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(71) Applicant: **QUALCOMM MEMS TECHNOLOGIES, INC.** [US/US]; 5775 Morehouse Drive, San Diego, California 92121-1714 (US).

(72) Inventors: **YUN, Changhan Hobie**; 5775 Morehouse Drive, San Diego, California 92121 (US). **LO, Chi Shun**; 11096 Virgo Place, San Diego, California 92126 (US). **ZUO, Chengjie**; 5775 Morehouse Drive, San Diego, California 92121 (US). **KIM, Jonghae**; 5775 Morehouse Drive, San Diego, California 92121 (US).

(74) Agents: **DONNELLY, Kevin M.** et al; Weaver Austin Villeneuve & Sampson LLP, P.O. Box 70250, Oakland, California 94612-0250 (US).

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[Continued on next page]

(54) Title: PIEZOELECTRIC TRANSFORMER

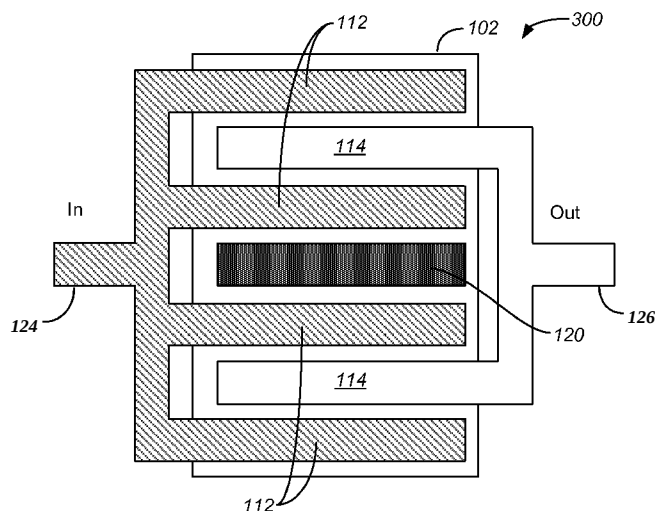


FIGURE 3

(57) Abstract: This disclosure provides implementations of electromechanical systems piezoelectric transformers, devices, apparatus, systems, and related processes. In one aspect, a transformer includes piezoelectric means including piezoelectric material, first conductive means arranged over a first surface of the piezoelectric material, and second conductive means arranged over a second surface opposite the first surface. The first conductive means includes a first set of electrodes (112) and a second set of electrodes (114) interdigitated with the first set. The second conductive means includes at least a third set of electrodes. The transformer also includes first coupling means capable of receiving an input signal, and second coupling means capable of being electrically connected to a load and capable of outputting an output signal. The first set of electrodes is in electrical connection with the first coupling means and the second set of electrodes is in electrical connection with the second coupling means.



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PIEZOELECTRIC TRANSFORMER

RELATED APPLICATIONS

[0001] This disclosure claims the benefit of priority of co-pending U.S. Patent
5 Application No. 13/305,293, titled "Piezoelectric MEMS Transformer", by Yun et al,
filed on November 28, 2011 (Attorney Docket No. 102814/QUALP078), which is
hereby incorporated by reference in its entirety and for all purposes.

TECHNICAL FIELD

[0002] This disclosure relates generally to electromechanical systems (EMS)
10 devices, and more specifically to piezoelectric EMS devices suitable for use as
transformers.

DESCRIPTION OF THE RELATED TECHNOLOGY

[0003] Electromechanical systems (EMS) include devices having electrical and
mechanical elements, transducers such as actuators and sensors, optical components
15 (including mirrors), and electronics. Electromechanical systems can be manufactured
at a variety of scales including, but not limited to, microscale and nanoscale. For
example, microelectromechanical systems (MEMS) devices can include structures
having sizes ranging from about one micron to hundreds of microns or more.
Nanoelectromechanical systems (NEMS) devices can include structures having sizes
20 smaller than one 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, mechanical, and
electromechanical devices.

25 [0004] One type of EMS device is called an interferometric modulator (IMOD).
As used herein, the term IMOD 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 IMOD 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 IMOD. IMOD 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.

- 10 [0005] Various electronic circuit components can be implemented at the EMS level, including transformers. A transformer transfers electrical energy from one circuit to another through inductively-coupled coils. A varying current, I_p , in a primary coil induces a voltage, V_s , in a secondary coil. When a load is connected to the secondary coil, electrical energy can be transferred through the coils to the load.
- 15 The induced voltage, V_s , in the second coil is generally proportional to a voltage, V_p , delivered to the first coil and is given by the ratio of the number of turns (windings) in the second coil, N_s , to the number of turns in the first coil, N_p . This transformation ratio is generally defined as follows:

$$V_s/V_p = N_s/N_p$$

- 20 [0006] In some modern circuits, small form factor transformers are specified. Conventional transformers made of relatively large metal spiral inductors often do not meet such specifications, especially as devices become increasingly smaller and power requirements become increasingly important.

SUMMARY

- 25 [0007] The structures, devices, apparatus, systems, and processes of the disclosure each have several innovative aspects, no single one of which is solely responsible for the desirable attributes disclosed herein.

[0008] Disclosed are example implementations of piezoelectric electromechanical systems (EMS) resonator transformers, devices, apparatus, systems, and related fabrication processes.

[0009] According to one innovative aspect of the subject matter described in this disclosure, a piezoelectric transformer includes piezoelectric means including piezoelectric material. The piezoelectric transformer also includes first conductive means arranged over a first surface of the piezoelectric material. The first conductive means includes a first set of one or more electrodes and a second set of one or more electrodes. The first set of electrodes is interdigitated with the second set of electrodes. The piezoelectric transformer also includes second conductive means arranged over a second surface of the piezoelectric material opposite the first surface. The second conductive means includes at least a third set of one or more electrodes. The piezoelectric transformer also includes first coupling means capable of receiving an input signal. The first set of electrodes is in electrical connection with the first coupling means. The piezoelectric transformer also includes second coupling means capable of being electrically connected to a load and capable of outputting an output signal. The second set of electrodes is in electrical connection with the second coupling means. In some implementations, a ratio of the number of electrodes of the second set to the number of electrodes of the first set characterizes a transformation ratio between the first coupling means and the second coupling means.

[0010] In some implementations, the piezoelectric means includes a layer of piezoelectric material. In some such implementations, the first conductive means includes a first conductive layer arranged over the first surface of the piezoelectric layer, the first conductive layer including the first set of one or more electrodes and the second set of one or more electrodes. In some such implementations, the second conductive means includes a second conductive layer arranged over the second surface of the piezoelectric layer opposite the first surface of the piezoelectric layer, the second conductive layer including the third set of one or more electrodes.

[0011] In some implementations, the ratio of the number of electrodes of the second set to the number of electrodes of the first set is 1:2. In some such

implementations, there are two electrodes of the second set and four electrodes of the first set. In some implementations, the piezoelectric transformer includes a first transformer stage and a second transformer stage. In some such implementations, the first transformer stage includes the first set of electrodes, the second set of electrodes and the third set of electrodes. In some such implementations, the first conductive means further includes a seventh set of one or more electrodes for the second transformer stage and an eighth set of one or more electrodes for the second transformer stage. The seventh set of electrodes is interdigitated with the eighth set of electrodes. In some such implementations, the second conductive means further includes at least a ninth set of one or more electrodes for the second transformer stage. The seventh set of electrodes of the second transformer stage are in electrical connection with the second coupling means. The transformer further includes third coupling means capable of outputting a second output signal. The eighth set of electrodes of the second transformer stage is in electrical connection with the third coupling means. In some such implementations, the first transformer stage includes four electrodes from the second set and eight electrodes from the first set, the second transformer stage includes two electrodes from the eighth set and four electrodes from the seventh set, and an effective transformation ratio of the combination of the first and second transformer stages between the third coupling means and the first coupling means is approximately 1:4.

[0012] In some implementations, the piezoelectric transformer includes a third transformer stage. In some such implementations, the first conductive means further includes a tenth set of one or more electrodes for the third transformer stage and an eleventh set of one or more electrodes for the third transformer stage, the tenth set of electrodes being interdigitated with the eleventh set of electrodes. In some such implementations, the second conductive means further includes at least a twelfth set of one or more electrodes for the third transformer stage. The tenth set of electrodes of the third transformer stage are in electrical connection with the third coupling means. The transformer further includes fourth coupling means capable of outputting a third output signal. The eleventh set of electrodes of the third transformer stage is in electrical connection with the fourth coupling means. In some such implementations, the third transformer stage includes one electrode from the eleventh set and two

electrodes from the tenth set, and an effective transformation ratio of the combination of the first, second and third transformer stages between the fourth coupling means and the first coupling means is approximately 1:8.

[0013] In some implementations, the second conductive means further includes a fourth set of one or more electrodes. In some such implementations, the first set of electrodes and the third set of electrodes are arranged in a first arrangement. The first arrangement includes a number of first pairs, each first pair including an electrode from the first set and a corresponding electrode from the third set. In some such implementations, the second set of electrodes and the fourth set of electrodes are arranged in a second arrangement. The second arrangement includes a number of second pairs, each second pair including an electrode from the second set and a corresponding electrode from the fourth set. The first arrangement is interdigitated with the second arrangement, and a ratio of the number of second pairs to the number of first pairs characterizes the transformation ratio between the first coupling means and the second coupling means.

[0014] In some such implementations, the first conductive means further includes a fifth set of electrodes and the second conductive means further includes a sixth set of electrodes. In some such implementations, the fifth set of electrodes and the sixth set of electrodes are arranged in a third arrangement. The third arrangement includes a number of third pairs, each third pair comprising an electrode from the fifth set and a corresponding electrode from the sixth set. The third arrangement is interdigitated with the first and second arrangements, and a ratio of the sum of the number of second pairs and the number of third pairs to the number of first pairs characterizes a second transformation ratio between the first coupling means and the second coupling means.

[0015] In some such implementations, the piezoelectric means includes a layer of piezoelectric material, the first conductive means includes a first conductive layer arranged over a first surface of the piezoelectric layer, and the second conductive means includes a second conductive layer arranged over the second surface of the piezoelectric layer opposite the first surface of the piezoelectric layer. The first

conductive layer includes the first set of one or more electrodes and the second set of one or more electrodes. The second conductive layer includes the third set of one or more electrodes and the fourth set of one or more electrodes. In some such implementations, the first coupling means includes or is electrically connected to a first input port capable of receiving a first component of a differential input signal, and to a second input port capable of receiving a second component of the differential input signal. In some such implementations, the second coupling means includes or is electrically connected to a first output port capable of being coupled to a load and of outputting a first component of a differential output signal, and to a second output port capable of being coupled to the load and of outputting a second component of the differential output signal. The first set of electrodes is electrically connected with the first input port, the second set of electrodes is electrically connected with the first output port, the third set of electrodes is electrically connected with the second input port, and the fourth set of electrodes is electrically connected with the second output port.

[0016] In some implementations, an output impedance is measureable at the second coupling means, an input impedance is measureable at the first coupling means, an impedance ratio of the transformer is a ratio of the output impedance to the input impedance, and the transformation ratio is related to the impedance ratio. In some implementations, the first conductive means further includes one or more floating electrodes interdigitated with at least ones of the electrodes of the first and second sets.

[0017] According to another innovative aspect of the subject matter described in this disclosure, a display apparatus includes a piezoelectric transformer as described above. The display apparatus also includes a display, a processor configured to communicate with the display and to process image data, and a memory device configured to communicate with the processor. In some such implementations, the display apparatus further includes a driver circuit configured to send at least one signal to the display, and a controller configured to send at least a portion of the image data to the driver circuit. In some such implementations, one or more of the electrodes described above are coupled to send the image data to the processor.

[0018] According to another innovative aspect of the subject matter described in this disclosure, a process for forming a resonator structure includes forming a lower conductive layer of electrodes, forming a piezoelectric layer over the lower electrode layer, and forming an upper conductive layer of electrodes over the piezoelectric

5 layer. The upper conductive layer includes at least a first set of one or more electrodes and a second set of one or more electrodes. The first set is interdigitated with the second set. The lower conductive layer includes at least a third set of one or more electrodes. A ratio of the number of electrodes of the second set to the number of electrodes of the first set characterizes a transformation ratio. In some
10 implementations, the lower conductive layer further includes a fourth set of one or more electrodes. In some such implementations, the first set of electrodes and the third set of electrodes are arranged in a first arrangement. The first arrangement includes a number of first pairs, each first pair including an electrode from the first set and a corresponding electrode from the third set. In some such implementations, the
15 second set of electrodes and the fourth set of electrodes are arranged in a second arrangement. The second arrangement includes a number of second pairs, each second pair including an electrode from the second set and a corresponding electrode from the fourth set. The first arrangement is interdigitated with the second arrangement, and a ratio of the number of second pairs to the number of first pairs
20 characterizes the transformation ratio.

[0019] In some implementations, the upper conductive layer further includes a fifth set of electrodes and the lower conductive layer further includes a sixth set of electrodes. In some such implementations, the fifth set of electrodes and the sixth set of electrodes are arranged in a third arrangement, the third arrangement including a
25 number of third pairs, each third pair comprising an electrode from the fifth set and a corresponding electrode from the sixth set. In some such implementations, the third arrangement is interdigitated with the first and second arrangements, and a ratio of the sum of the number of second pairs and the number of third pairs to the number of first pairs characterizes a second transformation ratio.

30 **[0020]** 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. Although the examples provided in this disclosure are primarily described in terms of electromechanical systems (EMS) and microelectromechanical systems (MEMS)-based displays, the concepts provided herein may apply to other types of displays, such as liquid crystal displays, organic light-emitting diode ("OLED") displays and field emission displays. 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

[0021] Figure 1 shows a cross-sectional side view of an example piezoelectric transformer.

[0022] Figure 2 shows a top view of the example piezoelectric transformer of Figure 1.

[0023] Figures 3-5 show top views of example piezoelectric transformers.

[0024] Figure 6 shows a top view of an example piezoelectric transformer arrangement that includes three piezoelectric transformers.

[0025] Figure 7 shows a cross-sectional side view of another piezoelectric transformer that uses a differential drive scheme.

[0026] Figures 8A and 8B show top and bottom views, respectively, of an example piezoelectric transformer arrangement that uses a differential drive scheme.

[0027] Figure 9 shows a cross-sectional side view of another example piezoelectric transformer.

[0028] Figure 10 shows a perspective cross-sectional view of an example piezoelectric transformer supported in a cavity.

[0029] Figure 11 shows a flow diagram illustrating an example process for forming an example piezoelectric transformer.

[0030] Figure 12A shows an isometric view depicting two adjacent example pixels in a series of pixels of an example interferometric modulator (IMOD) display device.

[0031] Figure 12B shows an example system block diagram illustrating an example electronic device incorporating an IMOD display.

[0032] Figures 13A and 13B show examples of system block diagrams illustrating an example display device that includes a plurality of IMODs.

[0033] Like reference numbers and designations in the various drawings indicate like elements.

10

DETAILED DESCRIPTION

[0034] The following detailed description is directed to certain implementations for the purposes of describing the innovative aspects. However, the teachings herein can be applied and implemented in a multitude of different ways.

[0035] The disclosed implementations include examples of structures and configurations of electromechanical systems (EMS) devices, including piezoelectric EMS transformers. Related apparatus, systems, and fabrication processes and techniques are also disclosed. In the disclosed implementations of piezoelectric EMS transformers (hereinafter "piezoelectric transformers"), electrodes are disposed in contact with or in proximity to a piezoelectric material. For instance, the electrodes can be located on the same surface or on opposite surfaces of a layer of the piezoelectric material.

[0036] Figure 1 illustrates a cross-sectional side view of an example piezoelectric transformer 100 that includes a piezoelectric layer 102, a first (upper) conductive layer 104 arranged over a first (upper) surface 106 of the piezoelectric layer 102 and a second (lower) conductive layer 108 arranged over a second (lower) surface 110 of the piezoelectric layer 102 opposite the first surface. In some implementations, the first conductive layer 104 includes a first set of one or more first electrodes 112 and a second set of one or more second electrodes 114. In some such implementations, the

first electrodes 112 are interdigitated with the second electrodes 114. In some implementations, the second conductive layer 108 includes at least a third set of one or more third electrodes 116.

[0037] The piezoelectric transformer 100 also includes a first port or node (hereinafter port and node may be used interchangeably) 124 capable of receiving an input signal, such as a varying input signal. The first electrodes 112 are electrically connected to or otherwise coupled to the first port 124. The piezoelectric transformer 100 also includes a second port 126 that can be electrically connected to or otherwise coupled to a load and capable of outputting an output signal. The second electrodes 114 are electrically connected to or otherwise coupled to the second port 126. In some such implementations, a ratio of the number of second electrodes 114 to the number of first electrodes 112 characterizes an effective transformation ratio of the piezoelectric transformer 100. In some implementations, the transformation ratio is related to the impedance ratio of the output impedance measurable at the second port 126 to the input impedance measurable at the first port 124. For reference, the transformation ratio is a characteristic that is more general than the impedance ratio. Depending on the source impedance or load impedance, the transformation ratio for a signal (voltage or current) may be equal or not to the impedance ratio of the transformer.

[0038] An electric field applied via the input signal between first electrodes 112 and third electrodes 116 is transduced into a mechanical strain in the piezoelectric material layer 102. For instance, a time-varying electrical signal can be provided to the first electrodes 112 of the transformer 100 and transduced to a corresponding time-varying mechanical motion. A portion of this mechanical energy can be transferred back to electrical energy at the second electrodes 114 and output over the second port 126. The frequencies of the input electrical signal that produce the greatest substantial amplifications of the mechanical displacement in the piezoelectric material are generally referred to as resonant frequencies. In implementations in which the piezoelectric material layer 102 is configured to resonate, the piezoelectric transformer 100 can thus be referred to as a piezoelectric resonator transformer.

[0039] Particular implementations of the subject matter described in this disclosure can be implemented to realize one or more of the following potential advantages. The disclosed piezoelectric devices can function as EMS transformers suitable for applications for which conventional wire inductor transformers are no longer feasible.

5 Some examples of the disclosed piezoelectric transformers provide the advantages of compact size, such as on the order of 1 μm (micrometer) to 100 μm in length and/or width, low insertion loss, low power consumption, and compatibility with high-yield mass-producible components.

[0040] Some implementations described herein are based on a contour mode resonator (CMR) configuration. In such implementations, the resonant frequency of a CMR can be substantially controlled by engineering the lateral (e.g., length and width) dimensions of the piezoelectric material layers and the electrode layers as well as engineering the periodicity of the electrodes and the thickness of the piezoelectric layer. One benefit of such a construction is that multi-frequency RF filters, clock
15 oscillators, transformers, transducers or other devices, each including one or more CMRs depending on the desired implementation, can be fabricated on the same substrate. For example, this may be advantageous in terms of cost and size by enabling compact, multi-band filter solutions for RF front-end applications on a single chip. In some examples, by co-fabricating multiple CMRs with different finger
20 widths, as described in greater detail below, multiple frequencies can be addressed on the same die. In some examples, arrays of CMRs with different frequencies spanning a range from MHz to GHz can be fabricated on the same substrate. In some other implementations, the piezoelectric transformers described herein can be based on other resonator or acoustic wave device configurations, such as surface acoustic wave
25 (SAW) devices, film bulk acoustic wave resonators (FBAR), bulk acoustic wave (BAW) resonators, and dilation mode resonators (DMRs).

[0041] In one or more implementations, the piezoelectric transformer structure is suspended in a cavity of a supporting structure. The piezoelectric transformer can be suspended in the cavity by specially designed tethers coupling the piezoelectric
30 transformer to the supporting structure, as further explained below. These tethers are often fabricated in the layer stack of the piezoelectric transformer itself. The

piezoelectric transformer can be acoustically isolated from the surrounding structural support and other apparatus by virtue of the cavity.

[0042] The disclosed piezoelectric transformers can be fabricated on a low-cost, high-performance, large-area insulating substrate, which, in some implementations, forms at least a portion of the supporting structure described herein. In some implementations, the insulating substrate on which the disclosed piezoelectric transformers are formed can be made of display-grade glass (alkaline earth borosilicate) or soda lime glass. Other suitable insulating materials of which the insulating substrate can be made include silicate glasses, such as alkaline earth aluminosilicate, borosilicate, modified borosilicate, and others. Also, ceramic materials such as aluminum oxide (AlOx), yttrium oxide (Y_2O_3), boron nitride (BN), silicon carbide (SiC), aluminum nitride (AlN_x), and gallium nitride (GaN_x) can be used as the insulating substrate material. In some other implementations, the insulating substrate is formed of high-resistivity silicon. In some implementations, silicon On Insulator (SOI) substrates, gallium arsenide (GaAs) substrates, indium phosphide (InP) substrates, and plastic (polyethylene naphthalate or polyethylene terephthalate) substrates, e.g., associated with flexible electronics, also can be used. The substrate can be in conventional Integrated Circuit (IC) wafer form, e.g., 4-inch, 6-inch, 8-inch, 12-inch, or in large-area panel form. For example, flat panel display substrates with dimensions such as 370 mm x 470 mm, 920 mm x 730 mm, and 2850 mm x 3050 mm, can be used.

[0043] In some implementations, the disclosed piezoelectric transformers are fabricated by depositing a sacrificial (SAC) layer on the substrate; forming one or more lower conductive electrode layers on the SAC layer; depositing a piezoelectric layer on the lower conductive electrode layer; forming one or more upper electrode layers on the piezoelectric layer; and removing at least part of the SAC layer to define a cavity. The resulting cavity separates at least a portion of the lower electrode layer from the substrate and provides openings along the sides of the piezoelectric resonator transformer, as illustrated in the accompanying figures, to allow the piezoelectric layer 102 to vibrate and move in one or more directions with substantial elastic isolation from the remaining substrate. In some other implementations, a portion of

the substrate itself serves as a SAC material. In these implementations, designated regions of the insulating substrate below the piezoelectric layer 102 can be removed, for example, by etching to define the cavity.

[0044] Figure 2 illustrates a top view of an example implementation of the piezoelectric transformer 100 of Figure 1 in which the ratio of the number of second electrodes 114 to the number of first electrodes 112 (hereinafter the "transformation ratio") is 1:2. In the implementation of Figure 2, the piezoelectric transformer 100 includes one second electrode 114 and two first electrodes 112. The second electrode 114 is arranged between the first electrodes 112.

[0045] In some implementations, the one or more third electrodes 116 in the implementations described with reference to Figures 1 and 2, as well as in some implementations described with reference to other Figures below, can be electrically connected or otherwise coupled to ground. In other implementations, the third electrodes 116 can be driven with a varying input signal, as described with reference to Figure 7. In some implementations, the one or more third electrodes 116 include only a single conductive plane 116. In other implementations, the third electrodes 116 can be arranged in a similar pattern to the first and second electrodes 112 and 114. For example, the third electrodes 116 can include a third electrode 116 arranged opposite each of the first electrodes 112 and each of the second electrodes 114.

[0046] Figure 3 illustrates a top view of an example implementation of a piezoelectric transformer 300 in which the transformation ratio (the number of second electrodes 114 to the number of first electrodes 112) is 1:2. In the implementation of Figure 3, the piezoelectric transformer 300 includes two second electrodes 114 and four first electrodes 112. The second electrodes 114 are interdigitated with the first electrodes; that is, for example, the second electrodes 114 are arranged between the first electrodes 112 in an alternating fashion as shown in Figure 3. In the example of Figure 3, the second electrodes 114 are interdigitated with the first electrodes 112 such that each second electrode 114 is arranged between two adjacent first electrodes 112.

[0047] Piezoelectric transformer 300 also includes a first port 124 capable of receiving an input signal. The first electrodes 112 are coupled to the first port 124. Piezoelectric transformer 300 also can include a second port 126 that can be electrically connected to or otherwise coupled to a load and capable of outputting an output signal. The second electrodes 114 are coupled to the second port 126.

[0048] In some implementations, the first and second ports 124 and 126, or the signals routed through them, can be reversed. For example, in Figure 3 the first port 124 receives an input signal and second port 126 transmits an output signal. In another implementation, second port 126 can receive the input signal and first port 124 can transmit the output signal. In such an implementation, the transformation ratio would be 2:1 rather than 1:2. The switching of the first and second ports, or the signals traversing them, can be switched in any of the implementations described or disclosed herein.

[0049] In some implementations, one or both of the first conductive layer 104 and the second conductive layer 108 also includes one or more floating electrodes (e.g., electrodes with no direct electrical connection) interdigitated with ones of the first electrodes 112, second electrodes 114 or third electrodes 116. In Figure 3, the first conductive layer 104 of the example piezoelectric transformer 300 includes a floating electrode 120 arranged between the middle two first electrodes 112, as shown.

[0050] Figure 4 illustrates a top view of an example implementation of a piezoelectric transformer 400 in which the transformation ratio (the number of second electrodes 114 to the number of first electrodes 112) is 1:2. In the implementation of Figure 4, the piezoelectric transformer 400 includes four second electrodes 114 and eight first electrodes 112. The second electrodes 114 are interdigitated with the first electrodes; that is, for example, the second electrodes 114 are arranged between the first electrodes 112 in an alternating fashion as shown in Figure 4. In the example of Figure 4, the second electrodes 114 are interdigitated with the first electrodes 112 such that each second electrode 114 is arranged between two adjacent first electrodes 112.

[0051] Piezoelectric transformer 400 also includes a first port 124 capable of receiving an input signal. The first electrodes 112 are electrically connected to or otherwise coupled to the first port 124. Piezoelectric transformer 400 also can include a second port 126 that can be coupled to a load and capable of outputting an output
5 signal. The second electrodes 114 are electrically connected to or otherwise coupled to the second port 126. In Figure 4, the first conductive layer 104 of the example piezoelectric transformer 400 also includes floating electrodes 120 each arranged between other ones of the adjacent first electrodes 112 not separated by a second electrode 114.

10 [0052] Figure 5 illustrates a top view of an example implementation of a piezoelectric transformer 500 in which the transformation ratio (the number of second electrodes 114 to the number of first electrodes 112) is 1:8. In the implementation of Figure 5, the piezoelectric transformer 500 includes one second electrode 114 and eight first electrodes 112. In such an implementation, the second electrode 114 can be
15 arranged between the middle-two first electrodes 112 as shown in Figure 5. In some implementations, one or both of the first conductive layer 104 and the second conductive layer 108 also includes one or more floating electrodes interdigitated with ones of the first electrodes 112, second electrode 114 or third electrodes 116.

[0053] The piezoelectric transformer 500 also includes a first port 124 capable of
20 receiving an input signal. The first electrodes 112 are electrically connected to or otherwise coupled to the first port 124. Piezoelectric transformer 500 also can include a second port 126 that can be electrically connected to or otherwise coupled to a load and capable of outputting an output signal. The second electrodes 114 are electrically
25 connected to or otherwise coupled to the second port 126. In Figure 5, the first conductive layer 104 of the example piezoelectric transformer 500 also includes floating electrodes 120 each arranged between other ones of the adjacent first electrodes 112 not separated by the second electrode 114.

[0054] In other implementations, two or more piezoelectric transformers can be connected, for example, in series, to achieve higher efficiency energy conversion. For
30 example, Figure 6 illustrates a top view of an example implementation of a

piezoelectric transformer arrangement 600 that also has an effective transformation ratio of about 1:8 like the implementation of Figure 5, but which achieves a significantly higher efficiency energy conversion than that achievable with the implementation of Figure 5. In the illustrated implementation, piezoelectric

5 transformer arrangement 600 includes a first piezoelectric transformer or "transformer stage" 601a (such as piezoelectric transformer 400 shown in Figure 4) electrically connected to or otherwise coupled with a second piezoelectric transformer or transformer stage 601b (such as piezoelectric transformer 300 shown in Figure 3), which is electrically connected to or otherwise coupled to a third piezoelectric

10 transformer or transformer stage 601c (such as piezoelectric transformer 100 shown in Figures 1 and 2). In some implementations, all of the transformer stages 601a, 601b, and 601c, share the same piezoelectric layer. The piezoelectric transformer arrangement 600 of Figure 6, although having a combined effective transformation ratio of 1:8 like the piezoelectric transformer of Figure 5, achieves higher efficiency at

15 least in part because each of piezoelectric transformers 601a-601c individually achieves high efficiency because each of piezoelectric transformers 601a-601c individually has a transformation ratio of 1:2.

[0055] In general, the closer the transformation ratio is to 1:1, the higher the possible efficiency. On the other hand, if the transformer has fewer floating

20 electrodes 120, the transformer can have higher electromechanical coupling or higher transformation efficiency. For example, simply because there is mechanical strain existing in all the fingers of the resonator, the energy of those fingers with floating electrodes is wasted if not collected by the output electrode.

[0056] In the illustrated implementation, piezoelectric transformer 601a includes a

25 first port 124 capable of receiving an input signal. The first electrodes 112 of piezoelectric transformer 601a are electrically connected to or otherwise coupled to the first port 124. Piezoelectric transformer 601a also includes a second port 126 capable of outputting a first output signal and to which the second electrodes 114 of piezoelectric transformer 601a are electrically connected to or otherwise coupled. In

30 the illustrated implementation, piezoelectric transformer 601b includes a first port 128 capable of receiving the first output signal. The first electrodes 112 of piezoelectric

transformer 601b are electrically connected to or otherwise coupled to the first port 128. Piezoelectric transformer 601b also includes a second port 130 capable of outputting a second output signal and to which the second electrodes 114 of piezoelectric transformer 601b are electrically connected to or otherwise coupled. In the illustrated implementation, piezoelectric transformer 601c includes a first port 132 capable of receiving the second output signal. The first electrodes 112 of piezoelectric transformer 601c are electrically connected to or otherwise coupled to the first port 132. Piezoelectric transformer 601c also includes a second port 134 capable of outputting a third output signal and to which the second electrodes 114 of piezoelectric transformer 601c are electrically connected to or otherwise coupled.

[0057] Figure 7 illustrates a cross-sectional side view of another example piezoelectric transformer 700 that operates according to a different differential drive and sense scheme. Piezoelectric transformer 700 includes a piezoelectric layer 102, a first (upper) conductive layer 104 arranged over a first (upper) surface 106 of the piezoelectric layer 102 and a second (lower) conductive layer 108 arranged over a second (lower) surface 110 of the piezoelectric layer 102 opposite the first surface. In some implementations, the first conductive layer 104 includes a first set of one or more first electrodes 112 and a second set of one or more second electrodes 114. In some such implementations, the first electrodes 112 are interdigitated with the second electrodes 114. In various implementations, each of the piezoelectric transformers 100, 300, 400, and 500 can be implemented with a similar drive scheme to that which will now be described, but for didactic purposes, a piezoelectric transformer having first electrodes 112 and second electrodes 114 as arranged in Figure 3 will be described.

[0058] In some implementations, the second conductive layer 108 includes a third set of one or more third electrodes 116 and a fourth set of one or more fourth electrodes 118. In Figure 7, each of the third electrodes 116 is arranged opposite a corresponding one of the first electrodes 112 while each of the fourth electrodes 118 is arranged opposite a corresponding one of the second electrodes 114.

[0059] In the implementation of Figure 7, piezoelectric transformer 700 includes a first input port 124p capable of receiving a first component of a differential input signal. The first electrodes 112 are electrically connected to or otherwise coupled to the first input port 124p. Piezoelectric transformer 700 also includes a second input port 124n capable of receiving a second component of the differential input signal. The third electrodes 116 are electrically connected to or otherwise coupled to the second input port 124n. In Figure 7, piezoelectric transformer 700 also includes a first output port 126p capable of being electrically connected to or otherwise coupled to a load and capable of outputting a first component of a differential output signal. The second electrodes 114 are electrically connected to or otherwise coupled to the first output port 126p. Piezoelectric transformer 700 also can include a second output port 126n capable of being electrically connected to or otherwise coupled to the load and capable of outputting a second component of the differential output signal. The fourth electrodes 118 are electrically connected to or otherwise coupled to the second output port 126n.

[0060] Like other implementations described above, the piezoelectric transformer 700 also can include one or more floating electrodes in one or both of the first conductive layer 104 and the second conductive layer 108.

[0061] Figures 8A and 8B show top and bottom views, respectively, of another example piezoelectric arrangement 800 in which two or more piezoelectric transformers can be connected, for example, in series, to achieve higher efficiency energy conversion. For example, Figure 8A illustrates a top view of an example implementation of a piezoelectric transformer arrangement 800 that also has an effective transformation ratio of about 1:8 like the implementation of Figure 5, but which achieves a significantly higher efficiency energy conversion than that achievable with the implementation of Figure 5. In the illustrated implementation, piezoelectric transformer arrangement 800 includes a first piezoelectric transformer or transformer stage 801a coupled with a second piezoelectric transformer or transformer stage 801b (such as piezoelectric transformer 700 shown in Figure 7), which is coupled to a third piezoelectric transformer or transformer stage 801c. In some implementations, all of the transformer stages 801a, 801b, and 801c, share the same

piezoelectric layer. The piezoelectric transformer arrangement 800 of Figures 8A and 8B, although having a combined effective transformation ratio of 1:8 like the piezoelectric transformer of Figure 5, achieves higher efficiency at least in part because each of piezoelectric transformers 801a-801c individually achieves high efficiency because each of piezoelectric transformers 801a-801c individually has a transformation ratio of 1:2.

[0062] In the arrangement of Figures 8A and 8B, the first piezoelectric transformer 801a includes a first input port 124p capable of receiving a first component of a differential input signal. The first electrodes 112 of piezoelectric transformer 801a are electrically connected to or otherwise coupled to the first input port 124p. Piezoelectric transformer 801a includes a second input port 124n capable of receiving a second component of the differential input signal. The third electrodes 116 of piezoelectric transformer 801a are electrically connected to or otherwise coupled to the second input port 124n. Piezoelectric transformer 801a also includes a first output port 126p capable of outputting a first component of a first differential output signal and to which the second electrodes 114 of piezoelectric transformer 801a are electrically connected to or otherwise coupled. Piezoelectric transformer 801a also includes a second output port 126n capable of outputting a second component of the first differential output signal and to which the fourth electrodes 114 of piezoelectric transformer 801a are electrically connected to or otherwise coupled.

[0063] In the illustrated implementation, the second piezoelectric transformer 801b includes a third input port 128p capable of receiving a first component of the first differential output signal. The first electrodes 112 of piezoelectric transformer 801b are electrically connected to or otherwise coupled to the third input port 128p. Piezoelectric transformer 801b includes a fourth input port 128n capable of receiving a second component of the first differential output signal. The third electrodes 116 of piezoelectric transformer 801b are electrically connected to or otherwise coupled to the fourth input port 128n. Piezoelectric transformer 801b also includes a third output port 130p capable of outputting a first component of a second differential output signal and to which the second electrodes 114 of piezoelectric transformer 801b are

electrically connected to or otherwise coupled. Piezoelectric transformer 801b also includes a fourth output port 130n capable of outputting a second component of the second differential output signal and to which the fourth electrodes 114 of piezoelectric transformer 801b are electrically connected to or otherwise coupled.

5 **[0064]** In the illustrated implementation, the third piezoelectric transformer 801c includes a fifth input port 132p capable of receiving a first component of the second differential output signal. The first electrodes 112 of piezoelectric transformer 801c are electrically connected to or otherwise coupled to the third input port 132p.

10 Piezoelectric transformer 801c includes a sixth input port 132n capable of receiving a second component of the second differential output signal. The third electrodes 116 of piezoelectric transformer 801c are electrically connected to or otherwise coupled to the sixth input port 132n. Piezoelectric transformer 801c also includes a fifth output port 134p capable of outputting a first component of a third differential output signal and to which the second electrodes 114 of piezoelectric transformer 801c are
15 electrically connected to or otherwise coupled. Piezoelectric transformer 801c also includes a sixth output port 134n capable of outputting a second component of the third differential output signal and to which the fourth electrodes 114 of piezoelectric transformer 801c are electrically connected to or otherwise coupled.

20 **[0065]** Figure 9 illustrates a cross-sectional side view of another example piezoelectric transformer 900 that operates according to a different single-ended drive and sense scheme. Piezoelectric transformer 900 includes a piezoelectric layer 102, a first (upper) conductive layer 104 arranged over a first (upper) surface 106 of the piezoelectric layer 102 and a second (lower) conductive layer 108 arranged over a second (lower) surface 110 of the piezoelectric layer 102 opposite the first surface.
25 The first conductive layer 104 includes a first set of one or more first electrodes 112, a second set of one or more second electrodes 114, and a fifth set of one or more fifth electrodes 122. The second conductive layer 108 includes a third set of one or more third electrodes 116, a fourth set of one or more fourth electrodes 118, and a sixth set of one or more sixth electrodes 124.

[0066] Piezoelectric transformer 900 also includes a first port 124 capable of receiving an input signal. The first electrodes 112 and sixth electrodes 124 are electrically connected to or otherwise coupled to the first port 124. Piezoelectric transformer 900 also includes a second port 126 that can be electrically connected to or otherwise coupled to a load and capable of outputting an output signal. The second electrodes 114 are electrically connected to or otherwise coupled to the second port 126. In some such implementations, the third electrodes 116, the fourth electrodes 118, and the fifth electrodes 122 are electrically connected to or otherwise coupled to ground.

[0067] Figure 10 shows a perspective cross-sectional view of an example piezoelectric resonator transformer, such as that shown in Figure 3. In Figure 10, piezoelectric resonator transformer 300 is suspended in a cavity 140 by virtue of a first tether, including tether interconnect 142 as well as a matching second tether (not shown) connected at the opposite end. In Figure 10, the tethers serve as physical anchors to hold the transformer in the cavity 140. The piezoelectric resonator transformer is capable of vibration by virtue of the piezoelectric material layers 102.

[0068] Some implementations disclosed herein with reference to Figures 1-10 have been described using examples in which the transformation ratios were 1:2 or 1:8, or their complements, 2:1 and 8:1, respectively. In other implementations considered for the applications described herein or for other applications, the transformation ratios can be different than 1:2 or 1:8. For example, the transformation ratios can be 1:3, 2:5, 3:7, 5:8 or other desired ratios as well as their complements, such as 3:1, 5:2, 7:3 and 8:5. In general, the disclosed implementations can be applied and adjusted to achieve any arbitrary transformation ratio.

[0069] The piezoelectric resonator transformers of Figures 1-10 include patterns of metal electrodes in the upper and lower conductive layers that, when provided one or more electrical input signals, cause the piezoelectric layers to have a motional response. The motional response can include a vibrational oscillation along one or more of the X, Y and Z axes. The resonant frequency response of the transformers can be controlled according to a periodic arrangement of the electrodes in the

conductive layers, for instance, by adjusting the width(s) as well as the spacing(s) of the electrodes from one another in a conductive layer, such as along the X axis as further explained below.

[0070] In Figures 1-10, the pattern of interdigitated first electrodes, second, third, and fourth electrodes of the respective conductive layers can be periodic in one direction, for instance, along the X axis. As illustrated, the periodic arrangement of electrodes includes alternating areas of metal, representing electrode regions, and space regions, i.e., areas without metal. Such space regions between the electrodes are also referred to herein as "spaces." In various implementations, the areas of metal and the spaces have the same width, the areas of metal are wider than the spaces, the areas of metal are narrower than the spaces, or any other appropriate relation between the metal widths and spaces. The finger width of the resonator, a parameter based on a combination of electrode width and spacing, can be adjusted to control one or more resonant frequencies of the structure. For instance, a first finger width in a conductive layer can correspond to a first resonant frequency, and a second finger width in the conductive layer can provide a different second resonant frequency.

[0071] The fundamental frequency for the displacement of the piezoelectric layer can be set in part lithographically by the planar dimensions of the upper electrodes, the lower electrodes, and/or the piezoelectric layer. At the device resonant frequency, the electrical signal across the device is reinforced and the device behaves as an electronic resonant circuit. For instance, the piezoelectric resonator transformers described above can be implemented by patterning the input electrodes and output electrodes of a respective conductive layer symmetrically.

[0072] The total width, length, and thickness of the piezoelectric resonator transformer are parameters that also can be designated to optimize performance. In some implementations, the finger width of the resonator is the main parameter that is controlled to adjust the resonant frequency of the structure, while the total width multiplied by the total length of the resonator (total area) can be set to control the impedance of the piezoelectric resonator transformer. In one example, the lateral dimensions, i.e., the total width and length of the piezoelectric resonator transformer

can be on the order of several 100 μm by several 100 μm for a device designed to operate around 1 GHz (the finger width can be a few microns for 1 GHz operation in case of AlN as the piezoelectric material). In another example, the lateral dimensions are several 100 μm by several 100 μm for a device designed to operate at around 10
5 MHz. A suitable thickness of the piezoelectric layer 102 can be about 0.01 to 10 μm thick.

[0073] Figure 11 shows a flow diagram illustrating an example process for forming an example piezoelectric transformer such as a piezoelectric resonator transformer. In one example, the piezoelectric resonator transformer is the piezoelectric transformer
10 300 shown in Figure 3. In Figure 11, process 1100 begins in block 1102 in which a sacrificial (SAC) layer is deposited on a substrate. The SAC layer can have various shapes and sizes, and can be shaped to cover all or some portion of the substrate, depending on the desired implementation. In block 1104, a lower electrode layer is formed on the SAC layer. The lower electrode layer is made of a conductive material
15 such as metal and can be patterned to define two or more sets of electrodes (e.g., third and fourth electrodes 116 and 118), depending on the desired configuration. When more than one electrode is defined, the electrodes can be connected at separate ports of the resonator device. In block 1106, a piezoelectric layer (such as piezoelectric layer 102) is deposited on the lower electrode layer. In block 1108, an upper
20 electrode layer is then formed on the piezoelectric layer. The upper electrode layer also can be patterned to define more than one electrode or set of electrodes (such as first and second electrodes 112 and 114). In some implementations, overlaying groups of electrodes can be defined in the upper and lower electrode layers on opposite surfaces of the upper and lower piezoelectric layers. In some
25 implementations, the piezoelectric layer is then etched or otherwise patterned in block 1110 so as to define a desired resonator geometry and to provide access to the SAC layer. In block 1112, part or all of the SAC layer is removed to define a cavity beneath the piezoelectric resonator transformer.

[0074] The piezoelectric materials that can be used in fabrication of the piezoelectric
30 layers of electromechanical systems resonators disclosed herein include, for example, aluminum nitride (AlN), zinc oxide (ZnO), gallium arsenide (GaAs), aluminum

gallium arsenide (AlGaAs), gallium nitride (GaN), quartz and other piezoelectric materials such as zinc-sulfide (ZnS), cadmium-sulfide (CdS), lithium tantalite (LiTaO₃), lithium niobate (LiNbO₃), lead zirconate titanate (PZT), members of the lead lanthanum zirconate titanate (PLZT) family, doped aluminum nitride (AlN:Sc), and combinations thereof. The conductive layers described above may be made of various conductive materials including platinum (Pt), aluminum (Al), molybdenum (Mo), tungsten (W), titanium (Ti), niobium (Nb), ruthenium (Ru), chromium (Cr), doped polycrystalline silicon, doped aluminum gallium arsenide (AlGaAs) compounds, gold (Au), copper (Cu), silver (Ag), tantalum (Ta), cobalt (Co), nickel (Ni), palladium (Pd), silicon germanium (SiGe), doped conductive zinc oxide (ZnO), and combinations thereof. In various implementations, the upper metal electrodes and/or the lower metal electrodes can include the same conductive material(s) or different conductive materials.

[0075] Upper and lower conductive layers 104 and 108 can be formed of aluminum (Al), Al/titanium nitride (TiN)/Al, aluminum copper (AlCu), Mo, or other appropriate materials, and have a thickness of 750 to 3000 Angstroms depending on the desired implementation. In some cases, one or both of the conductive layers 104 and 108 is deposited as a bi-layer with a metal such as Mo deposited on top of a seed layer such as AlN. An appropriate thickness for the seed layer can be, for example, 100 to 1000 Angstroms. When Mo is used, the total thickness of the metal layer 1816 can be about 3000 Angstroms. Other suitable materials for conductive layers 104 and 108 include aluminum silicon (AlSi), AlCu, Ti, TiN, Al, platinum (Pt), nickel (Ni), tungsten (W), ruthenium (Ru), and combinations thereof. Thicknesses can range from about 0.1 μm to about 0.3 μm , depending on the desired implementation.

[0076] The description herein is directed to certain implementations for the purposes of describing the innovative aspects of this disclosure. However, a person having ordinary skill in the art will readily recognize that the teachings herein can be applied in a multitude of different ways. The described implementations may be implemented in any device or system that can be 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 described implementations

may be included 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

5 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 (i.e., e-readers), computer monitors, auto displays (including odometer and speedometer displays, etc.), cockpit controls and/or displays, 10 camera view displays (such as the 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 (such as in electromechanical systems 15 (EMS), microelectromechanical systems (MEMS) and non-MEMS applications), aesthetic structures (e.g., display of images on a piece of jewelry) and a variety of EMS 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 20 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 one having ordinary skill 25 in the art.

[0077] 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 30 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 IMOD. 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.

[0078] Figure 12A shows an example of an isometric view depicting two adjacent pixels in a series of pixels of an 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.

[0079] 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 actuated, reflecting light outside of the visible range (such as infrared light). 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.

[0080] The depicted portion of the pixel array in Figure 12A includes two adjacent IMODs 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.

[0081] In Figure 12A, 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 IMOD 12 on the left. Although not illustrated in detail, it will be understood by one 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 IMOD 12.

[0082] 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, such as various metals, for example indium tin oxide (ITO). The partially reflective layer can be formed from a variety of materials that are partially reflective, such as 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 conductor, while different, 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 a conductive/absorptive layer.

[0083] 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 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, such as 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 separation between posts 18 may be approximately 1-1000 μm , while the gap 19 may be less than 10,000 Angstroms (**A**).

[0084] 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 IMOD 12 on the left in Figure 12A, with the gap 19 between the movable reflective layer 14 and optical stack 16. However, when a potential difference, e.g., 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.

5 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 IMOD 12 on the right in Figure 12A. 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
10 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
15 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
20 elements.

[0085] Figure 12B shows an example of a system block diagram illustrating an electronic device incorporating a 3x3 IMOD display. The electronic device of Figure 12B represents one implementation in which a piezoelectric resonator transformer constructed in accordance with the implementations described above with respect to
25 Figures 1-10 can be incorporated. The electronic device in which device 11 is incorporated may, for example, form part or all of any of the variety of electrical devices and electromechanical systems devices set forth above, including both display and non-display applications.

[0086] Here, the electronic device includes a controller 21, which may include one or
30 more general purpose single- or multi-chip microprocessors such as an ARM®, Pentium®, 8051, MIPS®, Power PC®, or ALPHA®, or special purpose

microprocessors such as a digital signal processor, microcontroller, or a programmable gate array. Controller 21 may be configured to execute one or more software modules. In addition to executing an operating system, the controller 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.

[0087] The controller 21 is configured to communicate with device 11. The controller 21 also 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. Although Figure 12B 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. Controller 21 and array driver 22 may sometimes be referred to herein as being "logic devices" and/or part of a "logic system."

[0088] Figures 13A and 13B show examples of system block diagrams illustrating a display device 40 that includes a plurality of IMODs. The display device 40 can be, for example, a smart phone, 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 such as televisions, tablets, e-readers, hand-held devices and portable media players.

[0089] 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.

[0090] 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, such as plasma, EL, OLED, STN LCD, or TFT LCD, or a non-

flat-panel display, such as a CRT or other tube device. In addition, the display 30 can include an IMOD display, as described herein.

5 [0091] The components of the display device 40 are schematically illustrated in Figure 13B. 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
10 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. In some implementations, a power supply 50 can provide power to substantially all components in the particular display device 40 design.

15 [0092] 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, for example, data processing requirements of the processor 21. The antenna 43 can transmit and receive signals. In some implementations, the antenna 43 transmits and
20 receives RF signals according to the IEEE 16.1 1 standard, including IEEE 16.11(a), (b), or (g), or the IEEE 802.1 1 standard, including IEEE 802.1 la, b, g, n, and further implementations thereof. 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
25 (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
30 (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, such as 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
5 process signals received from the processor 21 so that they may be transmitted from the display device 40 via the antenna 43.

[0093] 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.
10 The processor 21 can control the overall operation of the display device 40. The processor 21 receives data, such as 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
15 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.

[0094] 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
20 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.

[0095] The driver controller 29 can take the raw image data generated by the
25 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
30 the formatted information to the array driver 22. Although a driver controller 29, such

as 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.

[0096] 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.

[0097] 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 (such as an IMOD controller). Additionally, the array driver 22 can be a conventional driver or a bi-stable display driver (such as an IMOD display driver). Moreover, the display array 30 can be a conventional display array or a bi-stable display array (such as 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, for example, mobile phones, portable-electronic devices, watches or small-area displays.

[0098] In some implementations, the input device 48 can be configured to allow, for example, a user to control the operation of the display device 40. The input device 48 can include a keypad, such as a QWERTY keyboard or a telephone keypad, a button, a switch, a rocker, a touch-sensitive screen, a touch-sensitive screen integrated with the display array 30, 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.

[0099] The power supply 50 can include a variety of energy storage devices. For example, the power supply 50 can be a rechargeable battery, such as 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.

[00100] 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.

[00101] 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.

[00102] 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.

[00103] 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.

[00104] 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 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.

[00105] 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.

[00106] 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 piezoelectric transformer comprising:
piezoelectric means including piezoelectric material;
5 first conductive means arranged over a first surface of the piezoelectric material and including a first set of one or more electrodes and a second set of one or more electrodes, the first set of electrodes being interdigitated with the second set of electrodes;
second conductive means arranged over a second surface of the piezoelectric
10 material opposite the first surface and including at least a third set of one or more electrodes;
first coupling means capable of receiving an input signal, the first set of electrodes being in electrical connection with the first coupling means; and
second coupling means capable of being electrically connected to a load and
15 capable of outputting an output signal, the second set of electrodes being in electrical connection with the second coupling means.
2. The piezoelectric transformer of claim 1, wherein a ratio of the number of electrodes of the second set to the number of electrodes of the first set characterizes
20 a transformation ratio between the first coupling means and the second coupling means.
3. The piezoelectric transformer of claims 1 or 2, wherein:
the piezoelectric means includes a layer of piezoelectric material;
25 the first conductive means includes a first conductive layer arranged over the first surface of the piezoelectric layer, the first conductive layer including the first set of one or more electrodes and the second set of one or more electrodes; and
the second conductive means includes a second conductive layer arranged over the second surface of the piezoelectric layer opposite the first surface of the
30 piezoelectric layer, the second conductive layer including the third set of one or more electrodes.

4. The piezoelectric transformer of any preceding claim, wherein the ratio of the number of electrodes of the second set to the number of electrodes of the first set is 1:2.

5

5. The piezoelectric transformer of claim 4, wherein there are two electrodes of the second set and four electrodes of the first set.

6. The piezoelectric transformer of any preceding claim, wherein:
10 the piezoelectric transformer includes a first transformer stage and a second transformer stage;

the first transformer stage includes the first set of electrodes, the second set of electrodes and the third set of electrodes;

the first conductive means further includes a seventh set of one or more
15 electrodes for the second transformer stage and an eighth set of one or more electrodes for the second transformer stage, the seventh set of electrodes being interdigitated with the eighth set of electrodes;

the second conductive means further includes at least a ninth set of one or more electrodes for the second transformer stage;

20 the seventh set of electrodes of the second transformer stage are in electrical connection with the second coupling means; and

the transformer further includes third coupling means capable of outputting a second output signal, the eighth set of electrodes of the second transformer stage being in electrical connection with the third coupling means.

25

7. The piezoelectric transformer of claim 6, wherein:

the first transformer stage includes four electrodes from the second set and eight electrodes from the first set;

the second transformer stage includes two electrodes from the eighth set and
30 four electrodes from the seventh set; and

an effective transformation ratio of the combination of the first and second transformer stages between the third coupling means and the first coupling means is approximately 1:4.

5 8. The piezoelectric transformer of claim 7, wherein:

the piezoelectric transformer includes a third transformer stage;

the first conductive means further includes a tenth set of one or more electrodes for the third transformer stage and an eleventh set of one or more electrodes for the third transformer stage, the tenth set of electrodes being

10 interdigitated with the eleventh set of electrodes;

the second conductive means further includes at least a twelfth set of one or more electrodes for the third transformer stage;

the tenth set of electrodes of the third transformer stage are in electrical connection with the third coupling means; and

15 the transformer further includes fourth coupling means capable of outputting a third output signal, the eleventh set of electrodes of the third transformer stage being in electrical connection with the fourth coupling means.

9. The piezoelectric transformer of claim 8, wherein:

20 the third transformer stage includes one electrode from the eleventh set and two electrodes from the tenth set; and

an effective transformation ratio of the combination of the first, second and third transformer stages between the fourth coupling means and the first coupling means is approximately 1:8.

25

10. The piezoelectric transformer of any preceding claim, wherein:

the second conductive means further includes a fourth set of one or more electrodes;

30 the first set of electrodes and the third set of electrodes are arranged in a first arrangement, the first arrangement including a number of first pairs, each first pair including an electrode from the first set and a corresponding electrode from the third set;

the second set of electrodes and the fourth set of electrodes are arranged in a second arrangement, the second arrangement including a number of second pairs, each second pair including an electrode from the second set and a corresponding electrode from the fourth set;

5 the first arrangement is interdigitated with the second arrangement; and
a ratio of the number of second pairs to the number of first pairs characterizes the transformation ratio between the first coupling means and the second coupling means.

10 11. The piezoelectric transformer of claim 10, wherein:
the first conductive means further includes a fifth set of electrodes;
the second conductive means further includes a sixth set of electrodes;
wherein:
the fifth set of electrodes and the sixth set of electrodes are arranged in
15 a third arrangement, the third arrangement including a number of third pairs,
each third pair comprising an electrode from the fifth set and a corresponding electrode from the sixth set;
the third arrangement is interdigitated with the first and second
arrangements; and
20 a ratio of the sum of the number of second pairs and the number of
third pairs to the number of first pairs characterizes a second transformation ratio between the first coupling means and the second coupling means.

25 12. The piezoelectric transformer of claim 10, wherein:
the piezoelectric means includes a layer of piezoelectric material;
the first conductive means includes a first conductive layer arranged over a first surface of the piezoelectric layer, the first conductive layer including the first set of one or more electrodes and the second set of one or more electrodes; and
the second conductive means includes a second conductive layer arranged
30 over the second surface of the piezoelectric layer opposite the first surface of the piezoelectric layer, the second conductive layer including the third set of one or more electrodes and the fourth set of one or more electrodes.

13. The piezoelectric transformer of claim 12, wherein:

the first coupling means includes or is electrically connected to a first input port capable of receiving a first component of a differential input signal, and to a
5 second input port capable of receiving a second component of the differential input signal;

the second coupling means includes or is electrically connected to a first output port capable of being coupled to a load and of outputting a first component of a differential output signal, and to a second output port capable of being coupled to the
10 load and of outputting a second component of the differential output signal;

the first set of electrodes is electrically connected with the first input port;

the second set of electrodes is electrically connected with the first output port;

the third set of electrodes is electrically connected with the second input port;

and

15 the fourth set of electrodes is electrically connected with the second output port.

14. The piezoelectric transformer of claims 12 or 13, wherein one or both of the first conductive layer and the second conductive layer further includes one or more floating electrodes.

20

15. The piezoelectric transformer of any preceding claim, wherein:

an output impedance is measureable at the second coupling means;

an input impedance is measureable at the first coupling means;

an impedance ratio of the transformer is a ratio of the output impedance to the
25 input impedance; and

the transformation ratio is related to the impedance ratio.

16. The piezoelectric transformer of any preceding claim, wherein the first conductive means further includes one or more floating electrodes interdigitated with
30 at least ones of the electrodes of the first and second sets.

17. A display apparatus comprising :
the piezoelectric transformer of any preceding claim;
a display;
a processor configured to communicate with the display, the processor being
5 configured to process image data; and
a memory device configured to communicate with the processor.

18. The display apparatus of claim 17, further comprising:
a driver circuit configured to send at least one signal to the display; and
10 a controller configured to send at least a portion of the image data to the driver
circuit.

19. The display apparatus of claims 17 or 18, wherein one or more of the
electrodes are coupled to send the image data to the processor.

15

20. A process for forming a resonator structure, comprising:
forming a lower conductive layer of electrodes;
forming a piezoelectric layer over the lower electrode layer; and
forming an upper conductive layer of electrodes over the piezoelectric layer;
20 wherein:
the upper conductive layer includes at least a first set of one or more
electrodes and a second set of one or more electrodes, the first set being interdigitated
with the second set;
the lower conductive layer includes at least a third set of one or more
25 electrodes; and
a ratio of the number of electrodes of the second set to the number of
electrodes of the first set characterizes a transformation ratio.

21. The process of claim 20, wherein:
30 the lower conductive layer further includes a fourth set of one or more
electrodes;

the first set of electrodes and the third set of electrodes are arranged in a first arrangement, the first arrangement including a number of first pairs, each first pair including an electrode from the first set and a corresponding electrode from the third set;

5 the second set of electrodes and the fourth set of electrodes are arranged in a second arrangement, the second arrangement including a number of second pairs, each second pair including an electrode from the second set and a corresponding electrode from the fourth set;

the first arrangement is interdigitated with the second arrangement; and

10 a ratio of the number of second pairs to the number of first pairs characterizes the transformation ratio.

22. The process of claim 20 or 21, wherein:

the upper conductive layer further includes a fifth set of electrodes;

15 the lower conductive layer further includes a sixth set of electrodes;
wherein:

the fifth set of electrodes and the sixth set of electrodes are arranged in a third arrangement, the third arrangement including a number of third pairs, each third pair comprising an electrode from the fifth set and a corresponding
20 electrode from the sixth set;

the third arrangement is interdigitated with the first and second arrangements; and

a ratio of the sum of the number of second pairs and the number of third pairs to the number of first pairs characterizes a second transformation ratio.

25

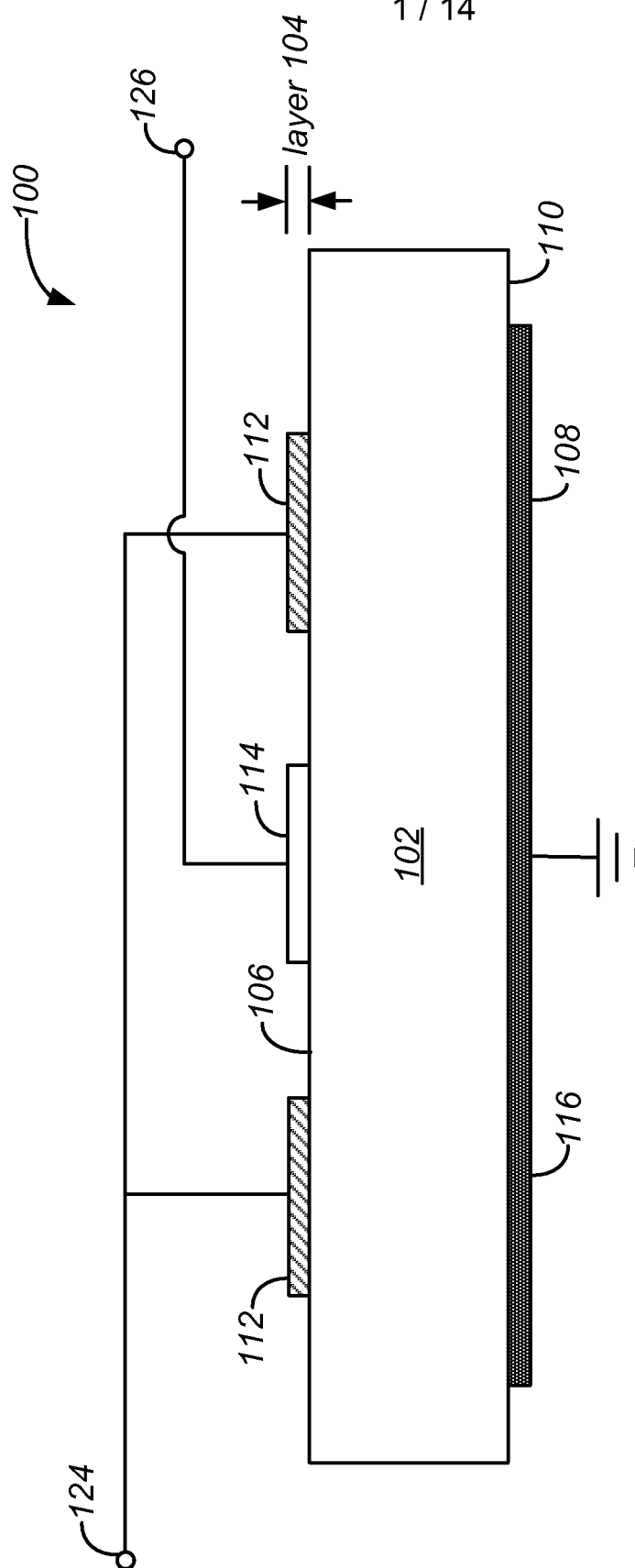
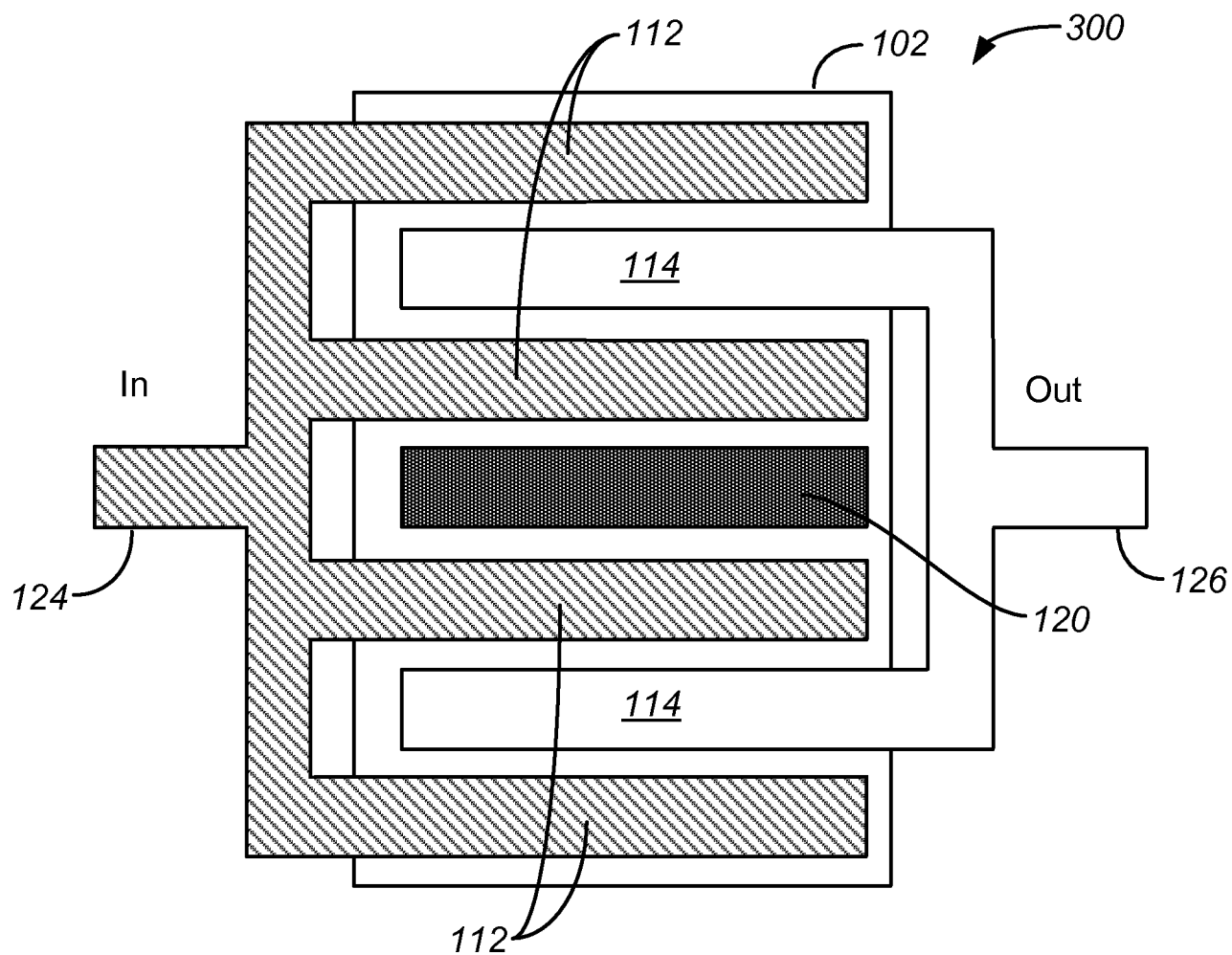
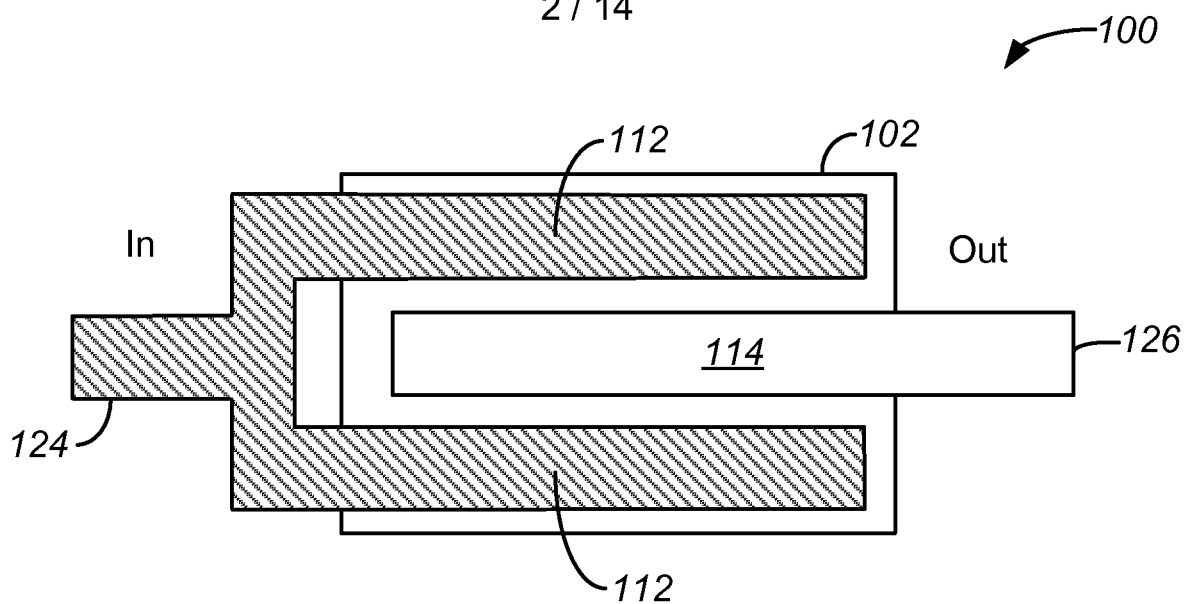


FIGURE 1

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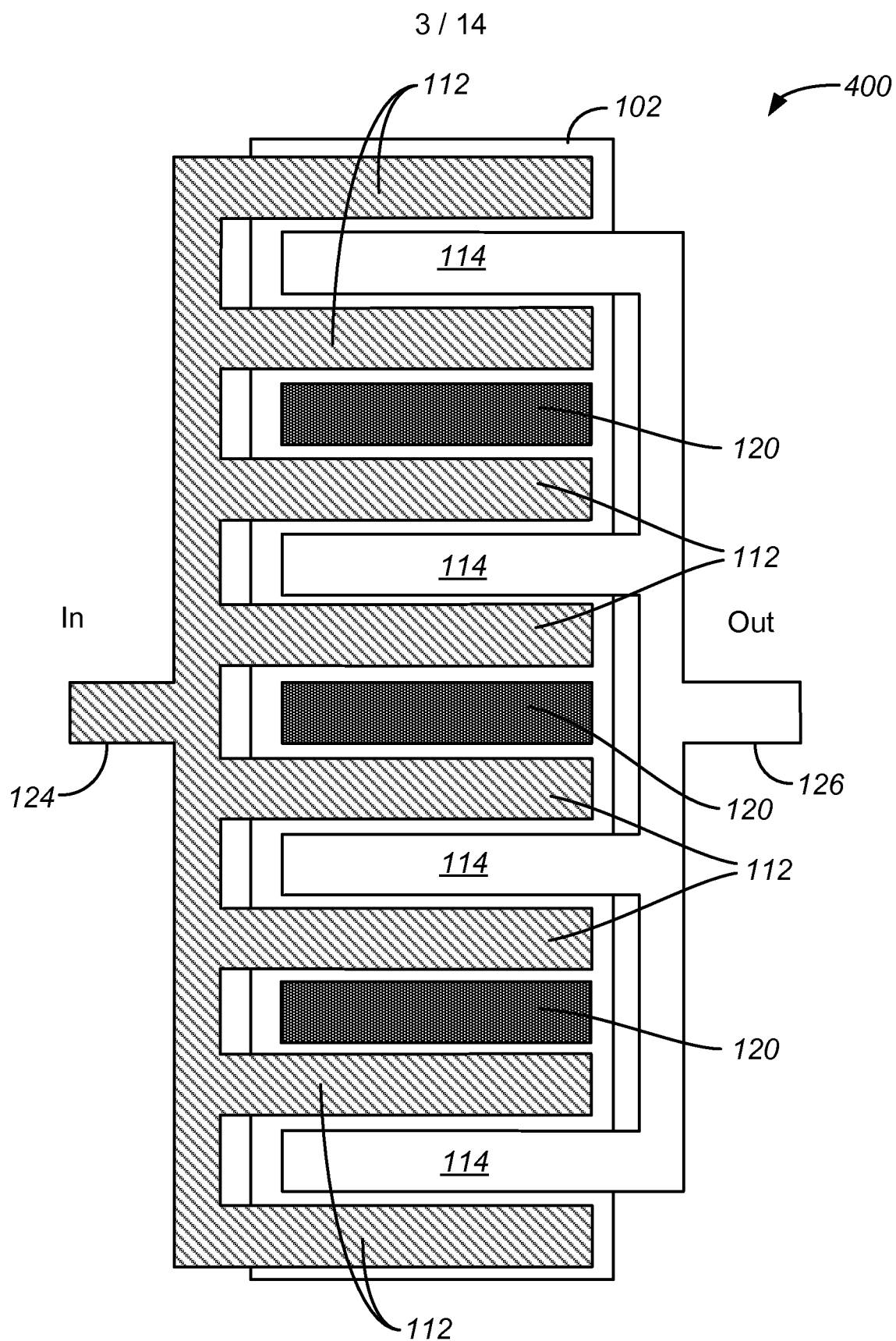
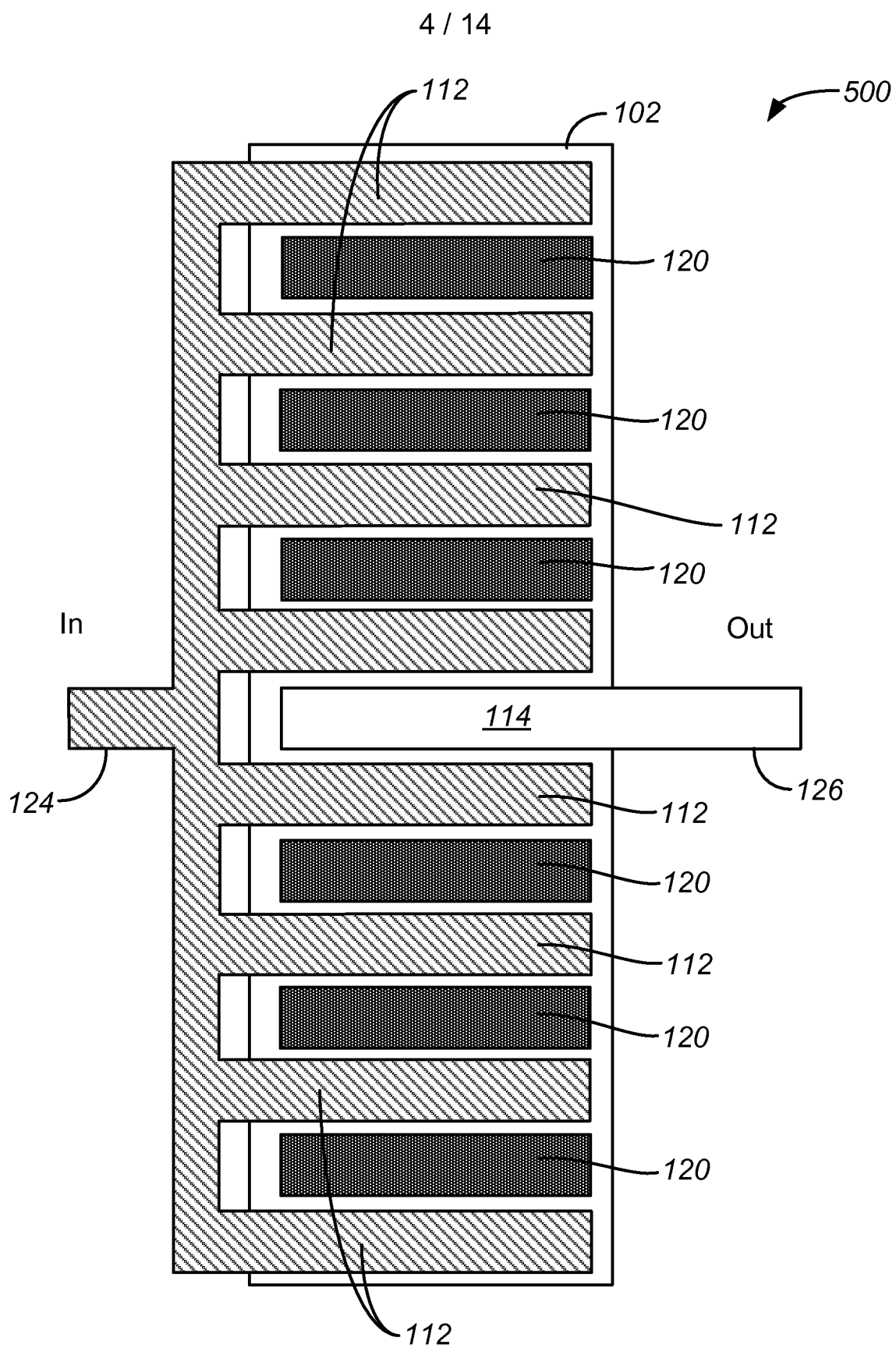


FIGURE 4

**FIGURE 5**

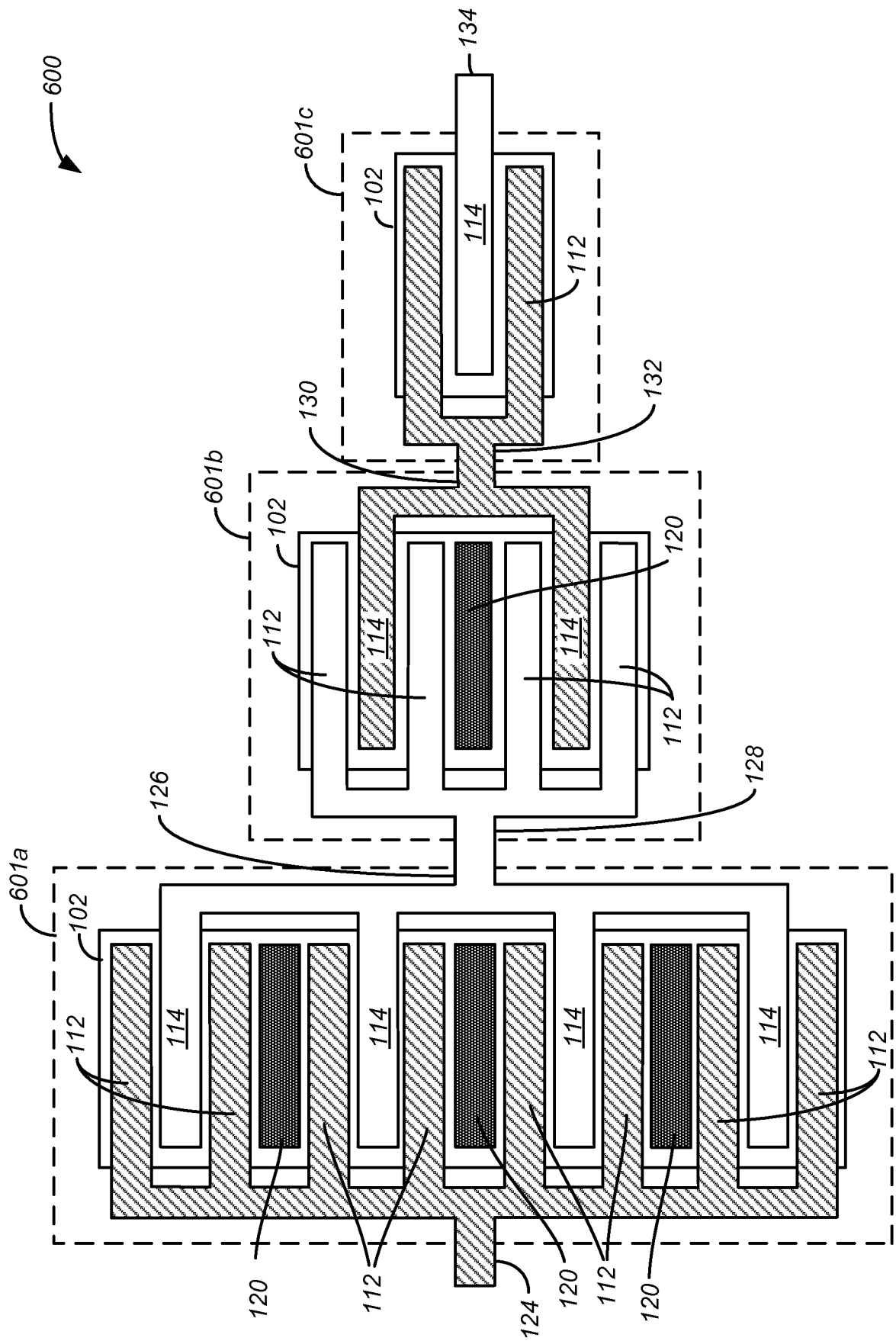


FIGURE 6

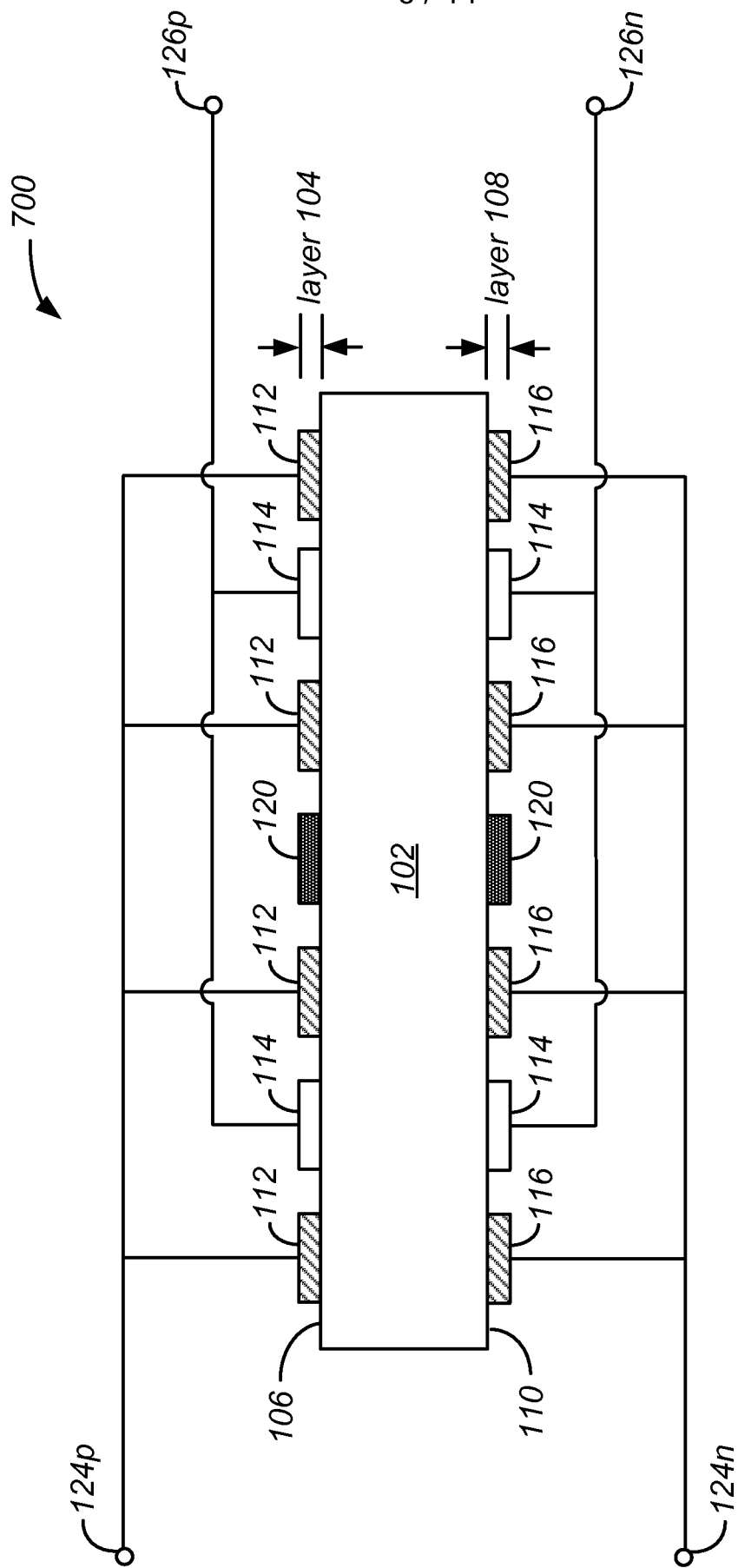


FIGURE 7

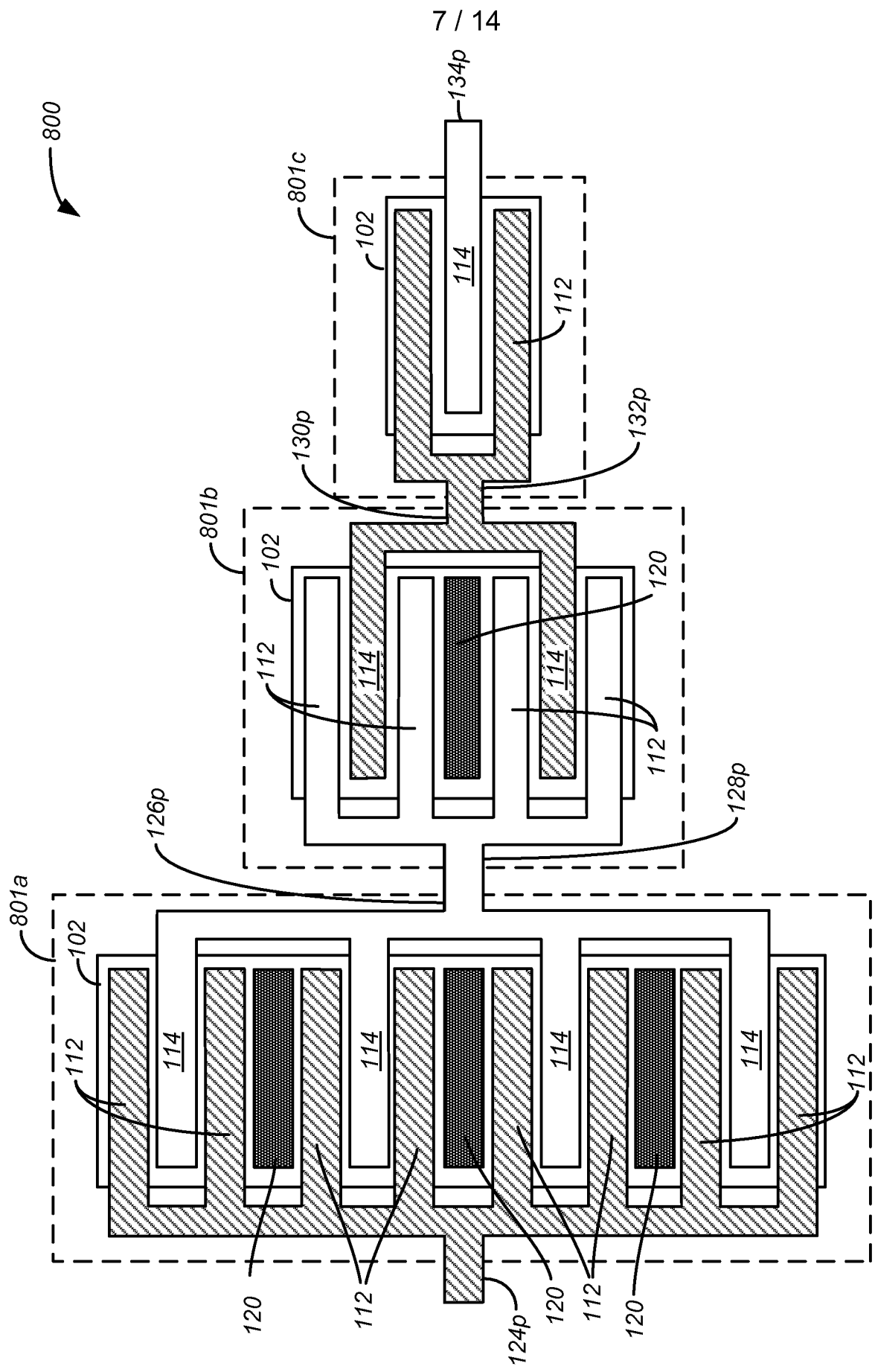


FIGURE 8A

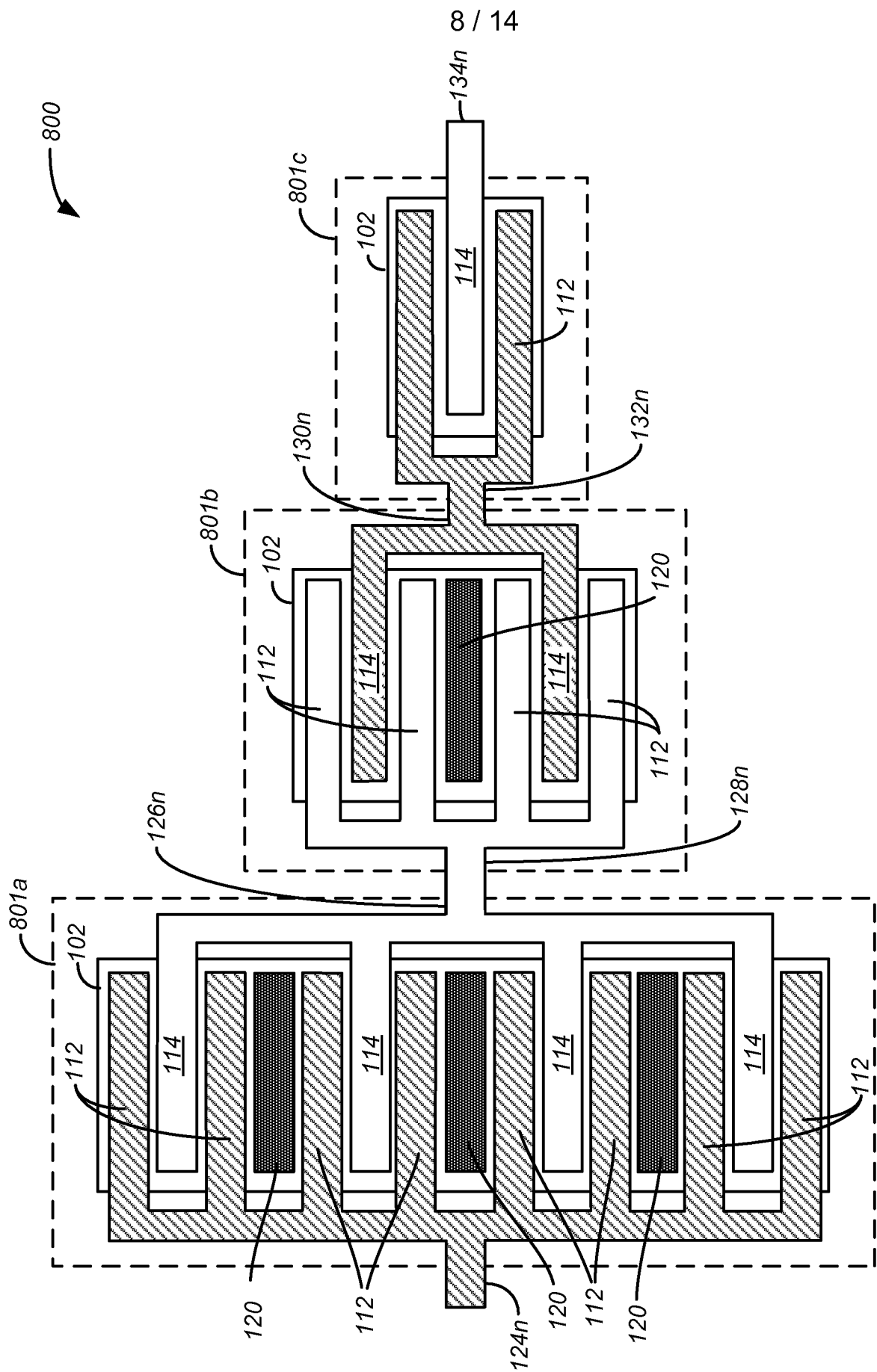


FIGURE 8B

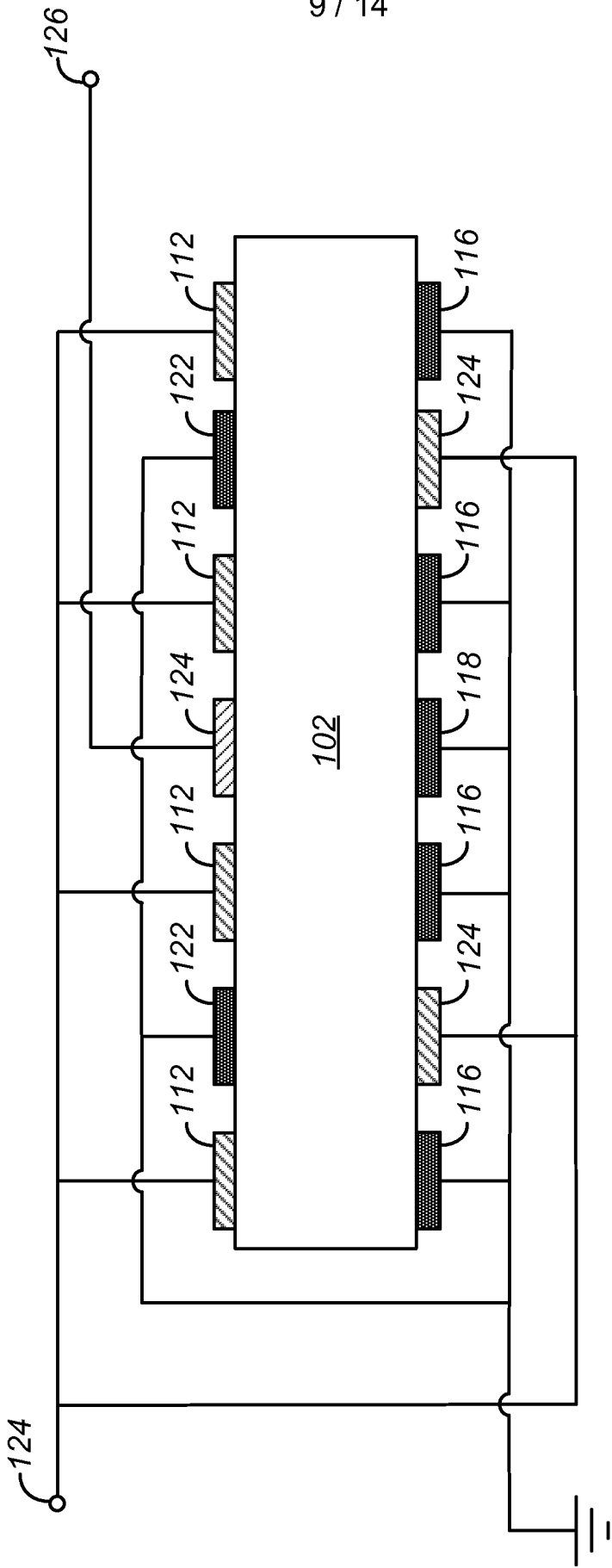
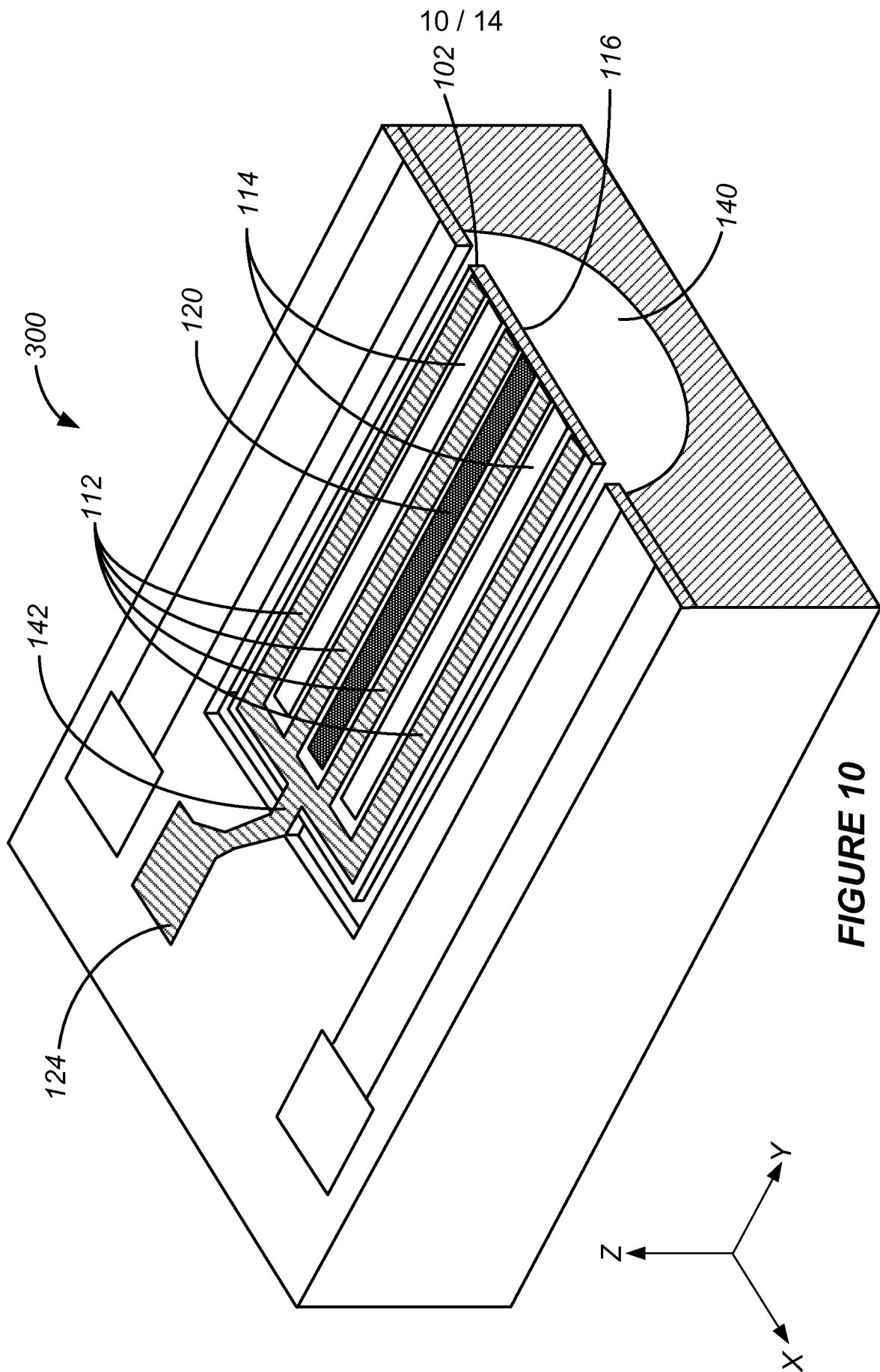
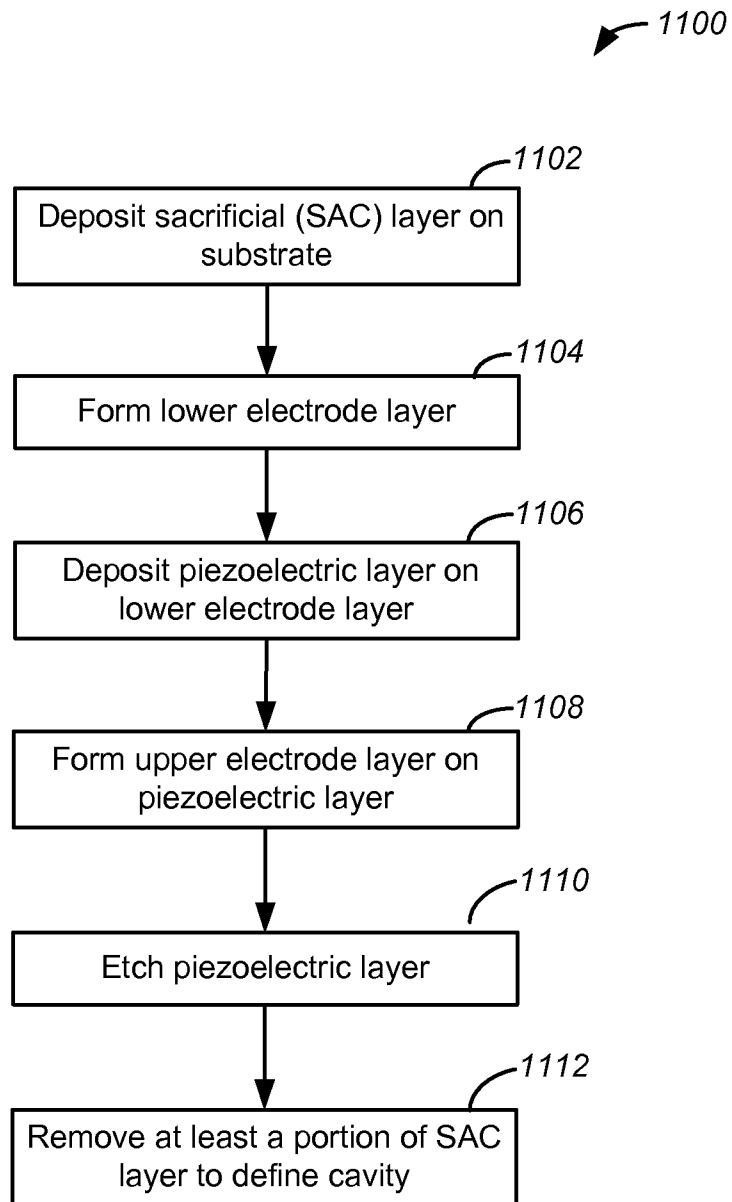


FIGURE 9



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**FIGURE 11**

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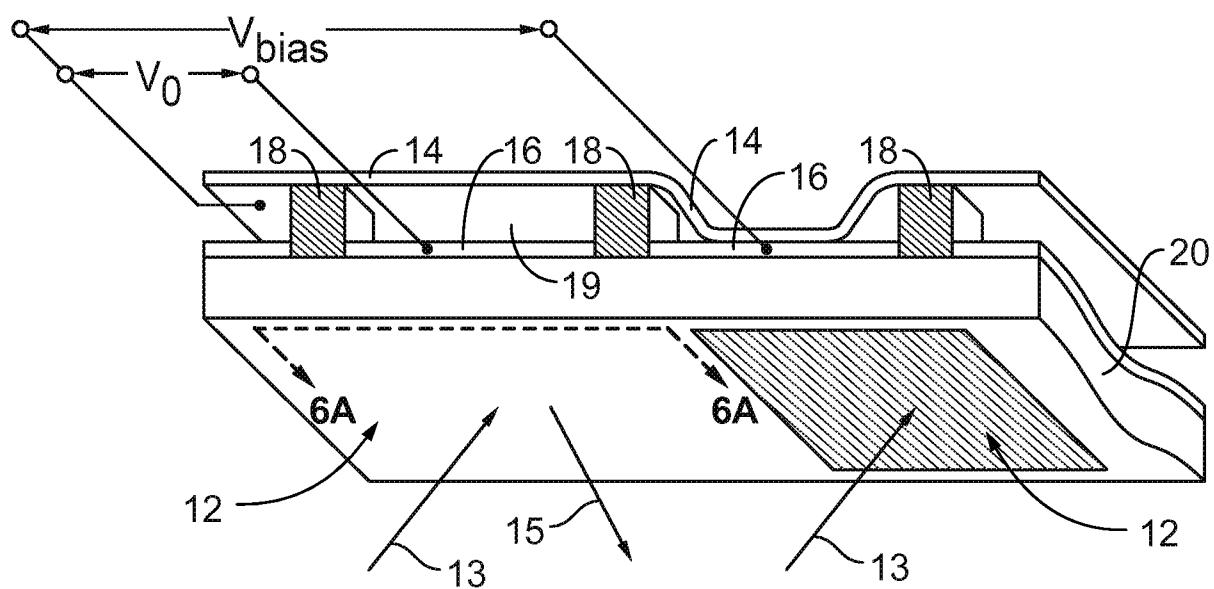
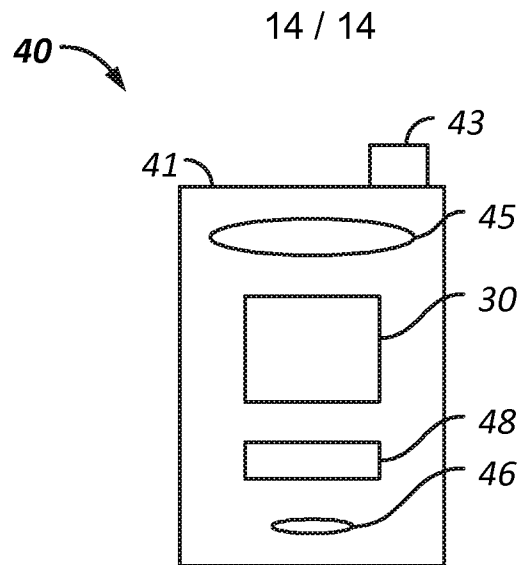
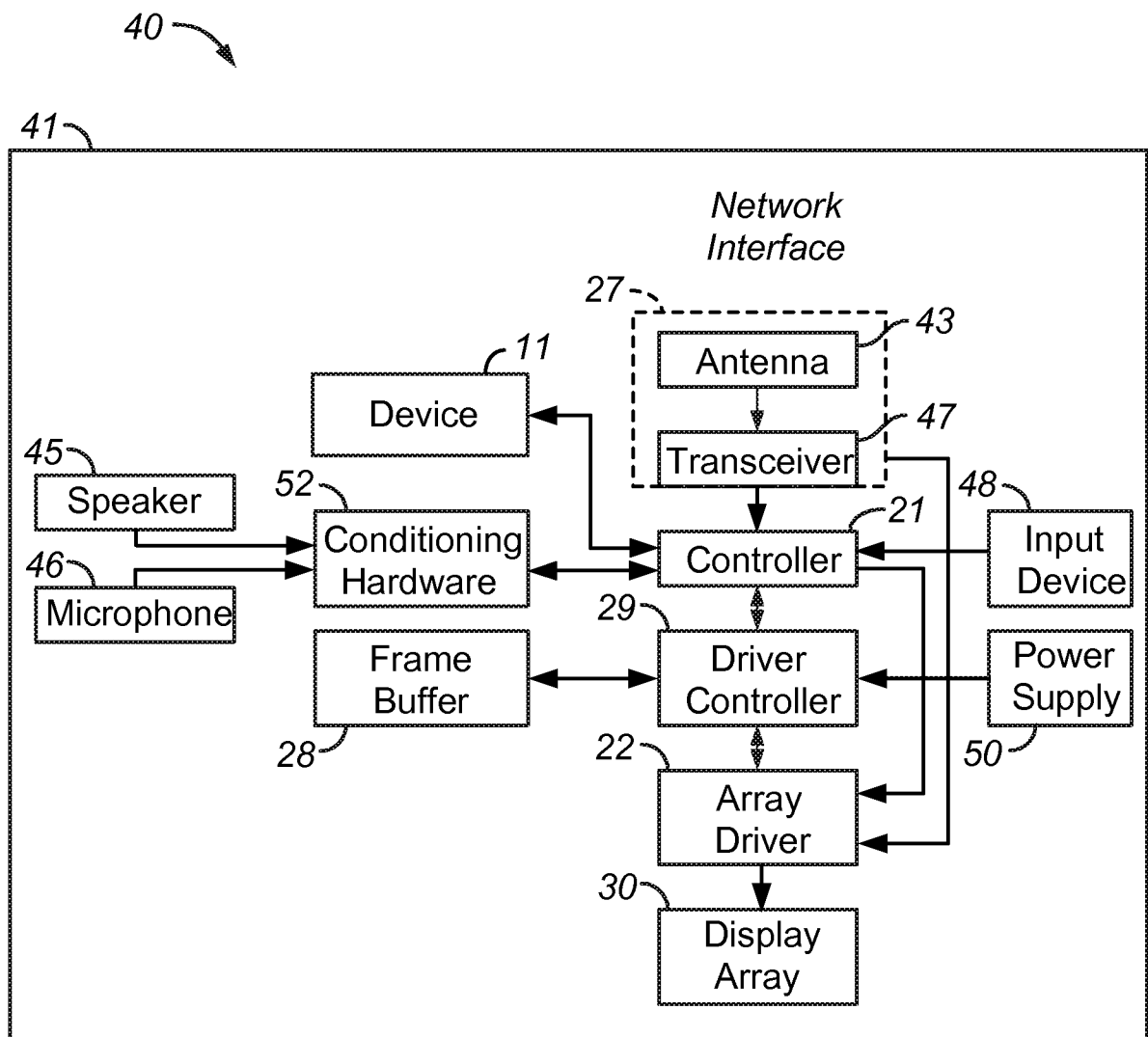


FIGURE 12A

**FIGURE 13A****FIGURE 13B**

INTERNATIONAL SEARCH REPORT

International application No

PCT/US2012/066558

A. CLASSIFICATION OF SUBJECT MATTER

INV. H01L41/047 H01L41/107 H01L41/29 H03H9/02
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)

H01L H03H

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 practicable, search terms used)

EPO-Internal , INSPEC

C. DOCUMENTS CONSIDERED TO BE RELEVANT

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Y	paragraph [0044] - paragraph [0090] ; figures 1-21	16
X	JP 2005 318547 A (SANYO ELECTRIC CO) 10 November 2005 (2005-11-10)	1-15 , 20-22
Y	abstract; figures 1-6,9-13	16
Y	EP 1 006 596 A2 (MURATA MANUFACTURING CO [JP]) 7 June 2000 (2000-06-07)	16
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	column 69, line 40 - line 54 column 78, line 1 - line 14	
	-/-	



Further documents are listed in the continuation of Box C.



See patent family annex.

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"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 February 2013

Date of mailing of the international search report

06/03/2013

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

Grbger, Andreas

INTERNATIONAL SEARCH REPORT

International application No

PCT/US2012/066558

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
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Information on patent family members

International application No

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