic loading or charge leakage issues.

Actuating a Neutral, Electrically Isolated Electrode

[0118] Figure 12 shows an example of a perspective view of an analog interferometric modulator **1200** which includes a middle electrode that can be moved, or actuated, between two charged electrodes without the use of a switch or series capacitor electrically connected to the middle electrode. As described in greater detail below with reference to Figures 21–23, the middle electrode can be moved toward either charged electrode to provide charge onto the middle electrode without the use of a switch or series capacitor electrically connected to the middle electrode.

[0119] The modulator **1200** includes an upper electrode **1202** and a lower electrode **1210** spaced apart from the upper electrode **1202** by a constant gap g. A movable middle electrode or plate **1206** is disposed in the gap g, and can be spaced a distance d_2 from the upper electrode **1202** and a distance d_1 from the lower electrode **1210**. The middle electrode **1206** may be a metal reflector or a mirror. The middle electrode **1206** can be electrically isolated, that is, it is not electrically connected to an external component, for example a switch, when the middle electrode **1206** is disposed in the gap g. The middle electrode **1206** is also charge neutral, having the same total number of positive charges as negative charges. In some implementations, the electrodes **1202**, **1206**, and **1210** are thin film electrodes. In some aspects, for example, a lateral dimension of a thin film upper electrode **1202** is D and the thickness of the thin film upper electrode **1202** is one-tenth the lateral dimension or less (D/10 or less). In some implementations, each of the three electrodes have thicknesses that are thin compared to the separation distances d_1 and d_2. For example, the thicknesses of each of the three electrodes can be one or more orders of magnitude thinner than the separation distances d_1 and d_2.

[0120] The middle electrode **1206** may be mechanically connected to and/or supported by structures or components (not shown in Figure 12). However, such structure (or components) can be configured such that the middle electrode **1206** remains electrically isolated (for example, the structure may be formed from a material which helps to electrically isolate the middle electrode **1206**. As discussed in greater detail below with reference to Figures 21, 26, and 34, such structures may include springs that exert a restorative mechanical force on the middle electrode **1206** to restore the middle electrode **1206** to a specific position in the gap g.

[0121] The uncharged, electrically isolated middle electrode **1206** can be actuated or moved toward either the upper electrode **1202** or the lower electrode **1210** upon application of an electric field between the upper electrode **1202** and the lower electrode **1210**. In one implementation, this is achieved by configuring one of the upper electrode **1202** and the lower electrode **1210** to be a different size than the other. For example, in the implementation illustrated in Figure 12, the upper electrode **1202** has a surface area A_2 while the lower electrode **1210** has a surface area A_1 that is greater than A_2. In other aspects, the lower electrode **1210** can have a surface area A_1 that is less than the surface area A_2 of the upper electrode **1202**. The middle electrode **1206** can have a surface area less than or about equal to the surface area of the lower electrode **1210**.

[0122] Applying a voltage V across the upper electrode **1202** and the lower electrode **1210** produces a non-uniform electric field between the two electrodes. Implementations of the modulator **1200** can include a control circuit configured to apply a voltage V across the upper electrode **1202** and the lower electrode **1210** to produce the non-uniform electric field.

[0123] Figure 13 shows an example of an equivalent circuit of the analog interferometric modulator configuration shown in Figure 12. C_1 represents the capacitance between the lower electrode **1210** and the middle electrode **1206**, while C_2 represents the capacitance between the upper electrode **1202** and the middle electrode

1206. ΔV_1 represents the potential difference between the lower electrode **1210** and the middle electrode **1206**, and is given by the equation:

$$\Delta V_1 = \frac{C_2}{C_1 + C_2} V \tag{1}$$

[0124] ΔV_2 represents the potential difference between the upper electrode **1202** and the middle electrode **1206**, and is given by the equation:

$$\Delta V_2 = \frac{C_1}{C_1 + C_2} V \tag{2}$$

[0125] Applying a voltage V to the upper electrode **1202** and the lower electrode **1210** provides an electrical charge on the upper electrode **1202** and the lower electrode **1210** which has the same magnitude. The electric force exerted on the middle electrode **1206** by either of these charged electrodes is inversely proportional to the surface area of the charged electrode. However, in this example, because the surface area of the upper electrode **1202** is less than that of the lower electrode **1210** in this example, the upper electrode **1202** exerts a larger electric force on the middle electrode **1206** than the lower electrode **1210**. In implementations where the surface area of the lower electrode **1210** is less than that of the upper electrode **1202**, the lower electrode **1210** will exert a larger electric force on the middle electrode **1206** than the upper electrode **1202**.

[0126] The net force acting on the middle electrode **1206** can be determined using the parallel plate approximation for the capacitances C_1 and C_2. Because the upper electrode **1202** and the lower electrode **1210** are stationary, the net electric force on the middle electrode **1206** can be approximated as:

$$F = \frac{\varepsilon_0 A_2 (\Delta V_2)^2}{2 d_2^2} - \frac{\varepsilon_0 A_1 (\Delta V_1)^2}{2 d_1^2} \tag{3}$$

where ε_0 represents the dielectric permittivity of a vacuum, A_1 represents the surface area of lower electrode **1210**, A_2 represents the effective surface area of upper electrode **1202**, ΔV_1 represents the potential difference between the lower electrode **1210** and the middle electrode **1206**, ΔV_2 represents the potential difference between the upper electrode **1202** and the middle electrode **1206**, d_1 represents the distance between the middle electrode **1206** and the lower electrode **1210**, and d_2 represents the distance between the middle electrode **1206** the upper electrode **1202**. Let $A_1 = A$ and $A_2 = \alpha A$, where α is the area factor. The force equation then simplifies to:

$$F = \varepsilon_0 \alpha A V^2 \frac{(1-\alpha)}{2[(1-\alpha)d_2 + \alpha g]^2} \qquad (4)$$

[0127] Thus, the application of an electric field across electrodes having disparate areas results in a net upward force on the charge neutral, electrically isolated middle plate **1206**, causing it to move up towards the upper electrode **1202** in implementations where the surface area of the upper electrode **1202** is less than that of the lower electrode **1210**. The middle plate **1206** is configured to move upward such that it makes contact with the upper electrode **1202**, or with contacts (e.g., resistive contacts) on and/or in electrical communication with the upper electrode **1202**. As described in greater detail below with reference to Figures 23 and 25, the contact between the middle electrode **1206** and the upper electrode **1202** can change the charge on the middle electrode **1206.**

[0128] Figure 14 shows an example of a graph illustrating how the net upward electric force acting on the middle electrode **1206** varies with the distance d_2 between the upper electrode **1202** and the middle electrode **1206** in the analog interferometric modulator configuration of Figure 12. In this example, the voltage V applied between the upper electrode **1202** and the lower electrode **1210** is 100 volts, the area factor α is 0.25, the total gap distance g is 1,000 nm, and the pixel size is 53 μm resulting in an area A of 2809μm^2 in this configuration.

[0129] In some implementations, the lower electrode **1210** can have an surface area A_2 that is less than the surface area A_1 of the upper electrode **1202**. In such cases, application of a voltage between the upper electrode **1202** and the lower electrode **1210** will result in a non-uniform electric field and a net downward force on the middle electrode **1206**, which can move the middle electrode **1206** to contact the lower electrode **1210**. As explained elsewhere, this can be exploited to charge the middle electrode **1206** by physical contact with the lower electrode **1210**.

[0130] The upper electrode **1202** and the lower electrode **1210** can be configured to produce an electric field therebetween capable of moving the electrically isolated, charge neutral middle electrode **1206** when a voltage V is applied across the upper electrode **1202** and the lower electrode **1210**. The series combination of two capacitors, C_{top} being the capacitance between the upper electrode and the middle electrode and C_{bot} being the capacitance between the middle electrode and the lower electrode is given by

$$C_{total} = \frac{1}{\frac{1}{C_{top}} + \frac{1}{C_{bot}}} = \frac{1}{\frac{d_2}{\varepsilon_0 \varepsilon_{top} A_1} + \frac{(g - d_2)}{\varepsilon_0 \varepsilon_{bot} A}} = \frac{1}{d_2\left(\frac{1}{\varepsilon_0 \varepsilon_{top} A_1} - \frac{1}{\varepsilon_0 \varepsilon_{bot} A}\right) + \frac{g}{\varepsilon_0 \varepsilon_{bot} A}} \qquad (5)$$

where ε_0 is the permittivity of free space, ε_{top} is the relative dielectric constant filling a top gap between the upper electrode and the middle electrode, A_1 is the surface area of the upper electrode, ε_{bot} is the relative dielectric constant filling a lower gap between the lower electrode and the middle electrode, d_2 is the gap between the upper and middle electrodes, g is the total distance between the upper and lower electrodes, and A is the surface area of the other lower and middle electrodes. If the electrode areas and the filling dielectric constants are the same for both the top and bottom capacitive sections, then the total capacitance value is a constant, independent of the gap between the upper and lower electrodes (for example, the distance d_2). If there is an imbalance in the electrode sizes and/or the dielectric constants of the gap filling media, then the total capacitance becomes a function of where the middle electrode is placed between the upper and lower electrodes. The electrical system will seek to increase the capacitance by moving the middle electrode up or down monotonically and this imbalance in the incremental capacitance (incremental with gap distance) can be a force that acts on the isolated and uncharged middle electrode.

[0131] In one implementation described above with reference to Figure 12, the upper electrode **1202** and the lower electrode **1210** having two different surface areas are configured to produce an electric field therebetween capable of moving the electrically isolated, charge neutral middle electrode **1206.** As explained above, the total capacitance is a function of where the middle electrode **1206** is placed between the upper electrode **1202** and lower electrode **1210**. Application of a voltage V across the upper electrode **1202** and the lower electrode **1210** produces a non-uniform electric field that can influence the middle electrode **1206** to move towards the upper electrode **1202** or the lower electrode **1210**. In another example, the electrically isolated, charge neutral middle electrode **1206** can be moved by an electric field generated between an upper and lower electrodes having different shapes. In one implementation, the upper and lower electrodes having different shapes have the same or substantially the same surface area. In another implementation, the upper and lower electrodes having different shapes have different surface areas. Such implementations may generate more electric field lines in certain areas between the upper and lower electrode, increasing the flux of the electric field in such areas. In another example discussed below with reference to Figure 15A, a voltage applied between an upper electrode and a lower electrode, with a grounded complimentary electrode near the upper electrode, can produce an electric field that can influence the electrically isolated, charge neutral middle electrode to move toward the upper electrode. In still another implementation, a lower and upper electrode configuration that cannot be approximated as a parallel plate electrode configuration can produce an electric field an electric field capable of moving the electrically isolated, charge neutral middle electrode. In yet a further implementation, an upper gap between an upper electrode **1202** and a middle electrode **1206** or a lower gap between a lower electrode **1210** and the middle electrode **1206** may be filled with a dielectric fluid or gas, or both the upper gap and the lower gap may be filled with a dielectric fluid or gas. The rate of change of capacitance as the upper gap changes differs from the rate of change of capacitance as the lower gap changes, causing the middle electrode **1206** to move towards the upper electrode **1202** or the lower electrode **1206** upon application of a voltage V across the upper electrode **1202** and the lower electrode **1210**. While certain implementations may be described as relating to a non-uniform electric field and/or certain capacitance characteristics, a person having ordinary skill in the art will understand there may be other ways to characterize and describe the electrical and physical properties of such implementations, and the included descriptions are not intended to be limiting.

Compound Electrode Configuration

[0132] Figure 15A shows an example of a cross-section of an analog interferometric modulator **1500** which includes a middle movable electrode **1506**, an upper electrode **1502**, and a lower electrode **1510** spaced apart from the upper electrode **1502** by a constant gap g. In a relaxed (or unactuated) position, the middle electrode **1506** is electrically isolated and is positioned within gap g. The middle electrode **1506** can have a net zero electrical charge in this implementation.

[0133] The modulator **1500** also includes a complementary electrode **1524** aligned laterally relative to the upper electrode **1502**. In the illustrated implementation, the complementary electrode **1524** is connected to electrical ground and electrically isolated from the upper electrode **1502**, such that the complementary electrode **1524** and the upper electrode **1502** are two electrically separate electrodes.

[0134] As illustrated in Figure 15B and described in greater detail below with reference to Figure 32, however, the upper electrode **1502** and the complementary electrode **1524** can be configured to be electrically connected during a calibration procedure to form a “compound” electrode **1526**. Figure 15B shows an example of the analog interferometric modulator **1500** after the compound electrode **1526** has been formed. When referred to herein, a “compound electrode” refers to the two electrodes that are included in the compound electrode in a state when they are electrically connected. The compound electrode **1526** has a surface A_2 that, in some implementations, is the same or substantially the same as the surface area A_1 of the lower electrode **1510**. In one implementation, when the complementary electrode **1524** is electrically connected to the upper electrode **1502** to form a compound electrode **1526**, the compound electrode **1526** configured as a parallel plate, such that applying a voltage across the compound electrode **1526** and the lower electrode **1510** generates a generally uniform electric field. This uniform electric field can be used during normal IMOD operations to, for example, move the middle electrode **1506** to various positions to reflect various colors. Additionally, during actuation and calibration procedures described with reference to Figures 26–33, the complementary electrode **1524** can aid actuation and calibration of the middle electrode **1506** as described below.

[0135] In some implementations, the complementary electrode **1524** may be disposed below the middle electrode **1506** and aligned laterally relative to the lower electrode **1510**, such that the lower electrode **1510** and the complementary electrode **1524** may form a compound electrode **1526**.

[0136] Referring again to Figure 15A in which the complementary electrode **1524** is connected to electrical ground and electrically isolated from the upper electrode **1502**, the electrode configuration illustrated in Figure 15A can increase the upward electric force acting on the middle electrode **1506** for a given applied voltage V. The complementary electrode **1524** can induce a positive charge on the top side **1528** of the middle electrode **1506** at its right and left ends. Because the middle electrode **1506** is net charge neutral and electrically isolated, the lower electrode **1510** induces a smaller positive charge on the bottom side **1530** of the middle electrode **1506** than in the configuration illustrated in Figure 12. As a result, the magnitude of the upward force acting on the middle electrode **1506** is increased compared to the configuration shown in Figure 12 where electric field non-uniformity is achieved solely through upper and lower electrodes of different areas.

[0137] Figure 16 shows an example of a schematic characterizing the analog interferometric modulator configuration shown in Figure 15A as an equivalent circuit. The forces acting on the middle electrode **1506** will now be further described in greater detail with reference to Figure 16. In this implementation, the surface area of the lower electrode **1510** is A, the surface area of the upper electrode **1502** is αA, and the surface area of the grounded complementary electrode **1524** is $(1-\alpha)A$. The potential difference between the upper electrode **1502** and the middle electrode **1506** is given by the equation:

$$\Delta V_2 = \frac{(C_1 + C_p)}{C_1 + C_2 + C_p} V = \frac{\left(\frac{1}{d_1} + \frac{1-\alpha}{d_2}\right)}{\frac{1}{d_1} + \frac{\alpha}{d_2} + \frac{1-\alpha}{d_2}} V \tag{6}$$

The potential difference between the lower electrode **1510** and the middle electrode **1506** is given by the equation:

$$\Delta V_1 = \frac{C_2}{C_1 + C_2 + C_p} V = \frac{\left(\frac{\alpha}{d_2}\right)}{\frac{1}{d_1} + \frac{\alpha}{d_2} + \frac{1-\alpha}{d_2}} V \tag{7}$$

The net force acting on the middle electrode **1506** is in an upward direction (e.g., toward the upper electrode **1502**), and is given by the equation:

$$F = \frac{\varepsilon_0 \alpha A (\Delta V_2)^2}{2d_2^2} + \frac{\varepsilon_0 (1-\alpha) A (\Delta V_1)^2}{2d_2^2} - \frac{\varepsilon_0 A (\Delta V_1)^2}{2d_1^2} \tag{8}$$

Comparing equation (8) to equation (4) above, it is evident that the magnitude of the net force shown in equation (8), corresponding to the implementation illustrated in Figure 15A, is larger than the magnitude of the net force acting on the middle electrode **1206** in the implementation illustrated in Figure 12.

[0138] Figure 17 shows an example of a graph illustrating on a logarithmic scale the magnitude of the net upward forces acting on the middle electrode **1206** in the Figure 12 configuration and the middle electrode **1506** in the Figure 15A configuration, as a function of the distance d_2 between the upper electrode **1202**, **1502** and the middle electrode **1206**, **1506**. In both implementations, the voltage V applied between the upper electrodes **1202**, **1502** and the lower electrodes **1210**, **1510** is 100 volts and the area factor α is 0.25. Figure 17 demonstrates that the magnitude of the net force F acting on the middle electrode **1506** in the Figure 15A configuration, in which the complementary electrode **1524** is connected to electrical ground and electrically isolated from the upper electrode **1502**, is greater than the magnitude of the net force F acting on the middle electrode **1206** for the single upper electrode **1202** configuration, where d_2 is less than 700 nm. Thus, the electrode configuration illustrated in Figure 15A may increase the upward electric force acting on the middle electrode **1506** for a given voltage V.

[0139] Figures 18–20 illustrate various electrode configurations including an upper electrode and a complementary electrode that can be electrically isolated and/or connected to form a compound electrode. Figure 18 shows an example of a plan view of the complementary electrode **1524** and the upper electrode **1502** shown in Figure 15A. In this implementation, a compound electrode may be formed in a ring configuration when the circular upper electrode **1502** is electrically connected to the ring-shaped complementary electrode **1524**. The complementary electrode **1524** is aligned laterally relative to the upper electrode **1502**. In this configuration, the upper electrode **1502** is positioned laterally inside the ring-shaped complementary electrode **1524**.

[0140] Implementations of compound electrodes described herein are not limited to circular or ring shapes. For example, Figure 19 shows an example of another electrode configuration, including a square-shaped upper electrode **1902** electrically isolated and/or connected to a square-frame-shaped complementary electrode **1924**. The upper electrode **1902** is positioned laterally inside the square-shaped complementary electrode **1924**. When electrically connected, the upper electrode **1902** and the complementary electrode **1924** can form a compound electrode having a surface area that is substantially the same as the surface area of a lower electrode **1910**.

[0141] Figure 20 shows an example of an interlocking configuration, where a complementary electrode **2024** is aligned laterally relative to an upper electrode **2002**. When electrically connected together, the electrodes **2002**, **2024** can form a compound electrode that has a surface area that is substantially the same or substantially the same as the surface area of a lower electrode **2010**. A person of ordinary skill in the art will understand other shapes and configurations for compound electrodes are also possible.

Placing Charge on an Electrode

[0142] Implementations of analog interferometric modulators described above can actuate a charge-neutral, electrically isolated middle electrode such that the middle electrode moves toward the upper or the lower electrode in the presence of a non-uniform electric field. Methods of providing a charge to the middle electrode after actuating its movement will now be described with reference to Figures 21–25.

Direct Charging of the Electrode

[0143] Figure 21 shows an example of a cross-section of an analog interferometric modulator **2100** which includes a middle electrode **2106** and an upper electrode **2102**, and a lower electrode **2110**. In this implementation, the upper electrode **2102** has a surface area that is less than the surface area of the middle electrode **2106** and the lower electrode **2110**. The middle electrode **2106** is illustrated prior to being actuated in the presence of a non-uniform electric field between the upper electrode **2102** and the lower electrode **2110**. Prior to being actuated, the middle electrode **2106** is disposed in a first position in the gap g between the upper electrode **2102** and the lower electrode **2110**. The middle electrode **2106** is electrically isolated in the first position as described in detail above with reference to Figure 12. Prior to actuation, the middle electrode **2106** has a net neutral electric charge. The modulator **2100** can also include one or more electrical contacts, for example, one or more conductive posts **2132** disposed on the upper electrode **2102**.

[0144] Figure 22 shows an example of a flowchart illustrating one method **2200** for providing charge onto a middle electrode of modulator **2100** in Figure 21. The method **2200** begins at block **2202** in which a charging actuation voltage V_{charge} is applied to produce a non-uniform electric field between the upper (or first) electrode **2102** and the lower (or second) electrode **2110**. The voltage V_{charge} can be less than 100 volts in some implementations. The voltage V_{charge} can between about 10 and about 20 volts in other implementations. In some cases, the voltage V_{charge} is under about 20 volts. As described in greater detail above, the middle electrode **2106** can be actuated and moved toward either the upper electrode **2102** or the lower electrode **2110** under the influence of the non-uniform electric field between electrodes **2102** and **2110** having disparate areas.

[0145] At block **2204,** upon the application of the charging actuation voltage the middle electrode **2106** moves, within the gap g, towards the first or second electrode. The remainder of the description of Figure 22 will describe the process with reference to the upper (first) electrode, but it is understood that method **2200** may also be implemented using the lower electrode using an applied charging actuation voltage of the appropriate polarity. In implementations where the middle electrode **2106** moves towards the upper electrode **2102**, the middle electrode **2106** moves in an upward direction under the influence of the non-uniform electric field towards the upper electrode **2102**. In other words, the middle electrode **2106** moves away from the first position in the gap g towards a second position closer to the upper electrode **2103**. At block **2206**, the middle electrode **2106** moves to a second position in the gap g and contacts an electrically conductive structure (for example, conductive posts **2132**) which is electrically connected to the upper electrode **2102**. An example where the middle electrode **2106** is in the second position in the gap g is shown in Figure 23.

[0146] Figure 23 shows an example of a cross-section of the modulator **2100** illustrating the middle electrode **2106** in the second position, after the middle electrode **2106** makes contact with the conductive posts **2132** on the upper electrode **2102**. When moved to the second position, the middle electrode **2106** contacts the conductive posts **2132**, and the middle electrode **2106** is electrically connected to the upper electrode **2102** (through the conductive posts **2132**) and is no longer electrically isolated.

[0147] With reference again to Figure 22, next at block **2208**, an electrical charge on the middle electrode **2106** is changed. After electrical contact is made, the middle electrode **2106** begins to lose some of its negative charge through the conductive posts **2132**, by dissipating or “leaking” of its charge. Thus, the middle electrode **2106** is not charge neutral in the second position, and becomes increasingly positively charged as leaking continues. In some implementations, the conductive posts **2132** are resistive posts that provide resistance to reduce the rate of change of the charge on the middle electrode **2106**. In some implementations, a resistor exists in a path between the conductive posts **2106** and ground.

[0148] Contact between the middle electrode **2106** and the upper electrode **2102** can be sensed such that the time at which charge begins to leak off of the middle electrode **2106** can be measured. In one implementation, the charging actuation voltage V_{charge} is decreased to a selected calibration voltage V_{cal} once charge on the middle electrode **2106** begins to change at block **2208**. Methods for determining a defined calibration voltage V_{cal} are discussed in greater detail below with reference to block **3104** in Figure 31.

[0149] The rate at which a negative charge is dissipated from the middle electrode **2106** can also be measured. In one implementation (discussed in greater detail with reference to Figure 37), the rate of dissipation can be decreased by increasing the resistance of the conductive path between the middle electrode **2106** and the upper electrode **2102**. For example, the resistance may be increased by connecting the conductive posts **2132** to the upper electrode **2102** through a resistor. Alternatively, conductive posts **2132** may be made of a highly resistive material.

[0150] As the middle electrode **2106** develops a net positive charge, the net upward electric force acting on the middle electrode **2106** diminishes. The middle electrode **2106** eventually develops just enough net positive charge that the upward electric force acting on the middle electrode **2106** can no longer balance the downward mechanical force exerted on the middle electrode **2106** by the mechanical spring force acting on the middle electrode **2106**.

[0151] At block **2210,** the middle electrode **2106** breaks contact with the conductive posts **2132** and moves in a downward direction away from the upper electrode **2102** to a third position in the gap g. In one implementation, the middle electrode **2106** moves to a third position just below the conductive posts **2132** after breaking contact. As used herein, a middle electrode **2106** positioned “just below” a conductive post **2132** is not in physical contact with the conductive post **2132**. In one implementation, the middle electrode **2106** moves to a distance of approximately 10 nanometers below the conductive posts **2132** when the middle electrode **2106** moves to a third position just below the conductive posts **2132**. After breaking electrical contact with the conductive posts **2132**, the middle electrode **2106** is electrically isolated. In contrast to the net-neutral middle electrode **2106** in the first position, the middle electrode **2106** is positively-charged in the third position.

[0152] The method **2200** next moves to block **2212**, in which charge on the middle electrode **2106** is calibrated. Devices and methods for calibrating charge on the middle electrode **2106** are described below with reference to Figures 39–41.

[0153] When the middle electrode **2106** moves to the third position at block **2210**, the amount of positive charge on the middle electrode **2106** is related to the strength of the spring force (e.g., the stiffness of the springs) holding the middle electrode **2106**. The stronger the spring force, the sooner the middle electrode **2106** breaks contact with the conductive posts **2132** resulting in the middle electrode **2106** having less of a positive charge than if it were connected longer. In one implementation, for example, the springs supporting a first middle electrode A are relatively stiffer than the springs holding a second middle electrode B. As a result, less negative charge is leaked off of the first middle electrode A (and consequently less positive charge imparted to the first middle electrode A), before the relatively stronger spring mechanical force acts to move the first middle electrode A down away from the upper electrode **2102**. In contrast, more negative charge is leaked off of the second middle electrode B (and more positive charge imparted to the second middle electrode B), before the mechanical force imparted by the relatively weaker springs will overcome the upward electric force acting on the second middle electrode B.

Induction Charging of the Electrode

[0154] Figure 24 shows an example of a cross-section of an analog interferometric modulator **2400** capable of providing charge onto a charge-neutral, electrically isolated middle electrode. The modulator **2400** is similar to the modulator **2100** shown in Figure 21 and includes a middle electrode **2406**, an upper electrode **2402**, and a lower electrode **2410**. In this implementation, the modulator **2400** includes a complementary electrode **2424** aligned laterally relative to the upper electrode **2402**. As described above with reference to the compound electrode **1526** illustrated in Figure 15B, the complementary electrode **2424** and the upper electrode **2402** can be electrically connected to form a compound electrode. In the implementation illustrated in Figure 24, however, the complementary electrode **2424** is electrically isolated from the upper electrode **2402**, and is connected to electrical ground.

[0155] As illustrated, the middle electrode **2406**, prior to actuation, is disposed in a first position in the gap between the upper electrode **2402** and the lower electrode **2410**. The middle electrode **2406** is electrically isolated in the first position. Prior to actuation, the middle electrode **2406** has a net neutral electric charge. The modulator **2400** can also include one or more electrical contacts. For example, one or more conductive posts **2432** are disposed on the complementary electrode **2424**.

[0156] Implementations of the analog modulator **2400** can provide a charge to the middle electrode **2406** through induction in accordance with the method **2200** illustrated in Figure 22. For example, a charging actuation voltage V_{charge} is applied to produce a non-uniform electric field between the upper or first electrode **2402** and the lower or second electrode **2410**. At block **2204**, the middle electrode **2406** moves in the gap in an upward direction towards the upper electrode **2402** under the influence of the non-uniform electric field. The middle electrode **2406** moves away from the first position in the gap towards a second position closer to the upper electrode **2402**. At block **2206**, the middle electrode **2406** moves to a second position in the gap and contacts the conductive posts **2432** on the complementary electrode **2424**, and the middle electrode **2406** receives a charge.

[0157] Figure 25 shows an example of a cross-section of the modulator **2400** illustrating the middle electrode **2406** in the second position, after the middle electrode **2406** makes contact with the conductive posts **2432** on the complementary electrode **2424**. When the middle electrode **2406** contacts the conductive posts **2432**, the middle electrode **2406** is no longer electrically isolated and is directly electrically connected to the complementary electrode **2424** (through the conductive posts **2432**) in the second position. This contact between the middle electrode **2406** and the complementary electrode **2424** provides a path to ground, which provides inductive charging of the middle electrode **2406**.

[0158] At block **2208** of Figure 22, the electrical charge on the middle electrode **2406** is changed. After electrical contact is made, positive charges on the middle electrode **2406** begin to dissipate (or leak) through the conductive posts **2432**. Thus, the middle electrode **2406** is not charge neutral in the second position, and becomes increasingly negatively charged as leaking continues. The rate at which charge on the middle electrode **2406** is dissipated can be controlled. For example, in one implementation described with reference to Figure 29, the rate of dissipation is decreased using a resistor (not illustrated in Figures 24–25) connecting the complementary electrode **2424** and the conductive posts **2432** to ground.

[0159] The charging actuation voltage V_{charge} can be decreased to a selected calibration voltage V_{cal} once discharge begins at block **2208**. As discharge continues and the middle electrode **2406** develops a net negative charge, the attraction between the upper electrode **2402** and the middle electrode **2406** diminishes. The middle electrode **2406** eventually develops just enough net negative charge that the upward electric force acting on the middle electrode **2406** can no longer balance the downward mechanical force exerted on the middle electrode **2406** that positions the middle electrode **2406** in the gap.

[0160] With reference again to Figure 22, after contact as shown in Figure 25, at block **2210**, the middle electrode **2406** breaks contact with the conductive posts **2432** and moves in a downward direction away from the upper electrode **2402** to a third position in the gap. When the middle electrode **2406** is released at block **2210**, the amount of positive charge on the middle electrode **2406** is related to the stiffness of the springs holding the middle electrode **2406**, as described in greater detail above.

[0161] After breaking electrical contact with the conductive posts **2432** and moving to the third position, the middle electrode **2406** is again electrically isolated but is now negatively-charged. Implementations of analog interferometric modulators **2400** can thus inductively charge a net-neutral, electrically isolated middle electrode by subjecting the middle electrode to a non-uniform electric field and moving the middle electrode into electrical contact with a charged plate, for example, in the implementations described above, the complimentary electrode **2424**.

[0162] The method **2200** next moves to block **2212**, in which charge on the middle electrode **2406** is calibrated. Devices and methods for calibrating charge on the middle electrode **2406** are described below with reference to Figures 31–33.

[0163] A person of ordinary skill in the art will understand that actuation and charging methods and devices described herein are not limited to an upper electrode **2402** that is subject to an applied voltage. For example, in one implementation, the upper electrode **2402** is connected to ground, and a charging actuation voltage is applied between the complementary electrode **2424** and the lower electrode **2410** to produce a non-uniform electric field. Conductive posts **2432** can be disposed on the upper electrode **2402** in such an implementation.

Calibrating Charge on the Electrode

[0164] In addition to actuating and providing charge onto an electrode, implementations of analog interferometric modulators described herein can calibrate the charge that has been placed on the electrode. Calibrating the charge on the middle electrodes in an array of interferometric modulators can compensate for variances in the spring constants of the mechanical structures holding the middle electrodes. Following a calibration procedure described in detail below, a series of positively- or negatively-charged, electrically isolated middle electrodes are suspended between their respective upper and lower electrodes. The positive (or negative) charge on each calibrated middle electrode is a function of the stiffness of the particular springs holding that electrode.

[0165] For example, following calibration procedures described herein, a middle electrode E_1 supported by relatively weak springs will have less positive charge than a middle electrode E_2 supported by relative stronger springs. If one global voltage, for example 1 volt, is applied across the upper and lower electrodes associated with E_1 and E_2, the resulting electric force acting on E_1 and E_2 from the applied electric field will be proportional to the charge on E_1 and E_2. The force acting on E_2, with a greater positive charge, will be greater than the force acting on E_1, with a lesser positive charge. The larger electric force acting on E_2 can compensate for the larger mechanical force exerted by its stiffer springs, such that it will move to the same position as E_1 with the same applied voltage. Thus, calibration of charge on a series of middle electrodes can be used to move the electrodes to the same location despite variances in their associated spring constants.

Induction Charging and Calibration of the Electrode

[0166] Systems and methods for inductively charging and calibrating a charge-neutral, electrically isolated electrode will now be described in detail with reference to Figures 26–33.

[0167] Figure 26 shows an example of a cross-section of an analog interferometric modulator **2600** capable of providing charge onto a charge-neutral, electrically isolated electrode and capable of then calibrating that charge to account for the particular mechanical spring force acting on the electrode. The modulator **2600** includes an upper or first electrode **2602** separated from a lower or second electrode **2610** by a gap g. The modulator **2600** also includes a complementary electrode **2624** aligned laterally relative to the upper electrode **2602**. The modulator **2600** also includes switches **2638** that allow the complementary electrode **2624** to be electrically connected to the upper electrode **2602** or, alternatively, switches **2638** allows the complementary electrode **2624** to be connected to ground.

[0168] The modulator **2600** also includes a middle electrode **2606** suspended in the gap g and supported by springs **2634**. When the middle electrode **2606** is suspended in the gap g in a first position as shown in Figure 26, the middle electrode **2606** is electrically isolated. The middle electrode is also charge neutral in the first position. When the middle electrode **2606** moves away from the first position, mechanical restorative forces applied to the middle electrode **2606** by the springs **2634** act to restore the middle electrode **2606** to the first position.

[0169] The complementary electrode **2624** includes one or more conductive posts **2632**. In some implementations, the complementary electrode **2624** is initially electrically isolated from the upper electrode **2602**, and is connected to electrical ground through a resistive component **2636**. In one implementation, the resistive component **2636** is a resistor configured to reduce current flow through the conductive posts **2632**. As described below with reference to Figure 32, the complementary electrode **2624** and the upper electrode **2602** can be electrically connected to form a compound electrode **2626**.

[0170] Figure 27 shows an example of a cross-section of the modulator **2600** illustrating the middle electrode **2606** disposed in a first position in the gap g between the upper electrode **2602** and the lower electrode **2610**. A charging actuation voltage V_{charge} is applied to the upper electrode **2602** and the lower electrode **2610** to produce a non-uniform electric field between, as described in greater detail above with reference to Figures 15 and 24.

[0171] Figure 28 shows an example of a cross-section of the modulator **2600** after the middle electrode **2606** is actuated under the influence of the non-uniform electric field. In this view, the middle electrode **2606** has moved upward away from the first position toward the upper electrode **2602**, but the middle electrode **2606** is still electrically isolated and charge neutral, having the same number of positive charges as negative charges.

[0172] Figure 29 shows an example of a cross-section of the middle electrode **2606** in the second position, after it has made electrical contact with the conductive posts **2632** on the complementary electrode **2624**. As described in greater detail with reference to Figure 25, the negative charges on the middle electrode **2606** are bound by the positive charges on the upper electrode **2602**, while the electrical contact between the middle electrode **2606** and the complementary electrode **2624** neutralizes positive charges on the middle electrode **2606**. The mechanical restoring force exerted on the middle electrode **2606** by the springs **2634** is less than the electric force exerted by the electric field between the upper electrode **2602** and the lower electrode **2610**. As positive charge on the middle electrode **2606** continues to dissipate through electrical contact with the conductive posts **2632**, the middle electrode **2606** becomes increasingly negatively charged. The description above and elsewhere in this disclosure assumes that a positive voltage is applied between the lower electrode **2610** and the upper electrode **2602**. However, in implementations where the applied charging actuation voltage is negative, the negative charge on the middle electrode **2606** will dissipate so that the middle electrode **2606** becomes increasingly positively charged.

[0173] The rate of dissipation of charge on the middle electrode can be controlled. For example, in one implementation, the rate of discharge is controlled and/or decreased by connecting the conductive posts **2632** and the complementary electrode **2624** to electrical ground through a resistor **2636**. The rate of discharge can be decreased by selecting a resistor **2636** having a specific or desired resistance to connect the conductive posts **2632** and the complementary electrode **2624** to electrical ground.

[0174] Figure 30 shows an example of a cross-section of the middle electrode **2606** in the third position, after the restoring spring force overcomes the electric force acting on the middle electrode **2606** and pulls the middle electrode **2606** downward away from the upper electrode **2602**. The middle electrode is again electrically isolated, but is now negatively charged. The negative charge on the middle electrode **2606** is related to the stiffness of the springs **2634** supporting the middle electrode **2606**.

[0175] Methods of actuating and providing charge onto a middle electrode **2606** have been described with reference to Figures 26–30. Methods and systems for calibrating a charge placed onto the middle electrode **2606** will now be described with reference to Figures 31–33.

[0176] Figure 31 shows an example of a flowchart illustrating one method **3100** for calibrating the amount of charge on a middle electrode using, for example, the modulator **2600** of Figure 26. In the disclosure that follows, reference will be also be made to features illustrated in Figures 32 and 33 as they relate to the blocks in the method 3100 illustrated in Figure 31. The method **3100** begins at block **3102** in which the complementary electrode **2624** is electrically connected to the upper electrode **2602** to form a compound electrode **2626**. In one implementation, the electrodes **2624** and **2602** are connected together with one or more switches **2638** configured to isolate or connect the electrodes **2624** and **2602**. In some aspects, each modulator **2600** includes 2 switches per pixel. In another implementation, the switches **2638** include transistors that can close to form the compound electrode **2626** or open to segment the compound electrode **2626** into two separate electrodes: complementary electrode **2624** and upper electrode **2602**.

[0177] Figure 32 shows an example of a cross-section of the modulator **2600** after the one or more switches **2638** have closed to form a compound electrode **2626**, which includes the complementary electrode **2624** and the upper electrode **2602**. The complementary electrode **2624** is no longer electrically isolated from the upper electrode **2602**, but electrically connected to it through the resistor **2636**. Now, both the complementary electrode **2624** and the upper electrode **2602** are electrically isolated from ground. After the one or more switches **2638** are closed, the surface area of the compound electrode **2626** is the same as or substantially the same as the surface area of the lower electrode **2610**.

[0178] After the middle electrode **2606** is actuated and is charged, as described above with reference to Figures 26–30, the middle electrode **2606** remains in the third position in the gap between the compound electrode **2626** and the lower electrode **2610**. In some implementations, the position of the middle electrode **2606** at the beginning of the calibration procedure is referred to as a "first" position. One having ordinary skill in the art will understand that the middle electrode **2606** is in the same position in the gap g whether it is described as being in the "third" position at the end of a charging procedure or in a "first position" at the beginning of a calibration procedure.

[0179] With reference again to Figure 31, in block **3104**, a voltage is applied between the lower electrode **2610** and the compound electrode **2626** equal to a selected calibration voltage, V_{cal}. Unlike the charging actuation voltage discussed above to place a charge onto the middle electrode 2606, the voltage V_{cal} applied between the lower electrode **2610** and the compound electrode **2626** is configured to create a uniform or substantially uniform electric field between the electrodes **2602** and **2626**. The voltage V_{cal} can be under 100 volts in some aspects. The voltage V_{cal} can between about 10 an about 20 volts in other aspects. In some cases, the voltage V_{cal} is under about 20 volts. A controller can be configured to apply the calibration voltage across the compound electrode **2626** and the lower electrode **2610** during a calibration procedure.

[0180] In some implementations, the calibration voltage V_{cal} is determined at the time of manufacture of the modulator **2600** or an array of modulators **2600**. For example, the mechanical spring force acting on the middle electrode **2606** in each modulator **2600** in an array of modulators can first be estimated to determine a range of mechanical spring forces in the array. This range can then be adjusted to account for anticipated changes in the mechanical spring forces due to aging, environmental factors, and other influences during the anticipated life of the array of modulators **2600**. A single calibration voltage V_{cal} to be applied to each modulator **2600** in the array can then be chosen based on this information. In one implementation, V_{cal} is chosen to ensure that the modulator **2600** having the strongest mechanical spring force in the array will move upward towards the second position in electrical contact with the compound electrode **2626**. In another implementation, V_{cal} is chosen to ensure that the middle electrode **2606** in each modulator **2600** in the array moves upward towards the second position in electrical contact with the compound electrode **2626** when V_{cal} is applied across the array to each modulator **2600**.

[0181] The method next moves to block **3106**, in which the negatively-charged middle electrode moves upward toward the compound electrode **2626** under the influence of the uniform electric field between the lower and compound electrodes **2610**, **2626**. The electric force applied to the middle electrode **2606** by the electric field thus causes the middle electrode **2606** to move away from the first position towards a second position in electrical contact with the compound electrode **2626**. Next at block **3108**, the middle electrode **2606** reaches the second position and is electrically connected to the compound electrode **2626** through the one or more conductive posts **2632** on the complementary electrode **2624**.

[0182] Figure 32 shows an example of a cross-section of the modulator **2600** illustrating the middle electrode **2606** in the second position and contacting the conductive posts **2632**. The middle electrode **2606** is no longer electrically isolated and is directly electrically connected to the compound electrode **2626** (through the conductive posts **2632**) in the second position.

[0183] With reference again to Figure 31, in block **3110**, the electrical charge on the middle electrode **2606** is changed. After the middle electrode **2606** contacts the compound electrode **2626**, some of the charge on the middle electrode **2606** is neutralized, until the middle electrode **2606** can no longer resist the mechanical restoring force of the springs **2634**.

[0184] Moving next to block **3112**, the middle electrode **2606** moves in a downward direction to a third position in the gap g when the mechanical restorative force exceeds the electric force applied to the third electrode **2606**. The third position in a calibration procedure, for example the third position referenced in block **3112** in Figure 31, can be but is not necessarily the same as a third position in an actuation procedure, for example the third position referenced in block **2210** in Figure 22. Figure 33 shows an example of a cross-section of the modulator **2600** after the middle electrode separates from the conductive posts **2632** and moves to the third position, thus isolating the negative charges which remain on the middle electrode **2606**. When the middle electrode **2606** is released at block **3112**, the amount of negative charge on the middle electrode **2606** is related to the stiffness of the springs holding the middle electrode **2606**. The modulator **2600** is now calibrated and in an operational range or operationally ready state.

[0185] Figure 33A shows an example of a cross-sectional schematic of an analog interferometric modulator having a middle electrode **2606** with a calibrated charge Q_c. The calibrated charge Q_c is related to the stiffness of springs **2634** supporting the middle electrode **2606**. In one implementation, the relationship between the calibrated charge Q_c on the middle electrode **2606** and the stiffness of the springs **2634** supporting the middle electrode **2606** is shown in the following equation:

$$Q_c = \frac{\varepsilon_0 A V_c}{2x_c}\left[1 - \sqrt{1 + \frac{4Kd_0x_c^2}{\varepsilon_0 A V_c^2}}\right] \tag{9}$$

where ε_0 represents the dielectric permittivity of a vacuum, A represents the surface area of middle electrode **2606**, V_c represents the voltage charging the upper electrode **2602**, x_c represents the distance from the location of the middle electrode **2606** at the quiescent (relaxed) position to a conductive post **2632**, K represents the spring constant, and d_0 represents the distance of the gap g.

[0186] The calibration procedure described with reference to Figure 31 can be applied to a series of modulators **2600** in an array. Following the calibration procedure described in Figure 31, a plurality of negatively-charged, electrically isolated middle electrodes are suspended between their respective upper and lower electrodes. The negative charge on each calibrated middle electrode is a function of the stiffness of the particular springs holding that electrode. The amount of negative charge on each calibrated middle electrode is also sufficient to ensure that each of the middle electrodes will reliably and consistently move to the same location when the same voltage is applied across all of the middle electrodes. Thus, calibration of charge on a series of middle electrodes can be used to move the electrodes to the same location despite variances in their associated spring constants.

[0187] The calibration procedure described herein can be used to calibrate modulators **2600** in a display. In one implementation, a display includes a plurality of analog interferometric modulators **2600** arranged in an array. Drive voltages can be applied across the plurality of modulators **2600** in the array to operate the display and display data. Operating the display can include actuating or moving the middle electrodes **2606** of the modulators in the array to various locations in the gap formed by the upper electrodes **2602** and lower electrodes **2610** to display an image and/or data. The location of the middle electrode **2606** in the gap helps to determine the reflected displayed color of an analog interferometric modulator pixel. Operating or driving the display can result in charge being dissipated from the middle electrode **2606** in each of the plurality of modulators **2600**. In some implementations, the middle electrodes **2606** become charge neutral after the display is operated. In other implementations, a charge remains on middle electrodes **2606** after the display is operated. In some implementations, a dissipation voltage may be applied to cause the middle electrode **2606** to contact a conductive post **2632** in order to dissipate all charge from the middle electrode **2606**.

[0188] The actuation, charging, and calibration procedures described with reference to Figures 26–33 can then be performed in preparation to display data on the display a second time. The complementary electrode **2624** in each of the modulators **2600** can be electrically isolated from the upper electrode **2602** and connected to electrical ground. The actuation procedure described above with reference to Figures 27–28 can then be performed. For example, a charging actuation voltage can be applied across the upper electrode **2602** and the lower electrode **2610** of each of the modulators **2600** to produce a non-uniform electric field in the gap between the upper electrode **2602** and the lower electrode **2610**. The charging actuation voltage may be the same or substantially the same as the drive voltage. As described with reference to Figures 27–28, the middle electrodes **2606** in each of the modulators **2600** will be actuated or moved toward the upper electrode **2602**.

[0189] The charging procedure described with reference to Figures 29–30 can then be performed across all modulators **2600** in the array. As described with reference to Figures 31–33, a calibration procedure can then be performed on each modulator **2600** to calibrate the charge that has been placed on each middle electrode **2606**. In one implementation, the calibration voltage used to actuate the middle electrodes **2606** during the calibration procedure is less than the charging actuation voltage. Following the calibration procedure, the modulators **2600** are in an operationally ready state. Drive voltages can again be applied across the plurality of modulators to operate the display to display data, beginning the cycle again. In some implementations, before the cycle is begun again, a dissipation voltage may be applied to return the middle electrode **2606** to a charge-neutral state, as mentioned above, or the middle electrode **2606** can still retain some charge when it is further charged and then calibrated. It will be understood that the above-described cycle of operation (for example, data display), actuation, charging, and calibration can be repeated where useful and adjusted to account for variances in the rate of charge leakage from the middle electrodes **2606** over the lifetime of the device.

Switchless Charging and Calibration of the Electrode

[0190] Systems and methods for charging and calibrating a charge-neutral, electrically isolated electrode without the use of switches will now be described in detail with reference to Figures 34–41.

[0191] Figure 34 shows an example of a cross-section of an analog interferometric modulator **3400** capable of providing a charge onto a charge-neutral, electrically isolated electrode, then calibrating that charge to account for the particular mechanical spring force acting on the electrode, using a switchless calibration geometry. The modulator **3400** includes an upper or first electrode **3402** separated from a lower or second electrode **3410** by a gap g. The modulator **3400** also includes a middle electrode **3406** suspended in the gap g and supported by springs **3434**.

[0192] When the middle electrode **3406** is suspended in the gap g in a first position as shown in Figure 34, the middle electrode **3406** is electrically isolated. The middle electrode is also charge neutral in the first position. When the middle electrode **3406** moves away from the first position, mechanical restorative forces applied to the middle electrode **3406** by the springs **3434** act to restore the middle electrode **3406** to the first position.

[0193] The modulator **3400** includes one or more resistive contacts or posts **3432** aligned laterally relative to the upper electrode **3402**. The conductive posts **3432** are electrically connected to the upper electrode **3402** through a resistive component **3436**. In one implementation, the resistive component **3436** is a resistor configured to reduce current flow through the conductive posts **3432**.

[0194] Figure 35 shows an example of a cross-section of the modulator **3400** at the beginning of an actuation and charging procedure. As shown in Figure 27, the middle electrode **3400** is initially charge neutral. A charging actuation voltage V_{charge} is applied to produce a non-uniform electric field between the upper electrode **3402** and the lower electrode **3410** (such as described in greater detail above with reference to Figures 12 and 23). In this implementation, the upper electrode **3402** has a positive charge and the lower electrode **3410** has a negative charge (relative to each other) as a result of the applied voltage V_{charge}.

[0195] Figure 36 shows an example of a cross-section of the modulator **3400** after the middle electrode **3406** is actuated under the influence of the non-uniform electric field, as described in greater detail with reference to Figure 23. In this view, the middle electrode **3406** has moved upward away from the first position toward the upper electrode **3402**, but it is still electrically isolated and charge neutral.

[0196] Figure 37 shows an example of a cross-section of the modulator **3400** illustrating the middle electrode **3406** in the second position, after it has made electrical contact with the conductive posts **3432**. As described in greater detail with reference to Figure 23, the electrical contact between the middle electrode **3406** and the conductive posts **3432** decreases negative charges on the middle electrode **3406**. In one implementation, the rate of changing the charge on the middle electrode **3406** is controlled and/or decreased by connecting the conductive posts **3432** to the upper electrode **3402** through a resistor **3436**. For example, the rate of changing the charge on the middle electrode **3406** can be controlled and/or decreased by selecting a resistor **3436** having a specific or desired resistance to connect the conductive posts **3432** and the upper electrode **3402**.

[0197] The middle electrode **3406** is thus charged by direct contact with the conductive posts **3432**. The mechanical restoring spring force exerted on the middle electrode **3406** by the springs **3434** is less than the electric force exerted by the electric field between the upper and lower electrodes **3402**, **3410**. As negative charge on the middle electrode **3406** dissipates through electrical contact with the conductive posts **3432**, the middle electrode **3406** becomes increasingly positively charged.

[0198] Figure 38 shows an example of a cross-section of the modulator **3400** illustrating the middle electrode **3406** in the third position, after the restoring spring force overcomes the electric force acting on the middle electrode **3406** and pulls the middle electrode **3406** downward away from the conductive posts **3432**. The middle electrode is again electrically isolated, but is now positively charged. The positive charge on the middle electrode **3406** is related to the stiffness of the springs **3434** supporting the middle electrode **3406**. The middle electrode **3406** now has a charge and returns to an electrically isolated position in the gap g, prior to a calibration procedure to calibrate the charge.

[0199] Methods of actuating and directly providing charge onto a middle electrode **3406** have been described with reference to Figures 34–38. Methods and systems for calibrating the charge that has been placed on the middle electrode **3306** will now be described with reference to Figures 39–41.

[0200] At the end of the actuation and charging procedure described above with reference to Figures 34–38, the middle electrode **3406** remains in the third position in the gap g between the top electrode **3402** and the lower electrode **3410**. In some implementations, the position of the middle electrode **3406** at the beginning of the calibration procedure is referred to as a "first" position.

[0201] Figure 39 shows an example of a flowchart illustrating one method **3900** for calibrating charge on a middle electrode using the modulator **3400** of Figure 34. The method **3900** begins at block **3902** in which the voltage applied between the upper electrode **3402** is set to a selected calibration voltage V_{cal}. Methods to determine V_{cal} are described in greater detail above with reference to block **3104** of Figure 31. In some implementations, the polarity of the applied voltage is reversed, so that a negative voltage is applied to the upper electrode 3402 and a positive voltage is applied to the lower electrode **3410**.

[0202] At block **3904**, the positively-charged middle electrode moves upward toward the conductive posts **3432** under the influence of an electric field between the upper and lower electrodes **3402**, **3410**. The force applied to the middle electrode **3406** by the electric field causes the middle electrode **3406** to move away from the first position towards a second position in electrical contact with the conductive posts **3432**.

[0203] Next at block **3906**, the middle electrode **3406** moves to the second position and is electrically connected to the conductive posts **3432**.

[0204] Figure 40 shows an example of a cross-section of the modulator **3400** illustrating the middle electrode **3406** in the second position and contacting the conductive posts **3432**. The middle electrode **3406** is no longer electrically isolated and is directly electrically connected to the conductive posts **3432** in the second position.

[0205] Next at block **3908**, the electrical charge on the middle electrode **3406** is changed. As shown in Figure 40, after electrical contact is made between the middle electrode **3406** and the conductive posts **3432**, some of the positive charge on the middle electrode **3406** is depleted until the middle electrode **3306** can no longer resist the mechanical restoring force of the springs **3434**.

[0206] Moving next to block **3910**, the middle electrode **3406** moves in a downward direction to a third position in the gap g when the mechanical restorative spring force exceeds the force applied to the third electrode **3406**. Figure 41 shows an example of a cross-section of the modulator **3400** after the middle electrode separates from the conductive posts **3432** and moves to the third position, thus isolating the positive charges which remain on the middle electrode **3406**. When the middle electrode **3406** releases at block **3910**, the amount of positive charge on the middle electrode **3406** is related to the stiffness of the springs holding the middle electrode **3406**, as described in greater detail above. The modulator **3400** is now calibrated and in an operational range or operationally ready state.

[0207] The calibration procedure described with reference to Figure 39 can be applied to a series of modulators **3400** in an array. Following the calibration procedure described in Figure 39, a series of positively-charged, electrically isolated middle electrodes are suspended between their respective upper and lower electrodes. The positive charge on each calibrated middle electrode is a function of the stiffness of the particular springs holding that electrode. Calibration of charge on a series of middle electrodes can be used to move the electrodes to the same location for a given applied voltage despite variances in their associated spring constants.

[0208] The calibration procedure described with reference to Figure 39 can be used to calibrate modulators **3400** in a display. In one implementation, a display includes a plurality of analog interferometric modulators **3400** arranged in an array. Drive voltages can be applied across the plurality of modulators **3400** in the array to operate the display and display data. Operating the display can include actuating or moving the middle electrodes **3406** of the modulators in the array to various locations in the gap formed by the upper electrodes **3402** and lower electrodes **3410** to display an image and/or data. Operating the display can result in charge being dissipated from the middle electrode **3406** in each of the plurality of modulators **3400**. In some implementations, operating the display can result in charge being dissipated from the middle electrode **3406** in each of the plurality of modulators **3400**, such that the middle electrodes **3306** have an uncalibrated charge. In some implementations, the charge is purposefully dissipated from the middle electrode **3406** by applying a dissipation voltage.

[0209] The actuation, charging, and calibration procedures described with reference to Figures 34–41 can then be performed in preparation to display data on the display a second time. To begin, the actuation procedure described above with reference to Figures 35–36 can be performed. For example, a charging actuation voltage can be applied across the upper electrode **3402** and the lower electrode **3410** of each of the modulators **3400** to produce a non-uniform electric field in the gap between the upper electrode **3402** and the lower electrode **3410**. The charging actuation voltage may be the same or substantially the same as the drive voltage. As described with reference to Figures 35–36, the middle electrodes **3406** in each of the modulators **3400** will be actuated or moved toward the upper electrode **3402**.

[0210] The charging procedure described with reference to Figures 37–38 can then be performed across all modulators **3400** in the array. As described with reference to Figures 39–41, a calibration procedure can then be performed on each modulator **3400** to calibrate the charge that has been placed on each middle electrode **3406**. In one implementation, the calibration voltage used to actuate the middle electrodes **3406** during the calibration procedure is less than the charging actuation voltage. Following the calibration procedure, the modulators **3400** are in an operationally ready state. Drive voltages can again be applied across the plurality of modulators to operate the display to display data, beginning the cycle again. In some implementations, multiple drive voltages are applied on any given modulator to display different colors at different points in time before it is actuated, charged, and calibrated once again. In some implementations, before the cycle is begun again, a dissipation voltage may be applied to return the middle electrode **3406** to a charge-neutral state, as mentioned above, or the middle electrode **3406** can still retain some charge when it is further charged and then calibrated. The above-described cycle of operation (for example, data display), actuation, charging, and calibration can be repeated where useful and adjusted to account for variances in the rate of charge leakage from the middle electrodes **3406** over the lifetime of the device.

[0211] The voltage to actuate the middle electrode in order to calibrate charge on the middle electrode in the "switchless" implementation illustrated in Figure 34 will be greater than the voltage to actuate the middle electrode for calibration in the implementation illustrated in Figure 26. The upper electrode **3402** in the "switchless" implementation illustrated in Figure 34 has a smaller surface area than the compound electrode **2626** in the implementation illustrated in Figure 32. As described above with reference to Figure 17, the force exerted by the smaller upper electrode **3402** in the "switchless" implementation illustrated in Figure 34 will generally be less than the force exerted by the compound electrode **2626** in the implementation illustrated in Figure 32, thus a higher voltage will generally be used to actuate the middle electrode. It will also be understood that the capacitance between the upper electrode **3402** and the lower electrode **3410** in the implementation illustrated in Figure 34 is not a constant, but a function of the position of the middle electrode **3406**. As a result, the capacitance between the upper electrode **3402** and the lower electrode **3410** is a nonlinear function of the displacement of the middle electrode **3406**. The degree of nonlinearity is governed by the disparity in area between the upper electrode **3402**, the middle electrode **3406**, and the lower electrode **3410**.

[0212] The actuation, charging, and calibration methods and systems described herein are not limited to electromechanical systems devices, or MEMS devices. The methods and systems described herein can be used in any display device involving actuation, placement of charge, or calibration of charge on electrodes, for example OLED or LCD devices. The devices, methods, and systems described herein can also be implemented in devices having torsional mirrors or electrodes. For example, an electrically isolated, charge neutral torsional mirror or electrode can be actuated to move rotationally under the influence of a non-uniform field.

[0213] Figures 42A and 42B show examples of system block diagrams illustrating a display device **40** that includes a plurality of interferometric modulators. The display device **40** can be, for example, a smart phone or a cellular or mobile telephone. However, the same components of the display device **40** or slight variations thereof are also illustrative of various types of display devices, for example televisions, e-readers, hand-held devices, and portable media players.

[0214] The display device **40** includes a housing **41**, a display **30**, an antenna **43**, a speaker **45**, an input device **48**, and a microphone **46**. The housing **41** can be formed from any of a variety of manufacturing processes, including injection molding, and vacuum forming. In addition, the housing **41** may be made from any of a variety of materials, including, but not limited to: plastic, metal, glass, rubber, and ceramic, or a combination thereof. The housing **41** can include removable portions (not shown) that may be interchanged with other removable portions of different color, or containing different logos, pictures, or symbols.

[0215] The display **30** may be any of a variety of displays, including a bi-stable or analog display, as described herein. The display **30** also can be configured to include a flat-panel display, for example plasma, EL, OLED, STN LCD, or TFT LCD, or a non-flat-panel display, for example a CRT or other tube device. In addition, the display **30** can include an interferometric modulator display, as described herein. For example, the display can include analog interferometric modulator pixels that are operated, actuated, charged, and/or calibrated using methods described herein.

[0216] The components of the display device **40** are schematically illustrated in Figure 42B. The display device **40** includes a housing **41** and can include additional components at least partially enclosed therein. For example, the display device **40** includes a network interface **27** that includes an antenna **43** which is coupled to a transceiver **47**. The transceiver **47** is connected to a processor **21**, which is connected to conditioning hardware **52**. The conditioning hardware **52** may be configured to condition a signal (e.g., filter a signal). The conditioning hardware **52** is connected to a speaker **45** and a microphone **46**. The processor **21** is also connected to an input device **48** and a driver controller **29**. The driver controller **29** is coupled to a frame buffer **28**, and to an array driver **22**, which in turn is coupled to a display array **30**. A power supply **50** can provide power to all components as required by the particular display device **40** design.

[0217] The network interface **27** includes the antenna **43** and the transceiver **47** so that the display device **40** can communicate with one or more devices over a network. The network interface **27** also may have some processing capabilities to relieve, e.g., data processing requirements of the processor **21**. The antenna **43** can transmit and receive signals. In some implementations, the antenna **43** transmits and receives RF signals according to the IEEE 16.11 standard, including IEEE 16.11(a), (b), or (g), or the IEEE 802.11 standard, including IEEE 802.11a, b, g or n. In some other implementations, the antenna **43** transmits and receives RF signals according to the BLUETOOTH standard. In the case of a cellular telephone, the antenna **43** is designed to receive code division multiple access (CDMA), frequency division multiple access (FDMA), time division multiple access (TDMA), Global System for Mobile communications (GSM), GSM/General Packet Radio Service (GPRS), Enhanced Data GSM Environment (EDGE), Terrestrial Trunked Radio (TETRA), Wideband-CDMA (W-CDMA), Evolution Data Optimized (EV-DO), 1xEV-DO, EV-DO Rev A, EV-DO Rev B, High Speed Packet Access (HSPA), High Speed Downlink Packet Access (HSDPA), High Speed Uplink Packet Access (HSUPA), Evolved High Speed Packet Access (HSPA+), Long Term Evolution (LTE), AMPS, or other known signals that are used to communicate within a wireless network, for example a system utilizing 3G or 4G technology. The transceiver **47** can pre-process the signals received from the antenna **43** so that they may be received by and further manipulated by the processor **21**. The transceiver **47** also can process signals received from the processor **21** so that they may be transmitted from the display device **40** via the antenna **43**.

[0218] In some implementations, the transceiver **47** can be replaced by a receiver. In addition, in some implementations, the network interface **27** can be replaced by an image source, which can store or generate image data to be sent to the processor **21**. The processor **21** can control the overall operation of the display device **40**. The processor **21** receives data, for example compressed image data from the network interface **27** or an image source, and processes the data into raw image data or into a format that is readily processed into raw image data. The processor **21** can send the processed data to the driver controller **29** or to the frame buffer **28** for storage. Raw data typically refers to the information that identifies the image characteristics at each location within an image. For example, such image characteristics can include color, saturation, and gray-scale level.

[0219] The processor **21** can include a microcontroller, CPU, or logic unit to control operation of the display device **40**. The conditioning hardware **52** may include amplifiers and filters for transmitting signals to the speaker **45**, and for receiving signals from the microphone **46**. The conditioning hardware **52** may be discrete components within the display device **40**, or may be incorporated within the processor **21** or other components.

[0220] The driver controller **29** can take the raw image data generated by the processor **21** either directly from the processor **21** or from the frame buffer **28** and can re-format the raw image data appropriately for high speed transmission to the array driver **22**. In some implementations, the driver controller **29** can re-format the raw image data into a data flow having a raster-like format, such that it has a time order suitable for scanning across the display array **30**. Then the driver controller **29** sends the formatted information to the array driver **22**. Although a driver controller **29**, for example an LCD controller, is often associated with the system processor **21** as a stand-alone Integrated Circuit (IC), such controllers may be implemented in many ways. For example, controllers may be embedded in the processor **21** as hardware, embedded in the processor **21** as software, or fully integrated in hardware with the array driver **22**.

[0221] The array driver **22** can receive the formatted information from the driver controller **29** and can re-format the video data into a parallel set of waveforms that are applied many times per second to the hundreds, and sometimes thousands (or more), of leads coming from the display's x-y matrix of pixels.

[0222] In some implementations, the driver controller **29**, the array driver **22**, and the display array **30** are appropriate for any of the types of displays described herein. For example, the driver controller **29** can be a conventional display controller or a bi-stable display controller (e.g., an IMOD controller). Additionally, the array driver **22** can be a conventional driver or a bi-stable display driver (e.g., an IMOD display driver). Moreover, the display array **30** can be a conventional display array or a bi-stable display array (e.g., a display including an array of IMODs). In some implementations, the driver controller **29** can be integrated with the array driver **22**. Such an implementation can be useful in highly integrated systems including cellular phones, watches and other small-area displays.

[0223] In some implementations, the input device **48** can be configured to allow, e.g., a user to control the operation of the display device **40**. The input device **48** can include a keypad, for example a QWERTY keyboard or a telephone keypad, a button, a switch, a rocker, a touch-sensitive screen, or a pressure- or heat-sensitive membrane. The microphone **46** can be configured as an input device for the display device **40**. In some implementations, voice commands through the microphone **46** can be used for controlling operations of the display device **40**.

[0224] The power supply **50** can include a variety of energy storage devices. For example, the power supply **50** can be a rechargeable battery, for example a nickel-cadmium battery or a lithium-ion battery. In implementations using a rechargeable battery, the rechargeable battery may be chargeable using power coming from, for example, a wall socket or a photovoltaic device or array. Alternatively, the rechargeable battery can be wirelessly chargeable. The power supply **50** also can be a renewable energy source, a capacitor, or a solar cell, including a plastic solar cell or solar-cell paint. The power supply **50** also can be configured to receive power from a wall outlet.

[0225] In some implementations, control programmability resides in the driver controller **29** which can be located in several places in the electronic display system. In some other implementations, control programmability resides in the array driver **22**. The above-described optimization may be implemented in any number of hardware and/or software components and in various configurations.

[0226] The various illustrative logics, logical blocks, modules, circuits and algorithm steps described in connection with the implementations disclosed herein may be implemented as electronic hardware, computer software, or combinations of both. The interchangeability of hardware and software has been described generally, in terms of functionality, and illustrated in the various illustrative components, blocks, modules, circuits and steps described above. Whether such functionality is implemented in hardware or software depends upon the particular application and design constraints imposed on the overall system.

[0227] The hardware and data processing apparatus used to implement the various illustrative logics, logical blocks, modules and circuits described in connection with the aspects disclosed herein may be implemented or performed with a general purpose single- or multi-chip processor, a digital signal processor (DSP), an application specific integrated circuit (ASIC), a field programmable gate array (FPGA) or other programmable logic device, discrete gate or transistor logic, discrete hardware components, or any combination thereof designed to perform the functions described herein. A general purpose processor may be a microprocessor, or, any conventional processor, controller, microcontroller, or state machine. A processor also may be implemented as a combination of computing devices, e.g., a combination of a DSP and a microprocessor, a plurality of microprocessors, one or more microprocessors in conjunction with a DSP core, or any other such configuration. In some implementations, particular steps and methods may be performed by circuitry that is specific to a given function.

[0228] In one or more aspects, the functions described may be implemented in hardware, digital electronic circuitry, computer software, firmware, including the structures disclosed in this specification and their structural equivalents thereof, or in any combination thereof. Implementations of the subject matter described in this specification also can be implemented as one or more computer programs, i.e., one or more modules of computer program instructions, encoded on a computer storage media for execution by, or to control the operation of, data processing apparatus.

[0229] Various modifications to the implementations described in this disclosure may be readily apparent to those skilled in the art, and the generic principles defined herein may be applied to other implementations without departing from the spirit or scope of this disclosure. Thus, the claims are not intended to be limited to the implementations shown herein, but are to be accorded the widest scope consistent with this disclosure, the principles and the novel features disclosed herein. The word “exemplary” is used exclusively herein to mean “serving as an example, instance, or illustration.” Any implementation described herein as “exemplary” is not necessarily to be construed as preferred or advantageous over other possibilities or implementations. Additionally, a person having ordinary skill in the art will readily appreciate, the terms “upper” and “lower” are sometimes used for ease of describing the figures, and indicate relative positions corresponding to the orientation of the figure on a properly oriented page, and may not reflect the proper orientation of the IMOD as implemented.

[0230] Certain features that are described in this specification in the context of separate implementations also can be implemented in combination in a single implementation. Conversely, various features that are described in the context of a single implementation also can be implemented in multiple implementations separately or in any suitable subcombination. Moreover, although features may be described above as acting in certain combinations and even initially claimed as such, one or more features from a claimed combination can in some cases be excised from the combination, and the claimed combination may be directed to a subcombination or variation of a subcombination.

[0231] Similarly, while operations are depicted in the drawings in a particular order, this should not be understood as requiring that such operations be performed in the particular order shown or in sequential order, or that all illustrated operations be performed, to achieve desirable results. Further, the drawings may schematically depict one more example processes in the form of a flow diagram. However, other operations that are not depicted can be incorporated in the example processes that are schematically illustrated. For example, one or more additional operations can be performed before, after, simultaneously, or between any of the illustrated operations. In certain circumstances, multitasking and parallel processing may be advantageous. Moreover, the separation of various system components in the implementations described above should not be understood as requiring such separation in all implementations, and it should be understood that the described program components and systems can generally be integrated together in a single software product or packaged into multiple software products. Additionally, other implementations are within the scope of the following claims. In some cases, the actions recited in the claims can be performed in a different order and still achieve desirable results.

CLAIMS

What is claimed is:

1. A method of calibrating an analog interferometric modulator in a display, comprising:

applying a calibration voltage across a first electrode and a second electrode to produce an electric field in a gap between the first electrode and the second electrode to move a third electrode, positioned in the gap, towards the first electrode from an electrically isolated first position to an electrically connected second position, the third electrode being subject to a mechanical restorative force; and

electrically connecting the third electrode to one or more conductive posts electrically connected to the first electrode, to change an electric charge on the third electrode when the third electrode is in the second position, until the mechanical restorative force on the third electrode exceeds an electric field force on the third electrode such that the third electrode moves to an electrically isolated third position, the third position being farther away from the first electrode than the second position.

2. The method of claim 1, wherein the first electrode includes an upper electrode and a complementary electrode aligned laterally relative to the upper electrode, wherein the method further comprises electrically connecting the complementary electrode to the upper electrode to form a compound electrode, and wherein applying a calibration voltage includes applying a calibration voltage across the compound electrode and the second electrode.

3. The method of claim 2, wherein electrically connecting the complementary electrode to the upper electrode includes closing one or more switches to connect the complementary electrode to the upper electrode.

4. The method of claim 2, wherein the compound electrode and the second electrode have substantially the same surface area and the electric field produced between the compound electrode and the second electrode is uniform.

5. The method of claim 2, wherein the complementary electrode is grounded before being electrically connected to the upper electrode.

6. The method of claim 2, wherein changing an electric charge includes dissipating an electric charge on the third electrode through the one or more conductive posts when the third electrode is in the second position.

7. The method of claim 2, further comprising calibrating a plurality of the analog interferometric modulators arranged in an array of the analog interferometric modulators in the display.

8. The method of claim 7, further comprising applying a dissipation voltage across the plurality of analog interferometric modulators in the array to dissipate a charge from the third electrode in each of the plurality of analog interferometric modulators in the array, such that the third electrodes become charge neutral.

9. The method of claim 8, further comprising electrically isolating the complementary electrode from the upper electrode, connecting the complementary electrode to ground in each of the plurality of analog interferometric modulators, and applying a charging actuation voltage across the upper electrode and the second electrode of each of the plurality of analog interferometric modulators.

10. The method of claim 1, wherein changing the electrical charge on the third electrode includes dissipating a charge on the third electrode through the one or more conductive posts when the third electrode is in the second position, and wherein the one or more conductive posts are electrically connected to the first electrode through a resistive component configured to reduce current flow through the one or more conductive posts.

11. The method of claim 1, wherein the second electrode has a greater surface area than the first electrode and the electric field produced between the first electrode and the second electrode is non-uniform.

12. The method of claim 1, further comprising calibrating a plurality of the analog interferometric modulators arranged in an array of the analog interferometric modulators in the display.

13. The method of claim 12, further comprising applying a dissipation voltage across the plurality of analog interferometric modulators in the array to dissipate a charge from the third electrode in each of the plurality of analog interferometric modulators in the array, such that the third electrodes become charge neutral.

14. The method of claim 12, further comprising applying a charging actuation voltage across the first electrode and the second electrode of each of the plurality of analog interferometric modulators to produce a non-uniform electric field in a gap between the first electrode and the second electrode, wherein the calibration voltage is less than the charging actuation voltage.

15. A device for modulating light, comprising:

a display element comprising

a first electrode;

a second electrode spaced apart from the first electrode by a gap, the first electrode and the second electrode configured to produce a non-uniform electric field therebetween when an actuation voltage is applied across the first electrode and the second electrode during an actuation procedure;

a complementary electrode aligned laterally relative to the first electrode, the complementary electrode configured to be electrically isolated from the first electrode during the actuation procedure and electrically connected to the first electrode to form a compound electrode during a calibration procedure, the compound electrode and the second electrode configured to produce a uniform electric field therebetween when a calibration voltage is applied across the compound electrode and the second electrode during the calibration procedure;

at least one electrical contact disposed on the complementary electrode; and

a movable third electrode disposed between the first electrode and the second electrode, the third electrode being configured to move within the gap between an electrically isolated first position, a second position in electrical communication with the at least one electrical contact, and an electrically isolated third position,

wherein the electrical contact is configured to change an electrical charge on the third electrode when the third electrode is in the second position, and wherein the third electrode is configured to move to the third position after the electrical charge on the third electrode has been changed.

16. The device of claim 15, wherein the at least one electrical contact includes one or more conductive posts electrically connected to the complementary electrode.

17. The device of claim 15, wherein the third electrode is configured to move to the second position in response to the non-uniform electric field during the actuation procedure.

18. The device of claim 15, wherein the third electrode is configured to move to the second position in response to the uniform electric field during the calibration procedure.

19. The device of claim 15, wherein the third electrode is configured to move from the first position to the second position and from the second position to the third position during the actuation procedure.

20. The device of claim 15, wherein the third electrode is configured to move from the third position to the second position and from the second position to the third position during the calibration procedure.

21. The device of claim 15, wherein the third electrode is configured to have a net neutral charge when the third electrode is in the first position.

22. The device of clam 15, wherein the complementary electrode is connected to electrical ground when it is electrically isolated from the first electrode during the actuation procedure and wherein the complementary electrode is electrically connected to the first electrode via switches during the calibration procedure.

23. The device of claim 15, further comprising:

a display including a plurality of the display elements;

a processor that is configured to communicate with the display, the processor being configured to process image data; and

a memory device that is configured to communicate with the processor.

24. The device of claim 23, further comprising:

a driver circuit configured to send at least one signal to the display.

25. The device of claim 24, further comprising:

a controller configured to send at least a portion of the image data to the driver circuit.

26. The device of claim 25, wherein the controller is configured to apply the calibration voltage across the compound electrode and the second electrode during the calibration procedure.

27. The device of claim 23, further comprising:

an image source module configured to send the image data to the processor.

28. The device of claim 27, wherein the image source module includes at least one of a receiver, a transceiver, and a transmitter.

29. The device of claim 23, further comprising:

an input device configured to receive input data and to communicate the input data to the processor.

30. A device for modulating light, comprising:

a display element comprising

means for producing a non-uniform electric field;

means for producing a uniform electric field;

a movable electrode disposed between a first electrode and a second electrode forming a gap therebetween, the movable electrode being configured to move within the gap between an electrically isolated first position, a second position, and an electrically isolated third position; and

means for changing an electrical charge on the movable electrode when the movable electrode is in the second position.

31. The device of claim 30, wherein the means for producing a non-uniform electric field includes the first electrode and the second electrode, the first electrode and the second electrode having different surface areas.

32. The device of claim 30, wherein the means for producing a uniform electric field includes the first electrode and the second electrode, the first electrode including an upper electrode electrically connected to a complementary electrode aligned laterally relative to the upper electrode.

33. The device of claim 30, wherein the means for changing an electrical charge includes at least one electrical contact.

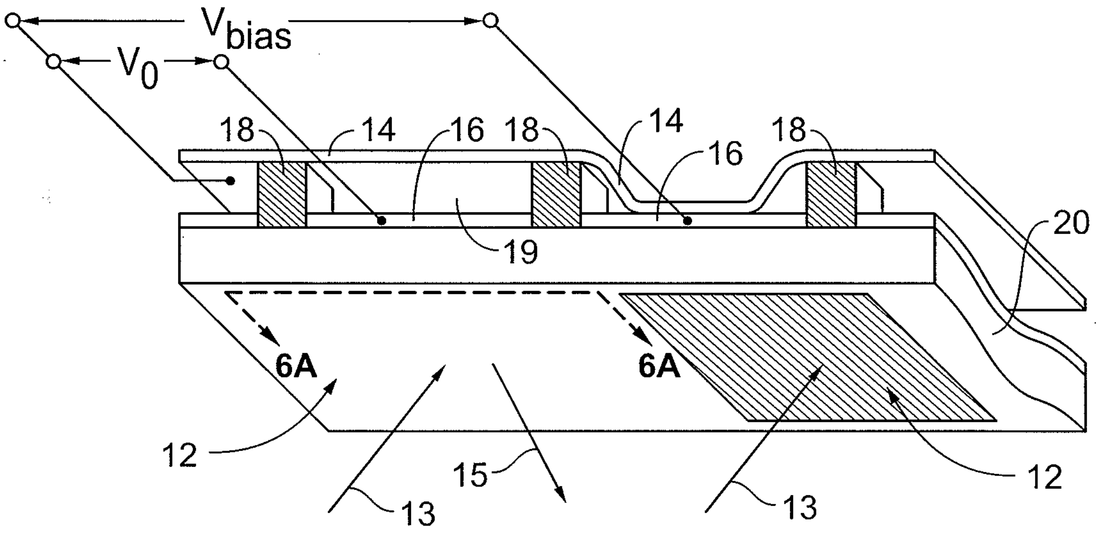


Figure 1

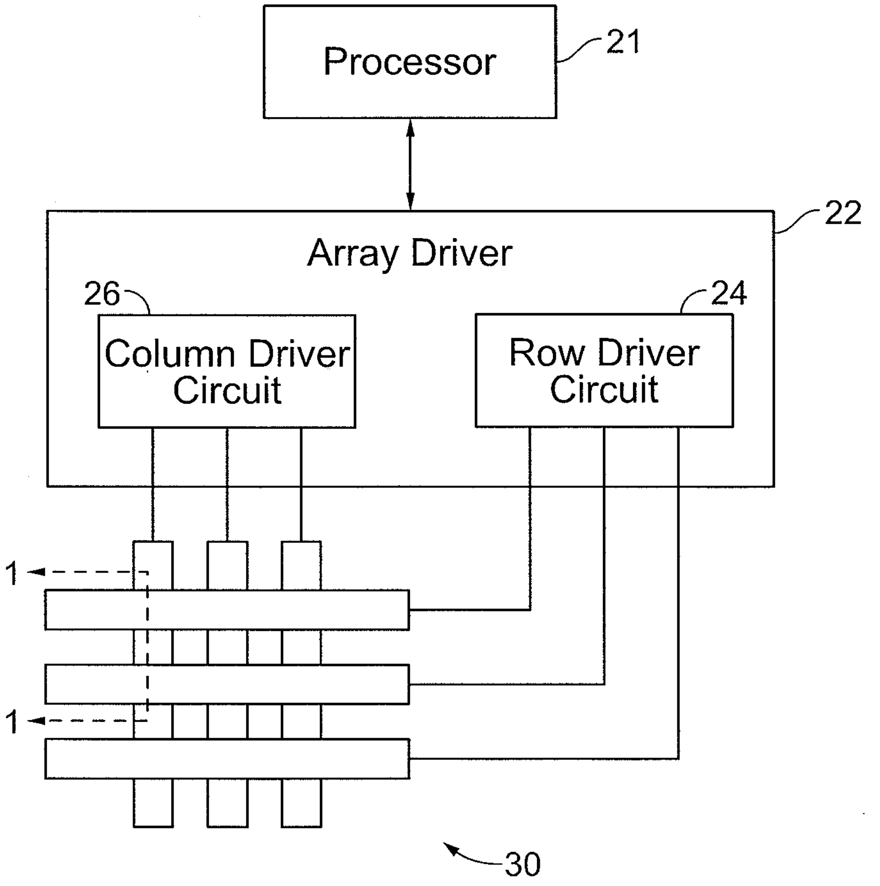


Figure 2

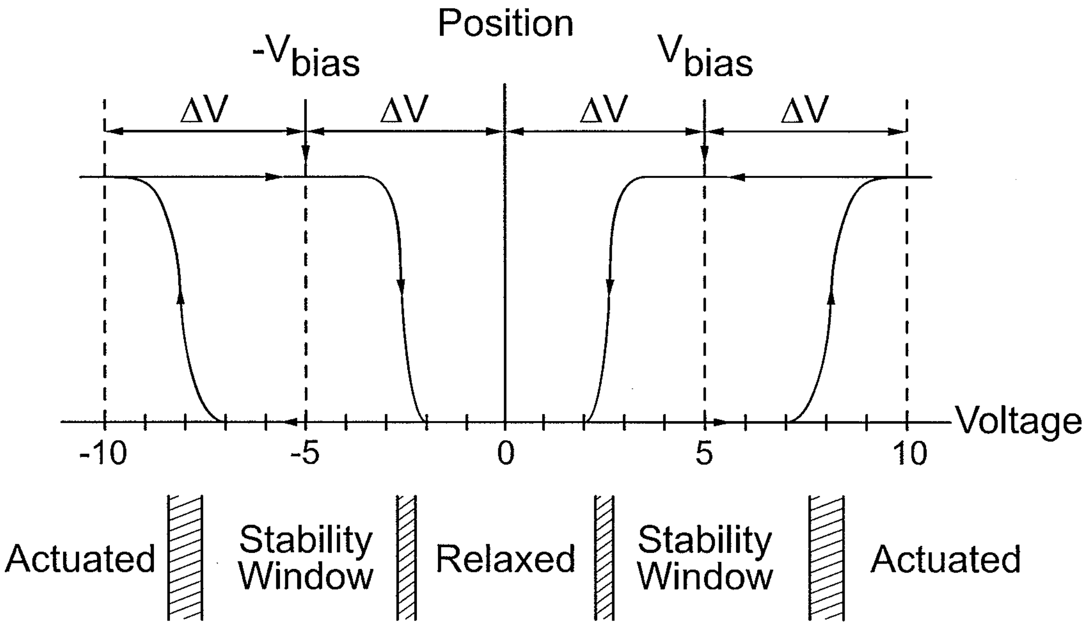


Figure 3

		Common Voltages				
Segment Voltages		VC_{ADD_H}	VC_{HOLD_H}	VC_{REL}	VC_{HOLD_L}	VC_{ADD_L}
	VS_H	Stable	Stable	Relax	Stable	Actuate
	VS_L	Actuate	Stable	Relax	Stable	Stable

Figure 4

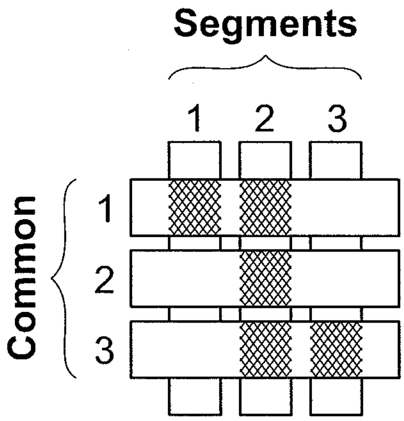


Figure 5A

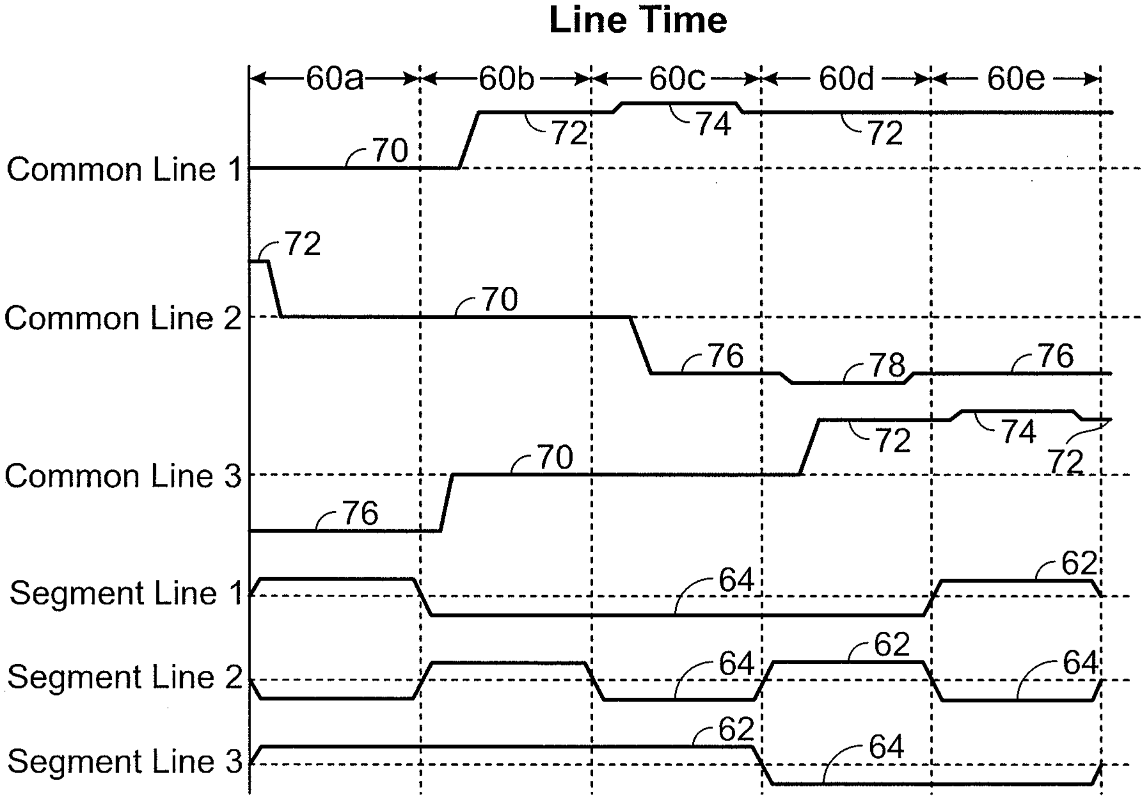


Figure 5B

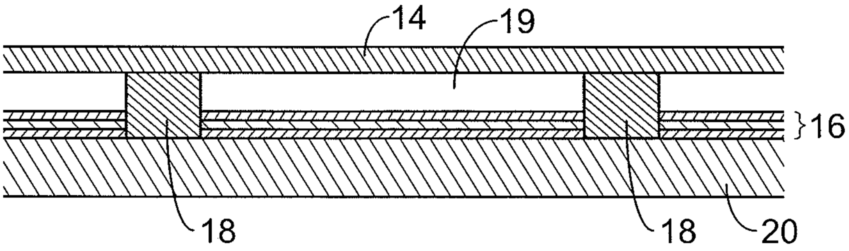


Figure 6A

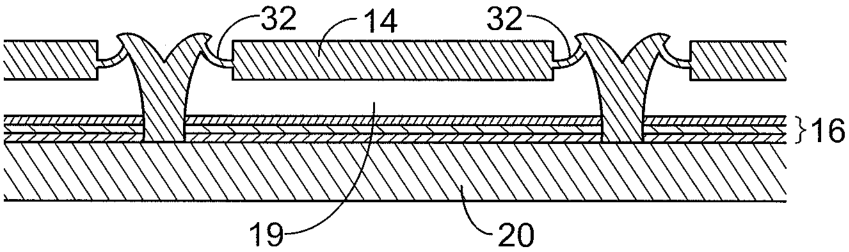


Figure 6B

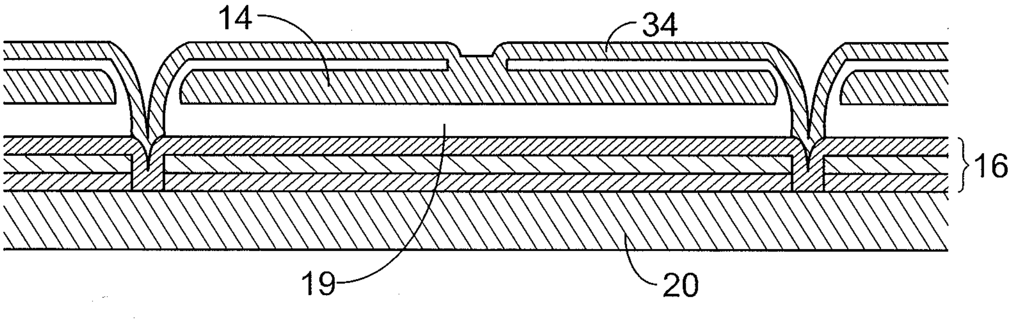


Figure 6C

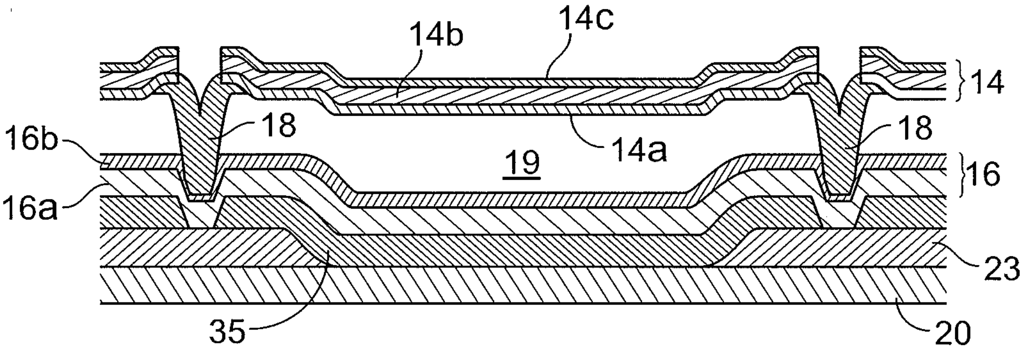


Figure 6D

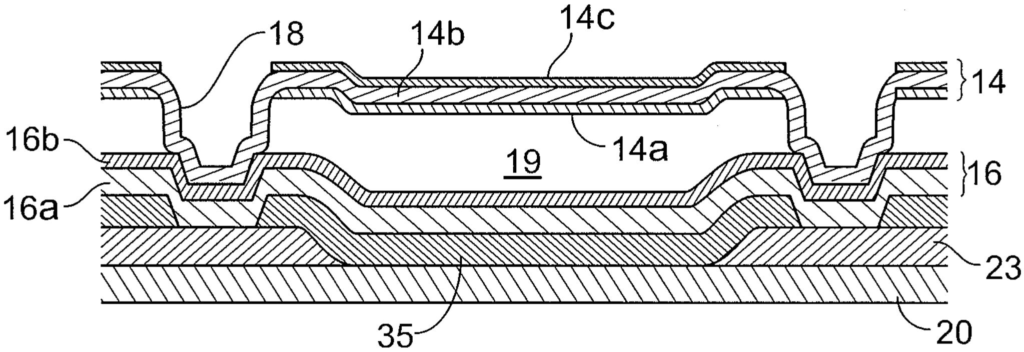


Figure 6E

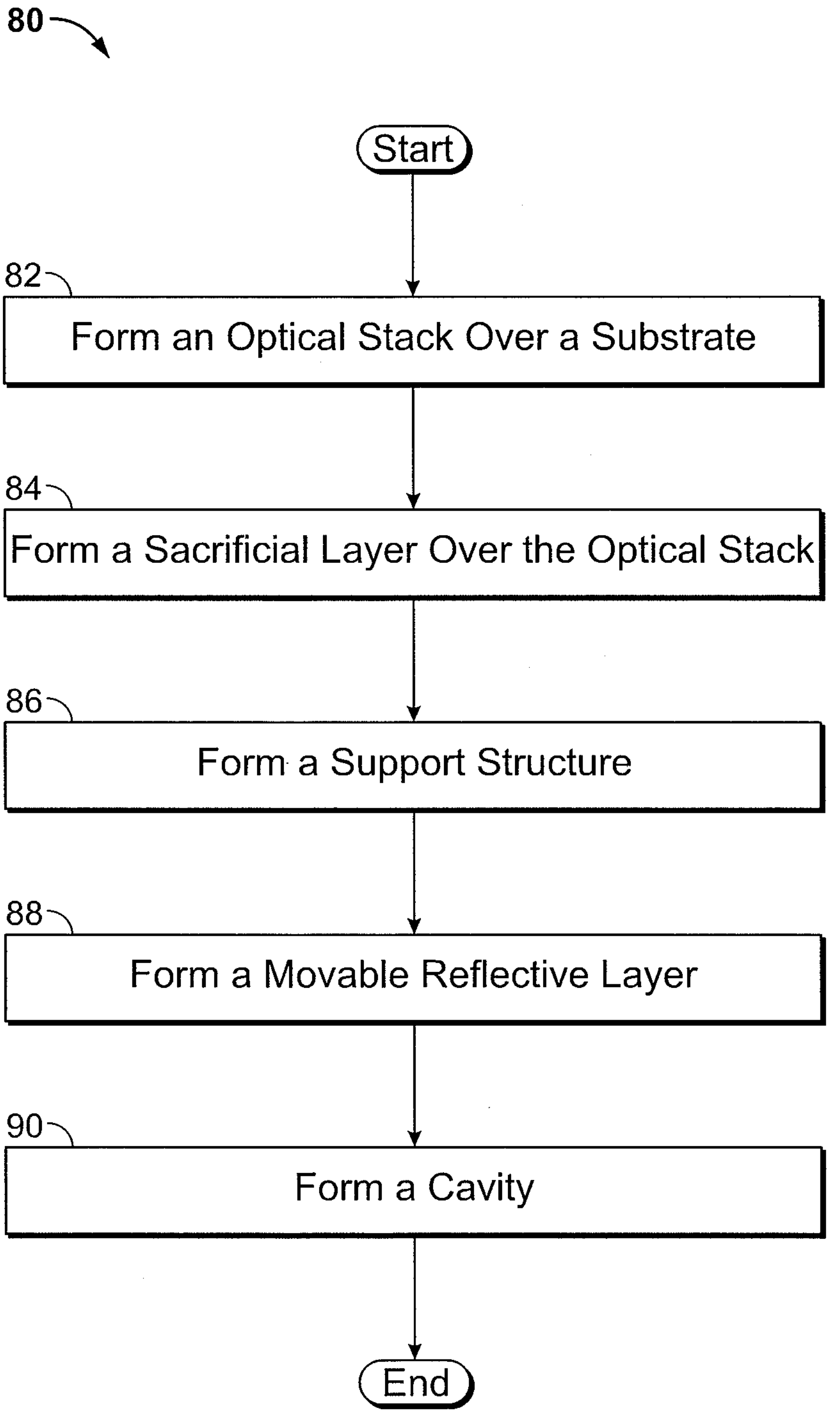

80
Start
82
Form an Optical Stack Over a Substrate
84
Form a Sacrificial Layer Over the Optical Stack
86
Form a Support Structure
88
Form a Movable Reflective Layer
90
Form a Cavity
End

Figure 7

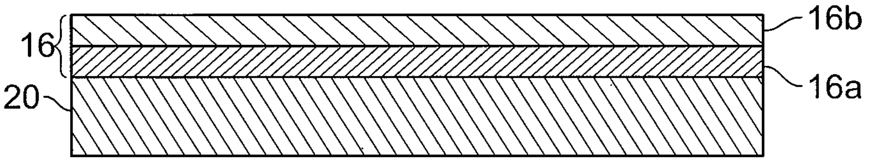


Figure 8A

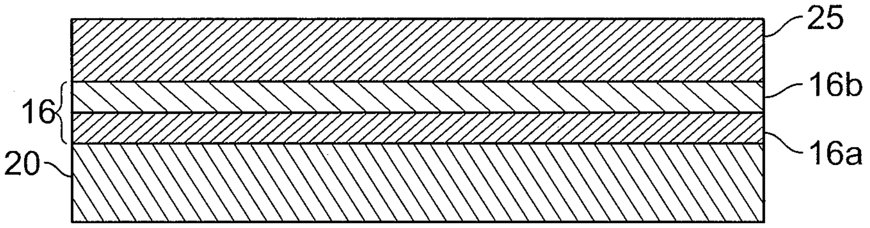


Figure 8B

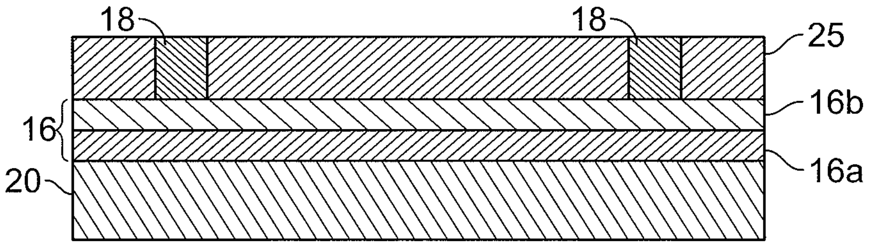


Figure 8C

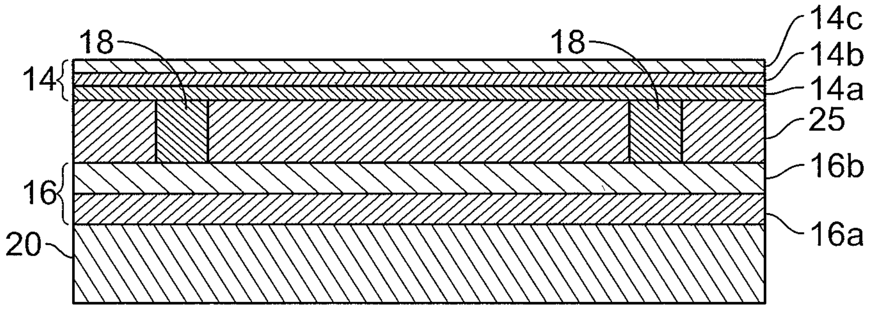


Figure 8D

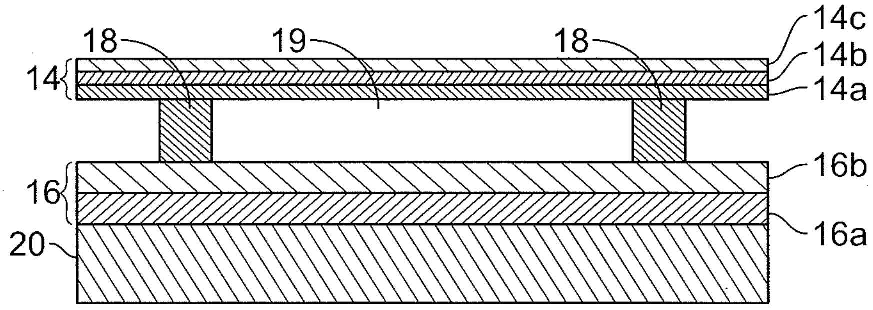


Figure 8E

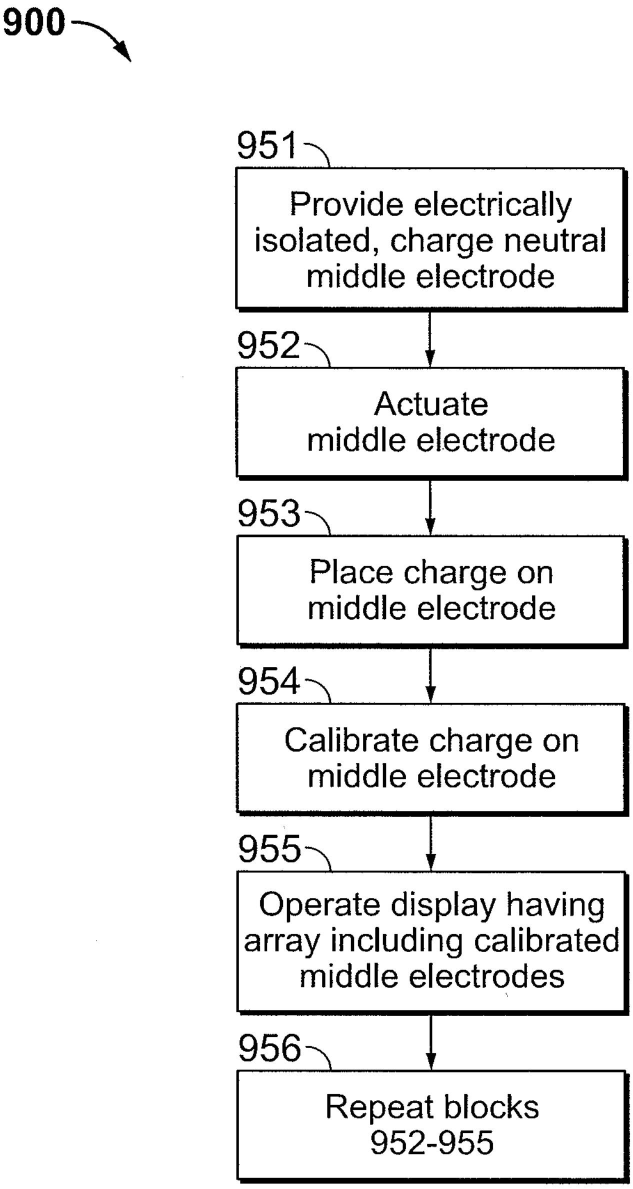

900
951
Provide electrically isolated, charge neutral middle electrode
952
Actuate middle electrode
953
Place charge on middle electrode
954
Calibrate charge on middle electrode
955
Operate display having array including calibrated middle electrodes
956
Repeat blocks 952-955

Figure 9

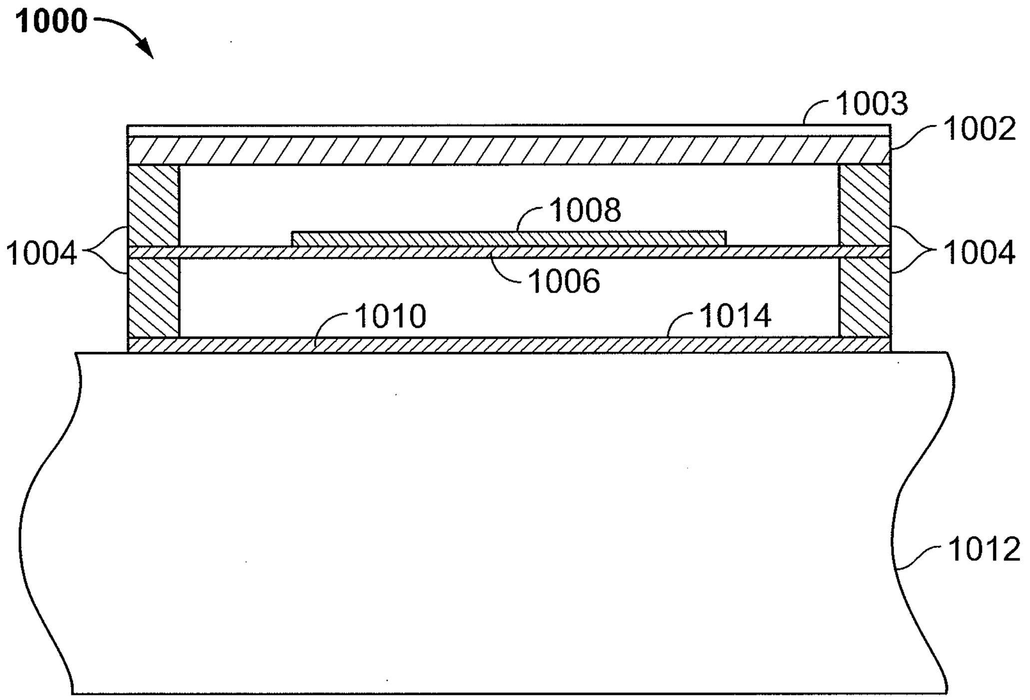


Figure 10

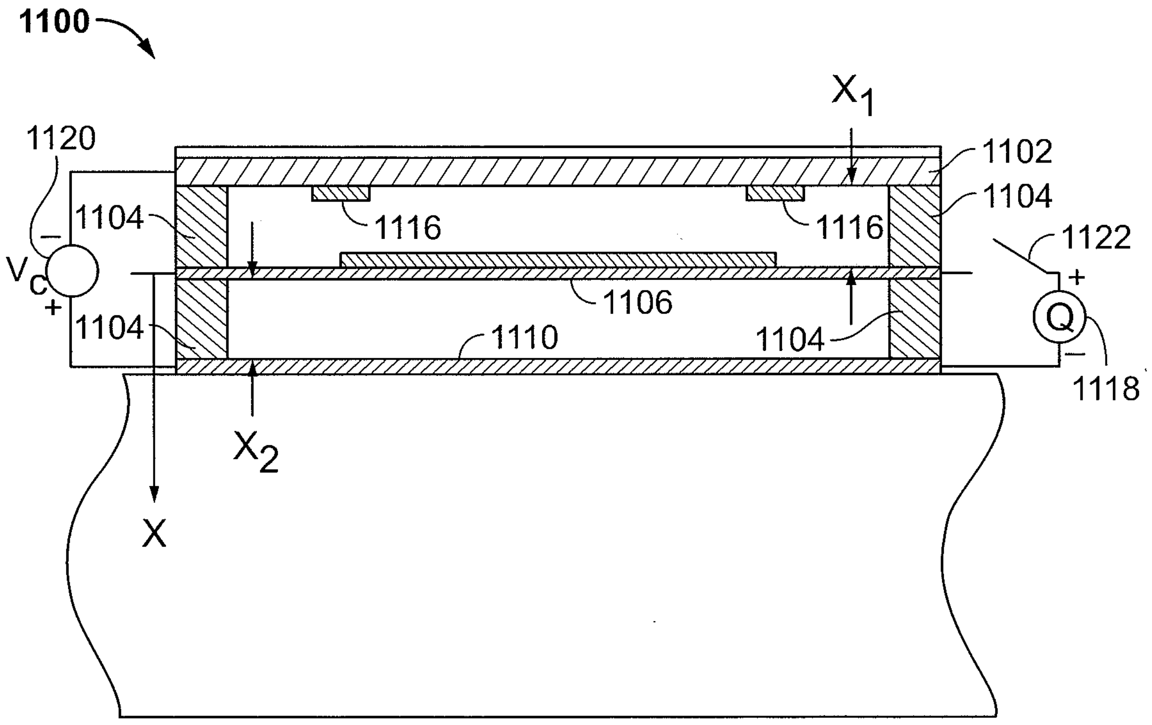
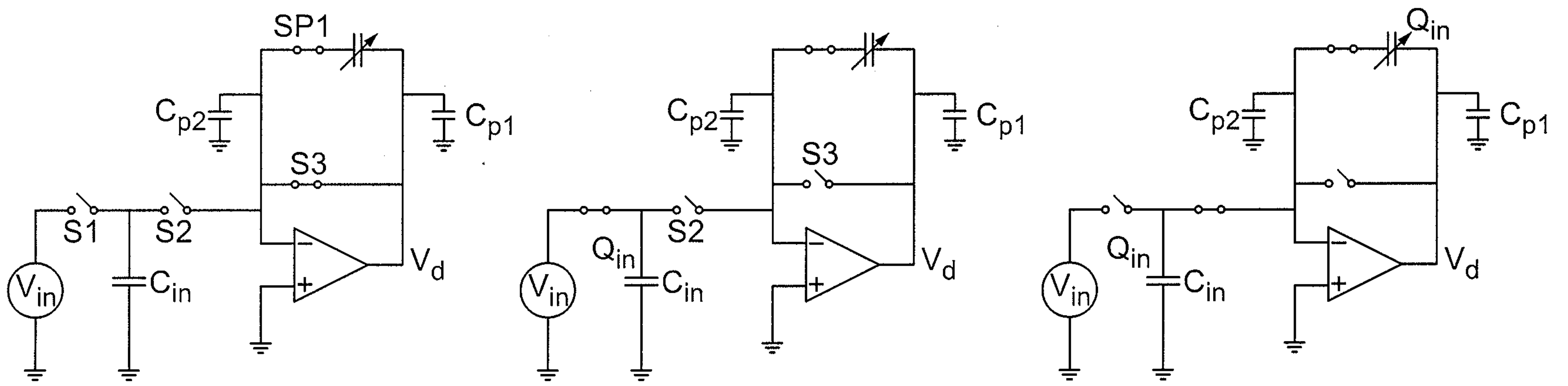


Figure 11A



Reset IMOD (variable cap)

Pre-charge Cin

Sample and transfer charge onto IMOD

Figure 11B

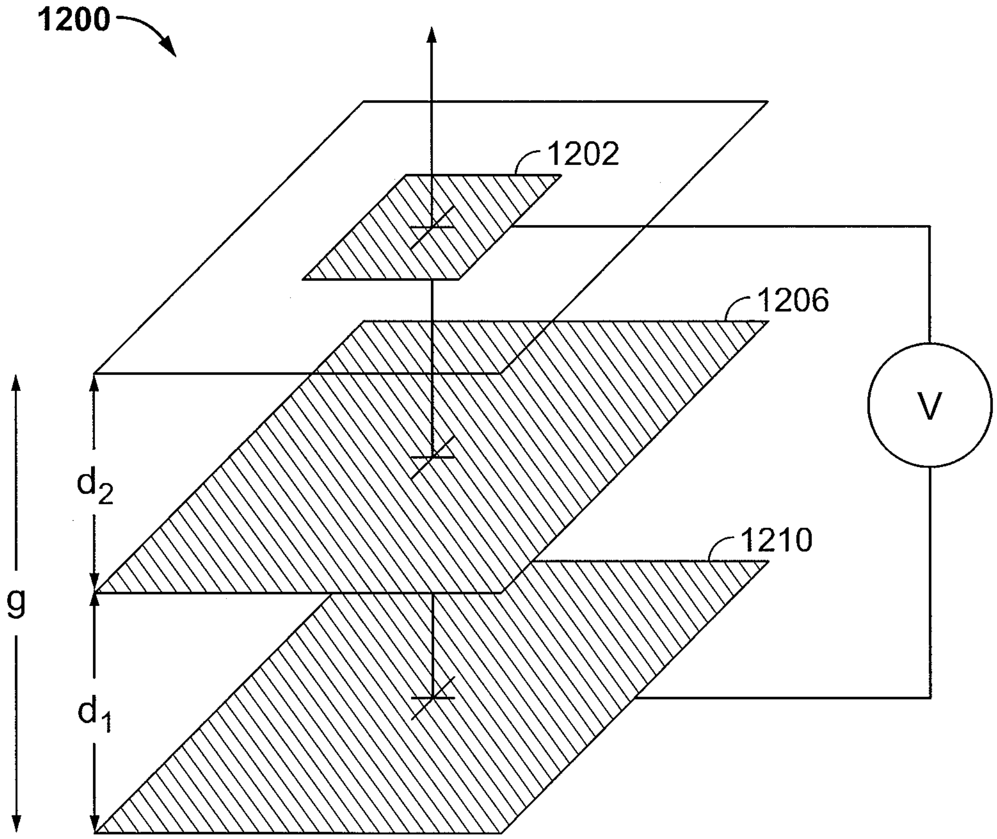


Figure 12

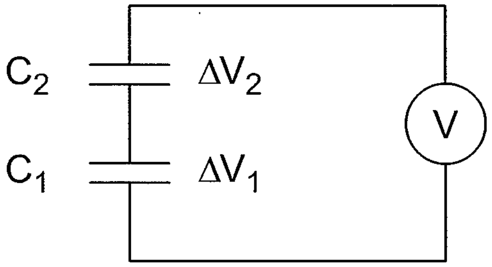


Figure 13

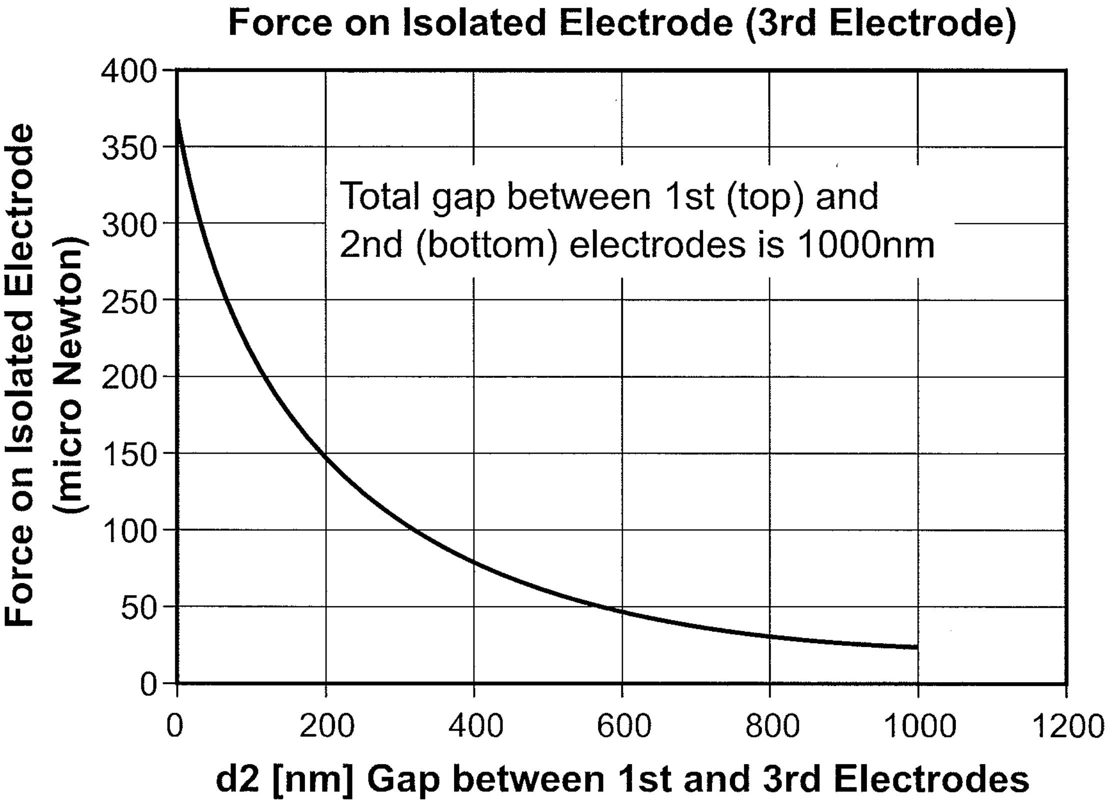


Figure 14

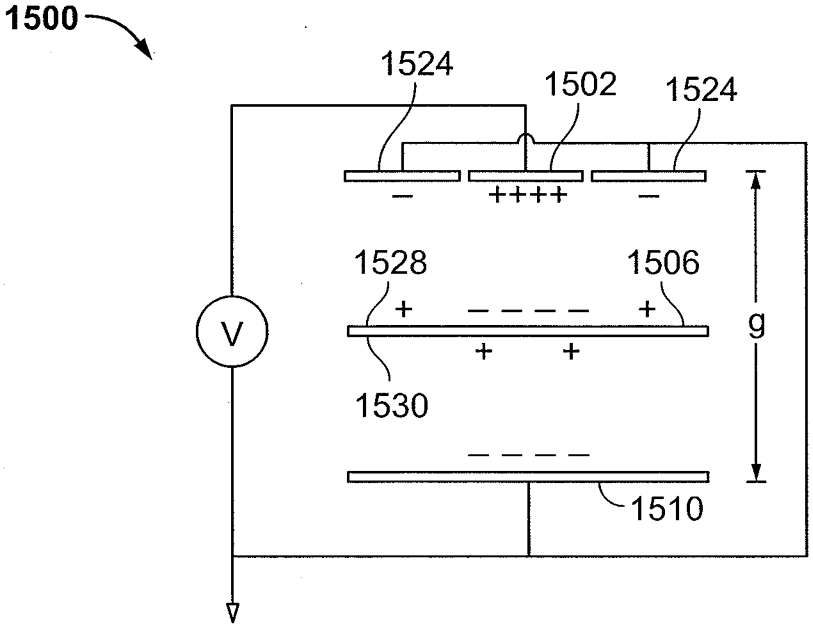


Figure 15A

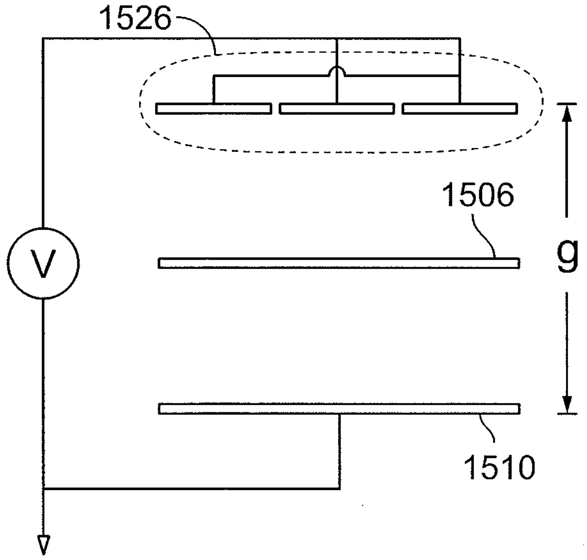


Figure 15B

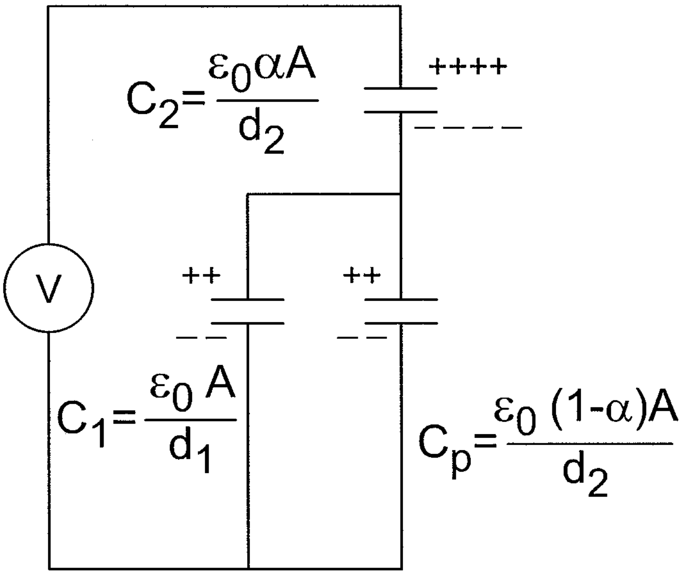

$C_2 = \frac{\varepsilon_0 \alpha A}{d_2}$
++++
– – – –
++
– –
++
– –
V
$C_1 = \frac{\varepsilon_0 A}{d_1}$
$C_p = \frac{\varepsilon_0 (1-\alpha) A}{d_2}$

Figure 16

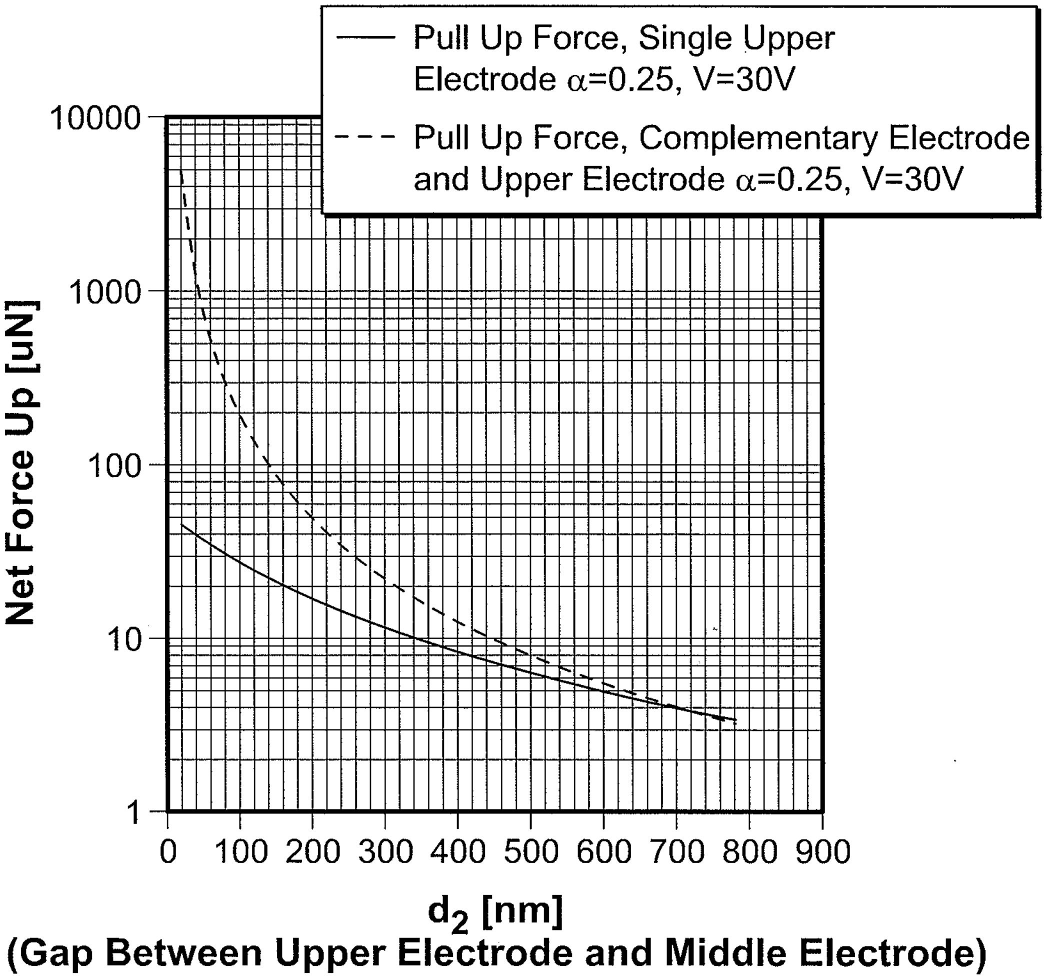


Figure 17

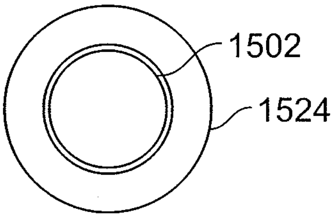


Figure 18

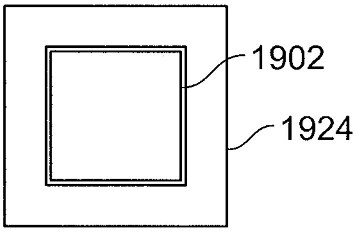


Figure 19

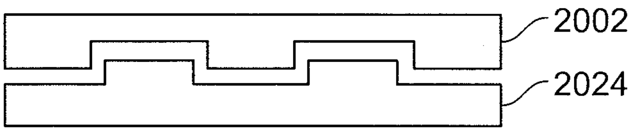


Figure 20

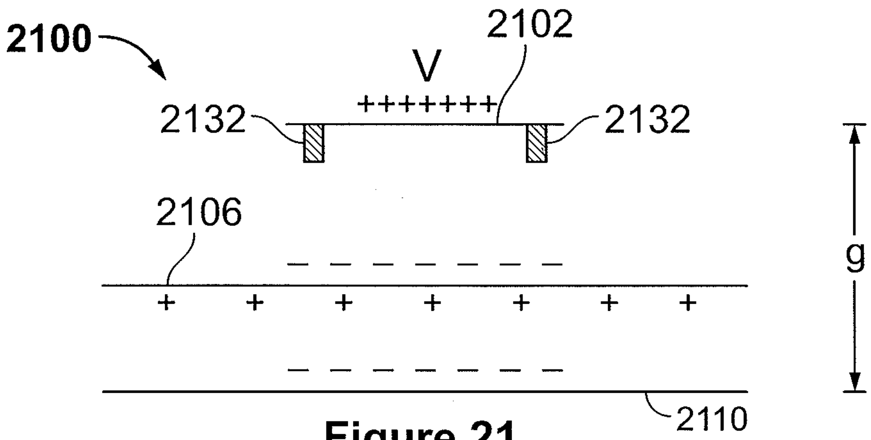


Figure 21

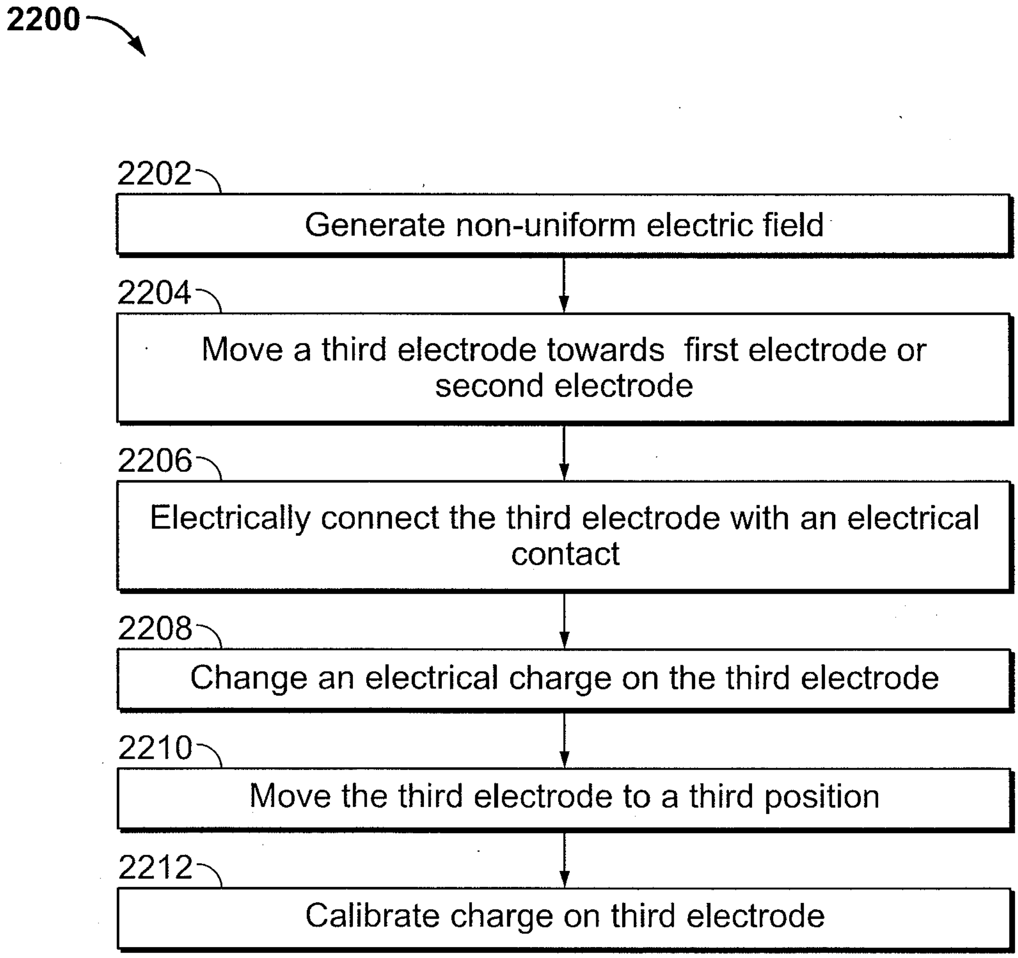


Figure 22

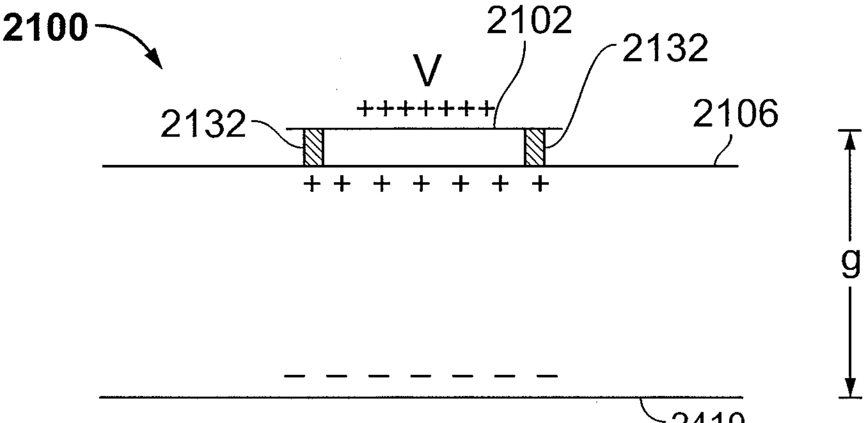


Figure 23

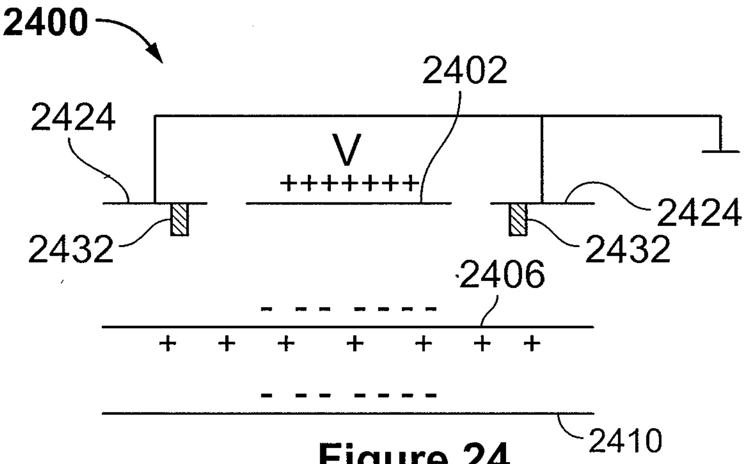


Figure 24

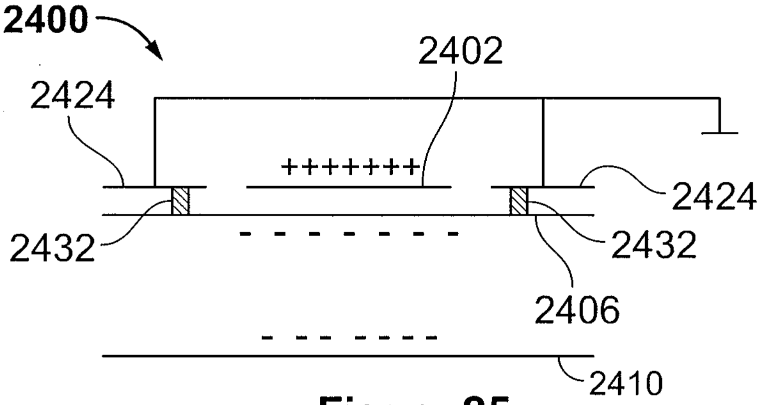


Figure 25

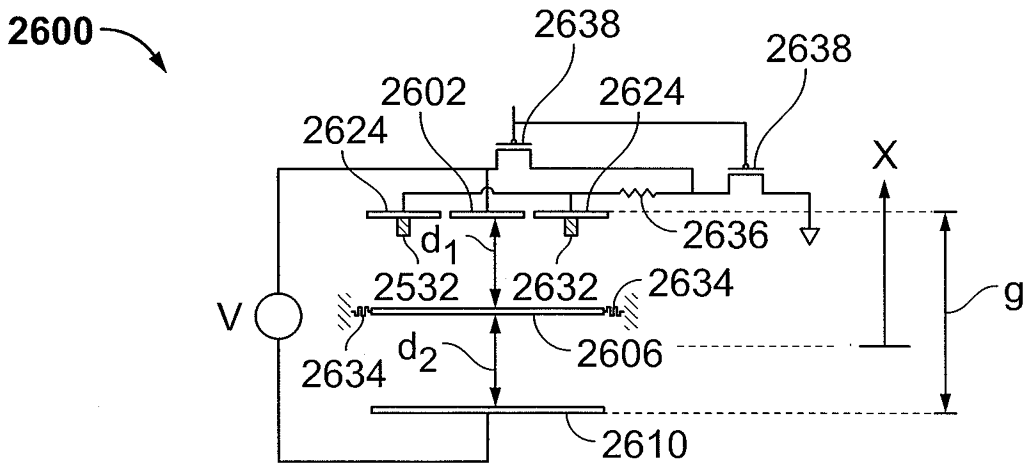


Figure 26

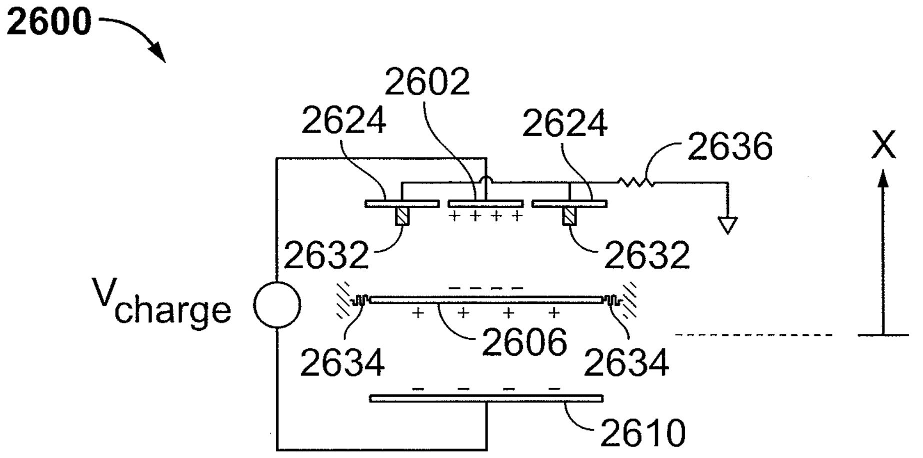


Figure 27

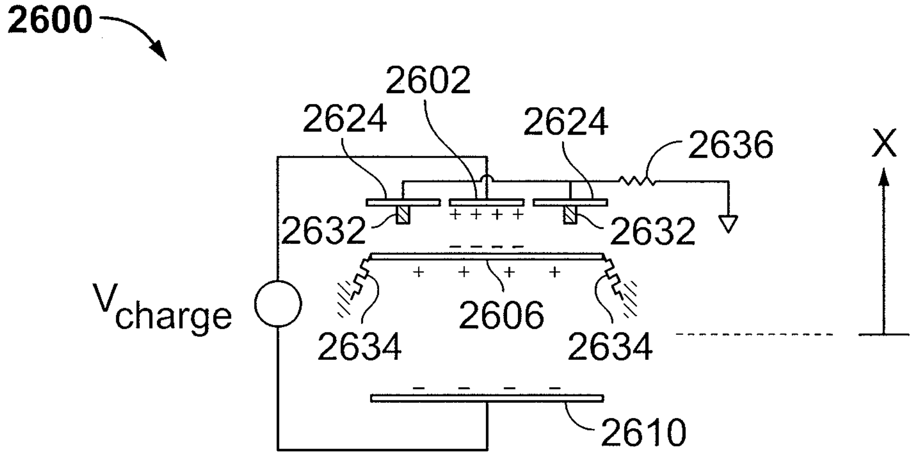


Figure 28

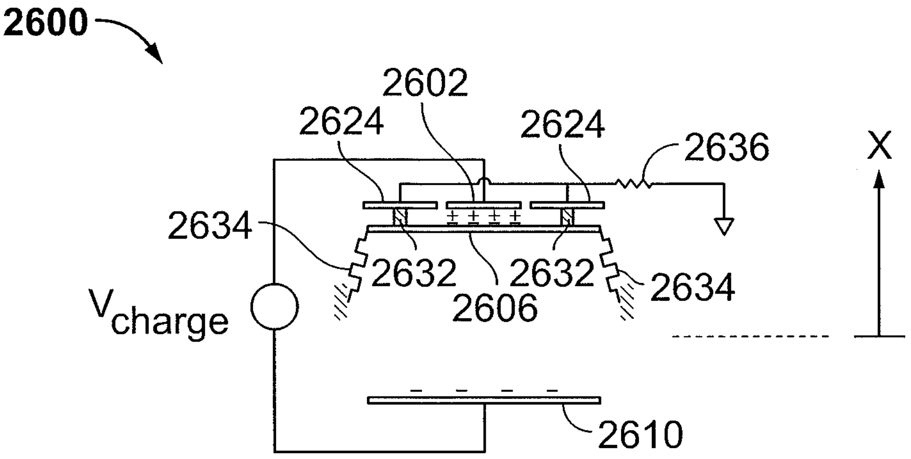


Figure 29

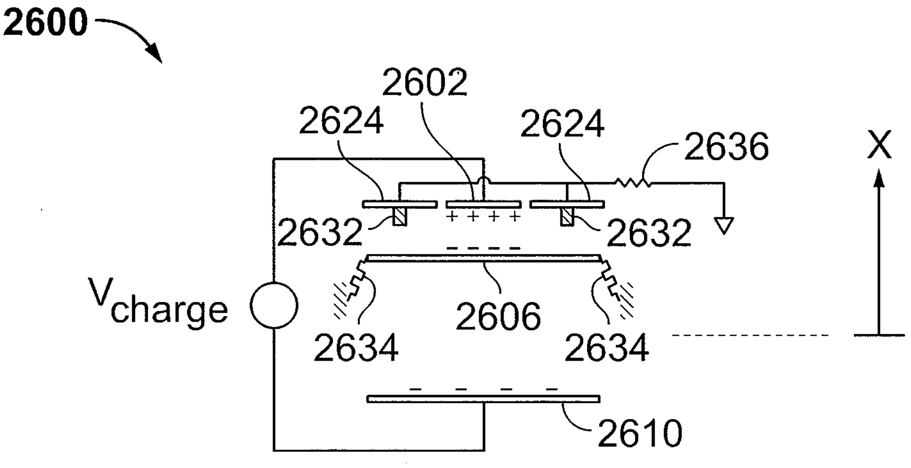


Figure 30

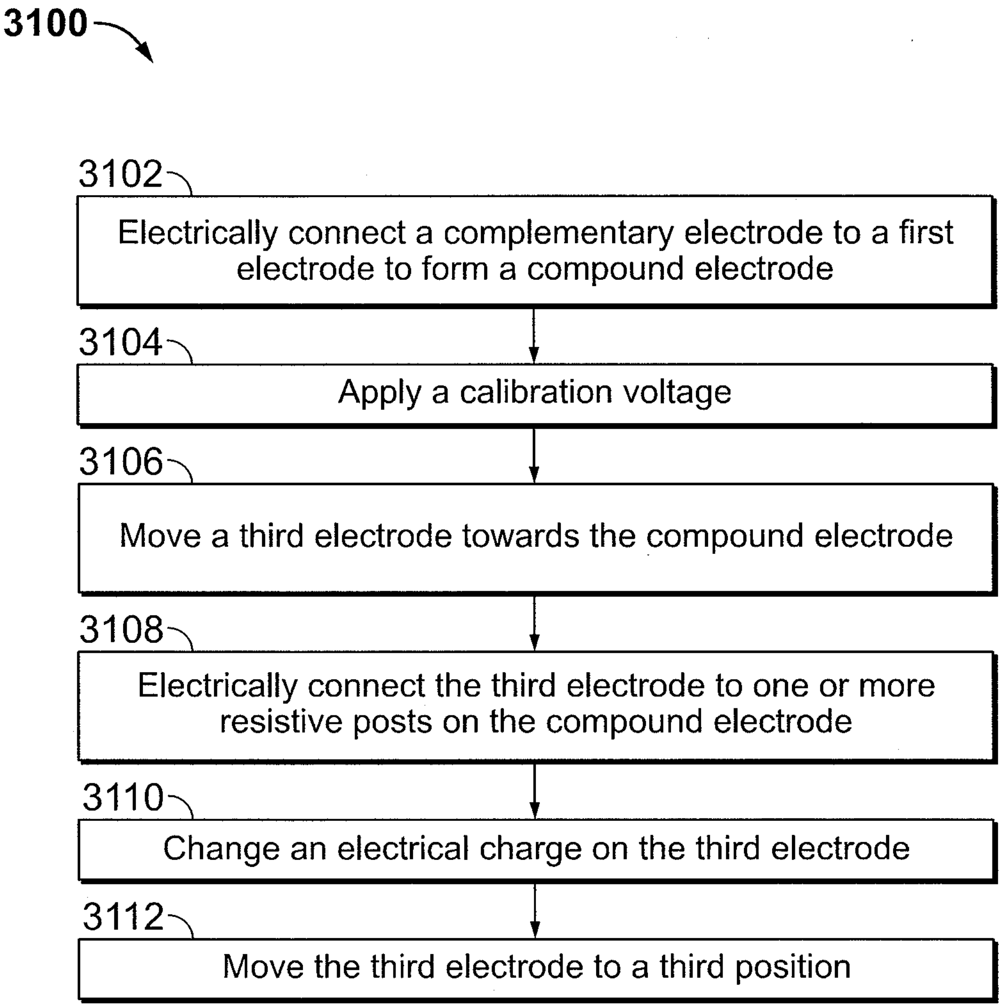

3100
3102
Electrically connect a complementary electrode to a first electrode to form a compound electrode
3104
Apply a calibration voltage
3106
Move a third electrode towards the compound electrode
3108
Electrically connect the third electrode to one or more resistive posts on the compound electrode
3110
Change an electrical charge on the third electrode
3112
Move the third electrode to a third position

Figure 31

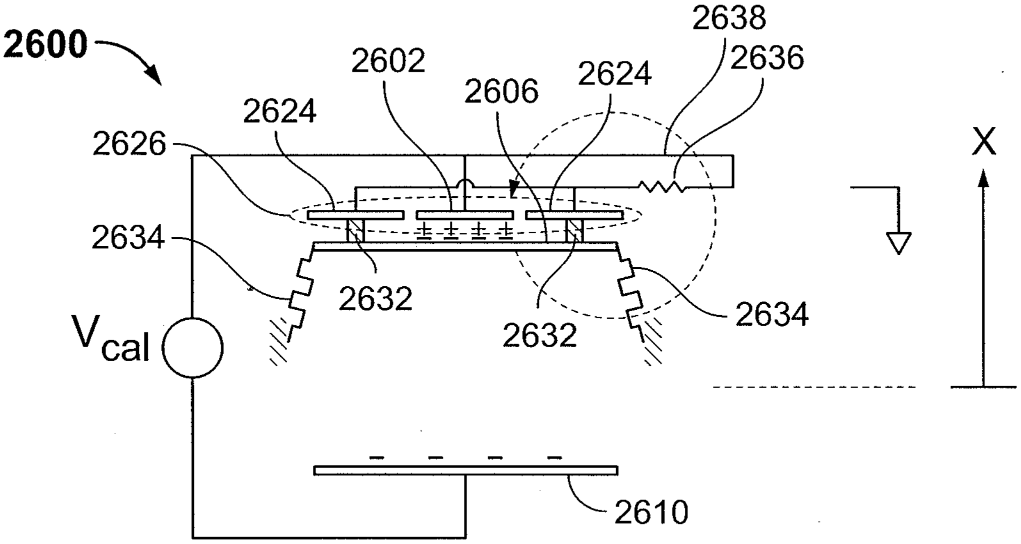


Figure 32

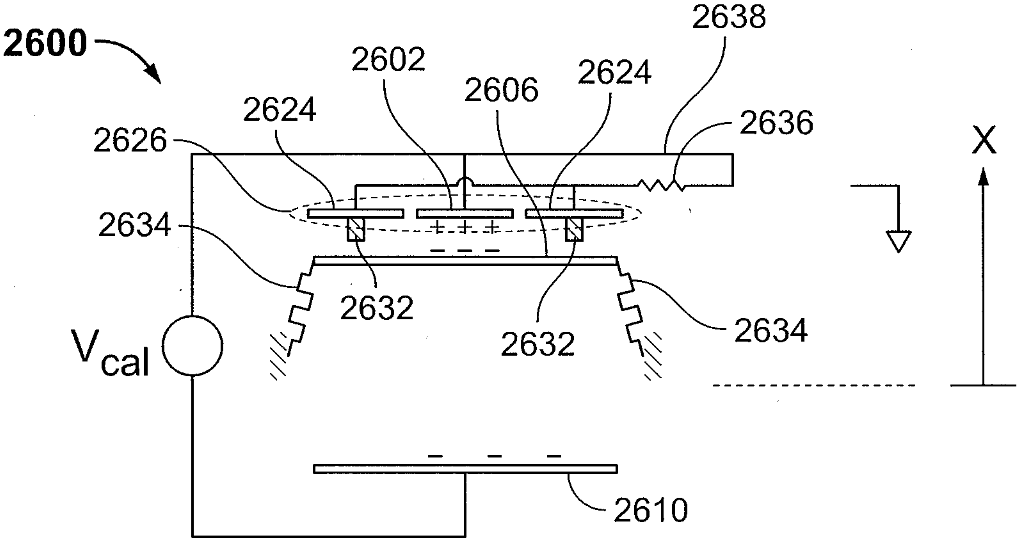


Figure 33

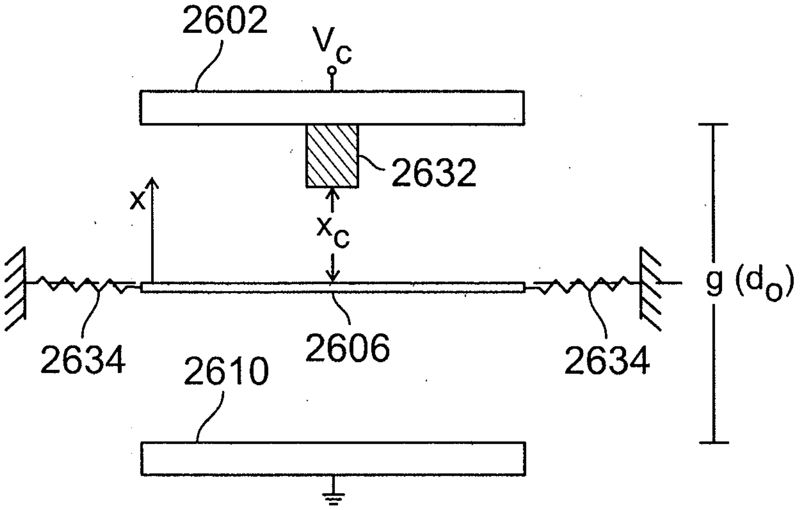


Figure 33A

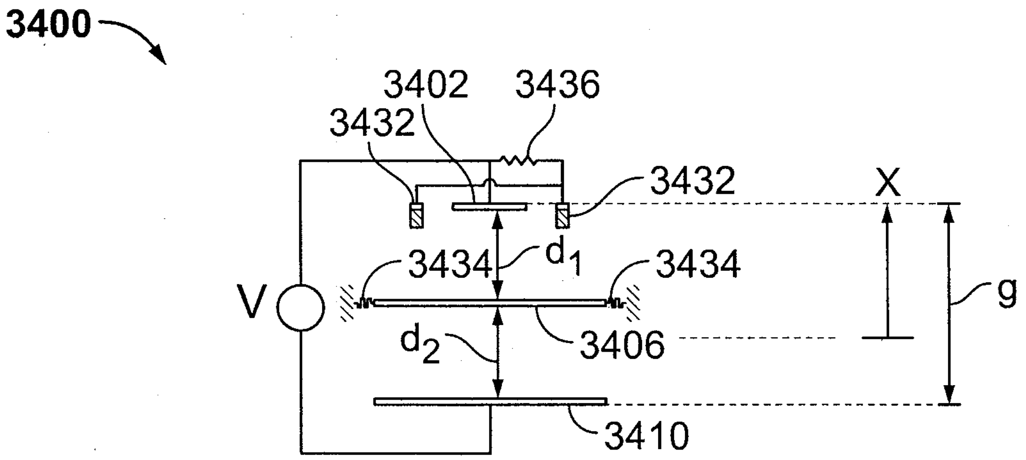


Figure 34

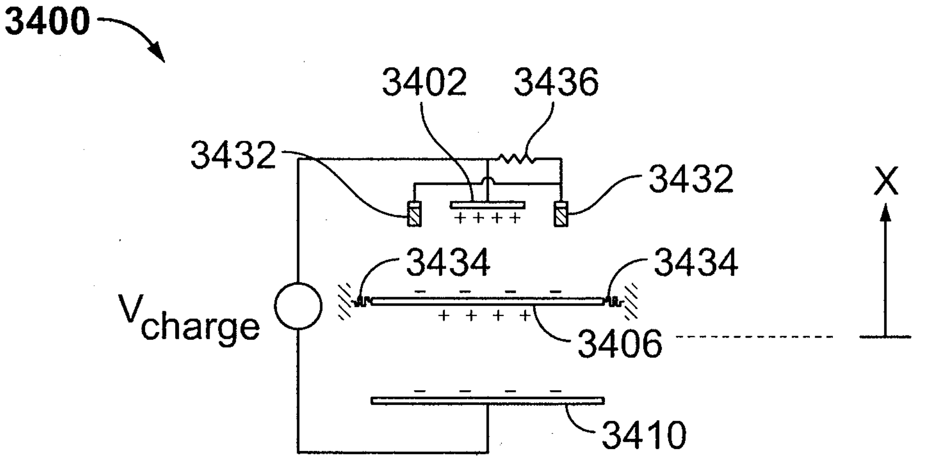


Figure 35

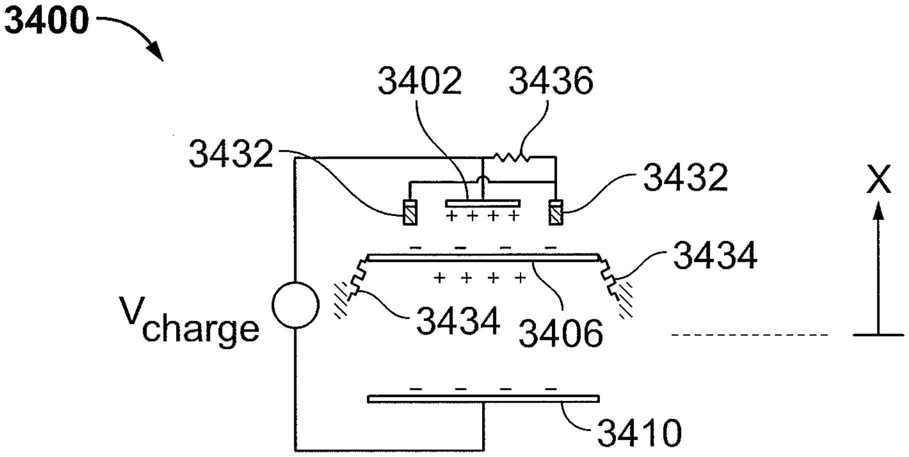


Figure 36

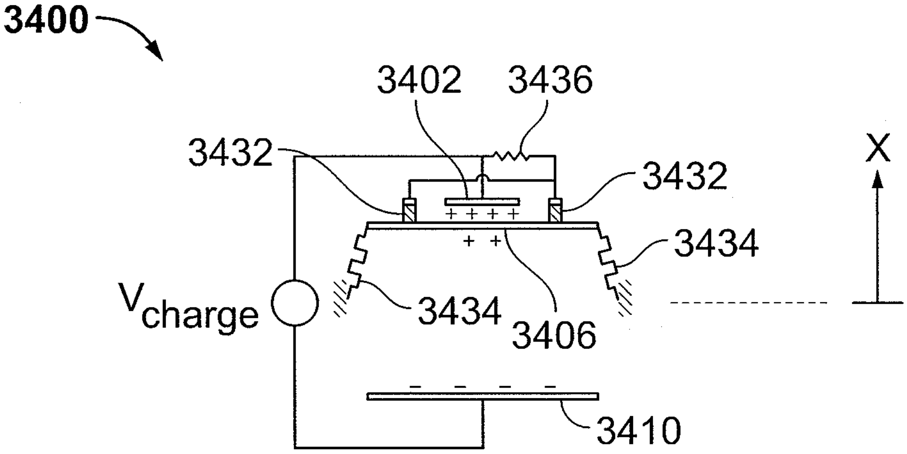


Figure 37

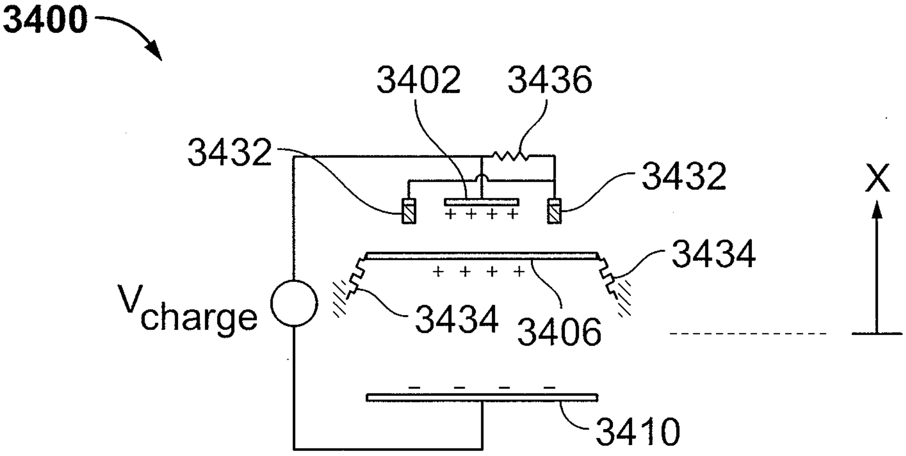


Figure 38

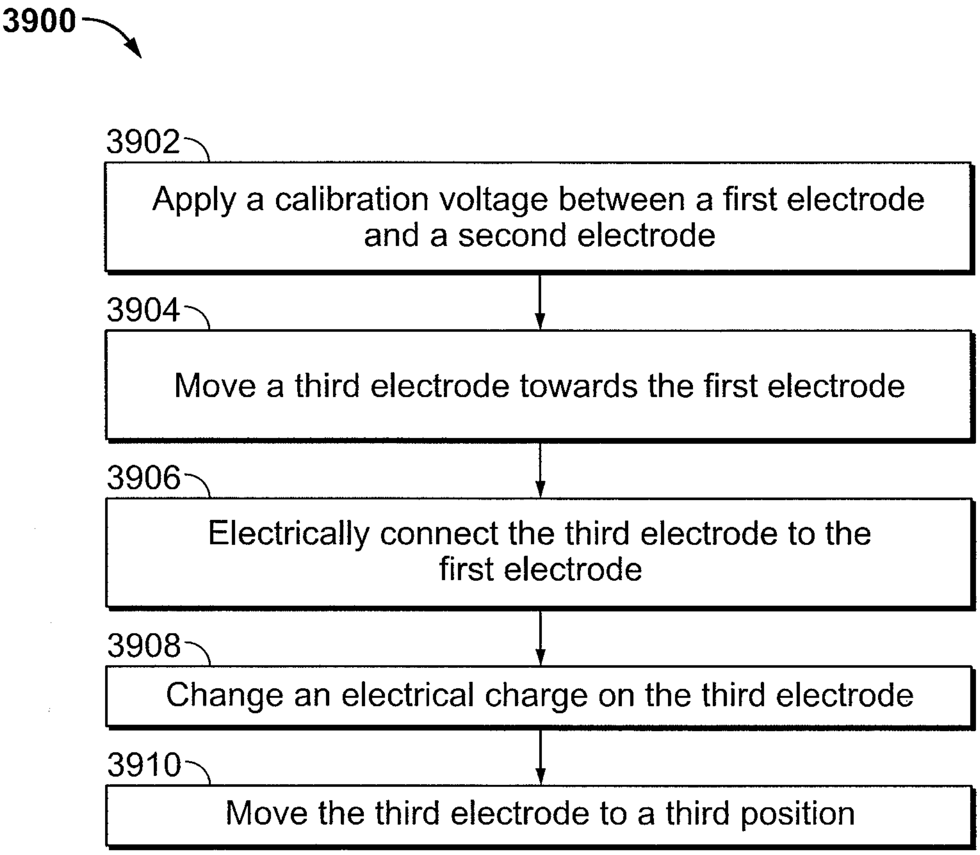

3900
3902
Apply a calibration voltage between a first electrode and a second electrode
3904
Move a third electrode towards the first electrode
3906
Electrically connect the third electrode to the first electrode
3908
Change an electrical charge on the third electrode
3910
Move the third electrode to a third position

Figure 39

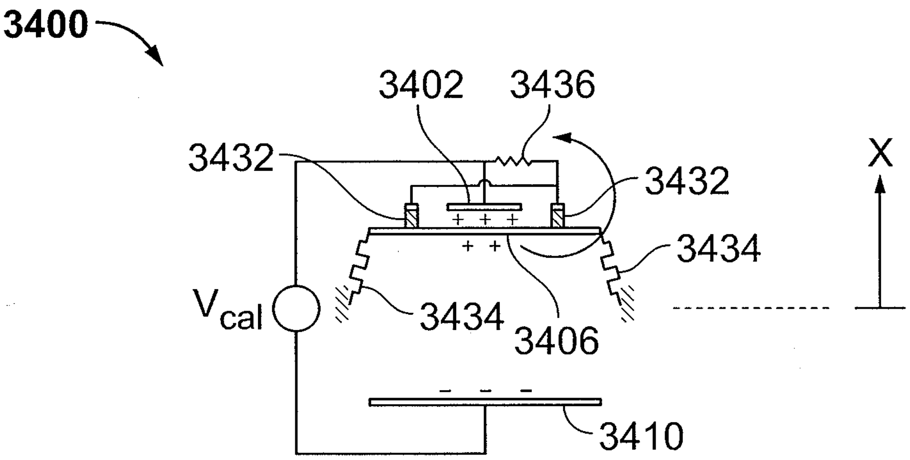


Figure 40

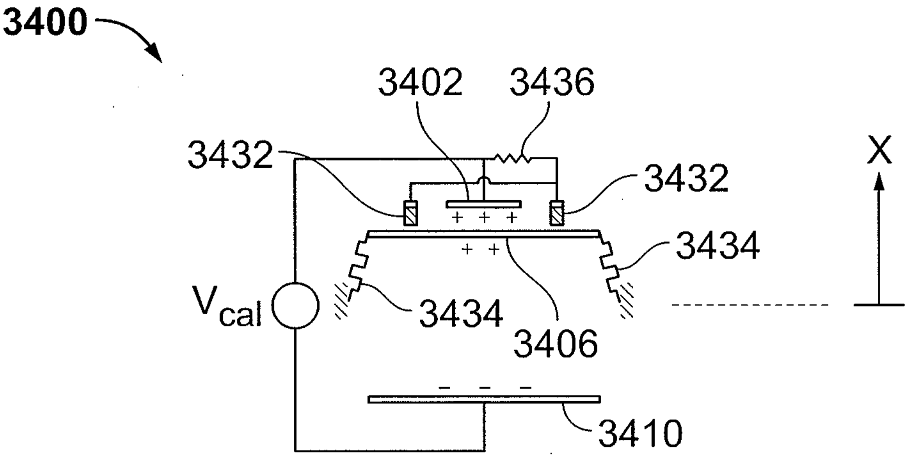


Figure 41

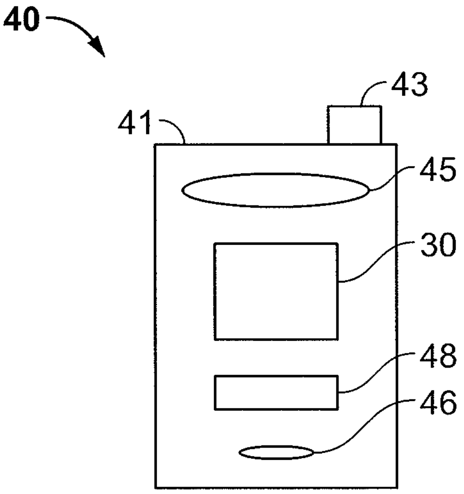


Figure 42A

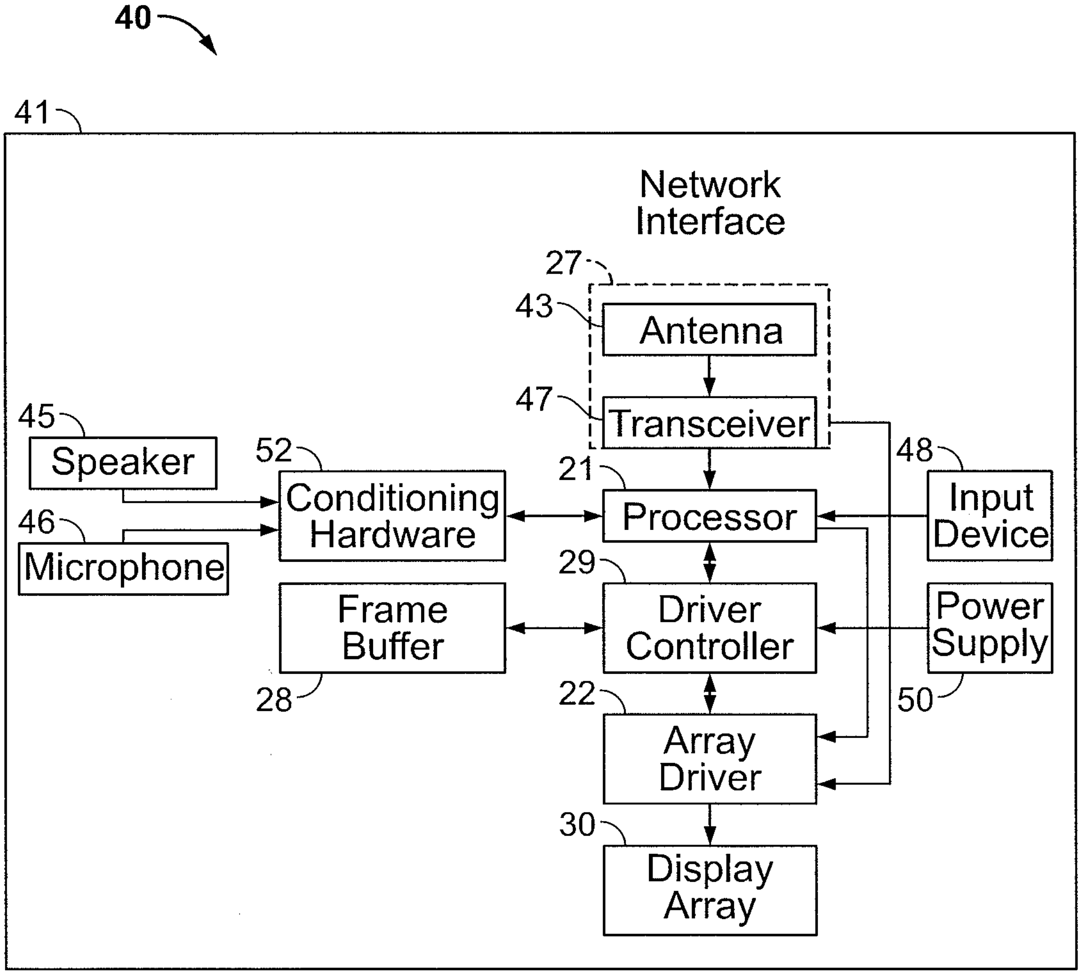


Figure 42B

INTERNATIONAL SEARCH REPORT

International application No
PCT/US2011/047790

A. CLASSIFICATION OF SUBJECT MATTER
INV. G09G3/34 G02B26/00
ADD.

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

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
G09G G02B

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

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

EPO-Internal, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 2006/066938 A1 (CHUI CLARENCE [US]) 30 March 2006 (2006-03-30) paragraph [0085] - paragraph [0100]; figures 12A-12C, 13A-13C -----	1-29
A	WO 2006/036386 A1 (IDC LLC [US]; CHUI CLARENCE [US]) 6 April 2006 (2006-04-06) paragraph [0061] - paragraph [0068]; figure 9 -----	1-29

☐ Further documents are listed in the continuation of Box C.

☒ See patent family annex.

* Special categories of cited documents :

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

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

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

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

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

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

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

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

"&" document member of the same patent family

Date of the actual completion of the international search 20 October 2011	Date of mailing of the international search report 18/01/2012
Name and mailing address of the ISA/ European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Fax: (+31-70) 340-3016	Authorized officer Fulcheri, Alessandro

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US2011/047790

Box No. II Observations where certain claims were found unsearchable (Continuation of item 2 of first sheet)

This international search report has not been established in respect of certain claims under Article 17(2)(a) for the following reasons:

1. ☐ Claims Nos.:
because they relate to subject matter not required to be searched by this Authority, namely:

2. ☐ Claims Nos.:
because they relate to parts of the international application that do not comply with the prescribed requirements to such an extent that no meaningful international search can be carried out, specifically:

3. ☐ Claims Nos.:
because they are dependent claims and are not drafted in accordance with the second and third sentences of Rule 6.4(a).

Box No. III Observations where unity of invention is lacking (Continuation of item 3 of first sheet)

This International Searching Authority found multiple inventions in this international application, as follows:

see additional sheet

1. ☐ As all required additional search fees were timely paid by the applicant, this international search report covers all searchable claims.

2. ☐ As all searchable claims could be searched without effort justifying an additional fees, this Authority did not invite payment of additional fees.

3. ☐ As only some of the required additional search fees were timely paid by the applicant, this international search report covers only those claims for which fees were paid, specifically claims Nos.:

4. ☒ No required additional search fees were timely paid by the applicant. Consequently, this international search report is restricted to the invention first mentioned in the claims; it is covered by claims Nos.:

1-29

Remark on Protest

☐ The additional search fees were accompanied by the applicant's protest and, where applicable, the payment of a protest fee.

☐ The additional search fees were accompanied by the applicant's protest but the applicable protest fee was not paid within the time limit specified in the invitation.

☐ No protest accompanied the payment of additional search fees.

FURTHER INFORMATION CONTINUED FROM PCT/ISA/ 210

This International Searching Authority found multiple (groups of) inventions in this international application, as follows:

1. claims: 1-29

Method and apparatus for calibrating an analog interferometric modulator

---

2. claims: 30-33

Light modulating device.
Comprises an display element for producing a non uniform electric field.

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No

PCT/US2011/047790

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
US 2006066938 A1	30-03-2006	US 2006066938 A1	30-03-2006
		US 2009135466 A1	28-05-2009
		US 2010110526 A1	06-05-2010
WO 2006036386 A1	06-04-2006	AU 2005290164 A1	06-04-2006
		BR PI0515363 A	15-07-2008
		CA 2577894 A1	06-04-2006
		EP 1803020 A1	04-07-2007
		HK 1103447 A1	30-04-2010
		JP 4649561 B2	09-03-2011
		JP 2008514985 A	08-05-2008
		KR 20070057189 A	04-06-2007
		MY 140901 A	29-01-2010
		US 2006077155 A1	13-04-2006
		US 2008055706 A1	06-03-2008
		WO 2006036386 A1	06-04-2006