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(54) **HAPTIC ACTUATOR SYSTEM INCLUDING A MULTI-LAYER INDUCTOR AND A MAGNETIC ELEMENT**

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(63) Continuation of application No. 18/128,923, filed on Mar. 30, 2023, now Pat. No. 12,321,529, which is a continuation-in-part of application No. 17/946,931, filed on Sep. 16, 2022, now Pat. No. 12,093,458, which is a continuation of application No. 17/626,669, filed on Jan. 12, 2022, filed as application No. PCT/US21/53660 on Oct. 5, 2021, now Pat. No. 11,880,506, said application No. 18/128,923 is a continuation-in-part of application No. 17/855,747, filed on Jun. 30, 2022, now Pat. No. 11,703,950, which is a continuation of application No. 17/367,572, filed on Jul. 5, 2021, now Pat. No. 11,422,631, which is a continuation-in-part of application No. 17/092,002, filed on Nov. 6, 2020, now Pat. No. 11,360,563, which is a continuation of application No. 16/297,426, filed on Mar. 8, 2019, now Pat. No. 10,866,642, which is a continuation-in-part of application No. 15/845,751, filed on Dec. 18, 2017, now Pat. No. 10,564,839, which is a continuation-in-part of application No. 15/476,732, filed on Mar. 31, 2017, now Pat. No. 10,331,265.

(60) Provisional application No. 63/404,768, filed on Sep. 8, 2022, provisional application No. 63/325,387, filed on Mar. 30, 2022, provisional application No. 63/088,359, filed on Oct. 6, 2020, provisional application No. 63/048,071, filed on Jul. 3, 2020, provisional application No. 62/640,138, filed on Mar. 8, 2018, provisional application No. 62/316,417, filed on Mar. 31, 2016, provisional application No. 62/343,453, filed on May 31, 2016.

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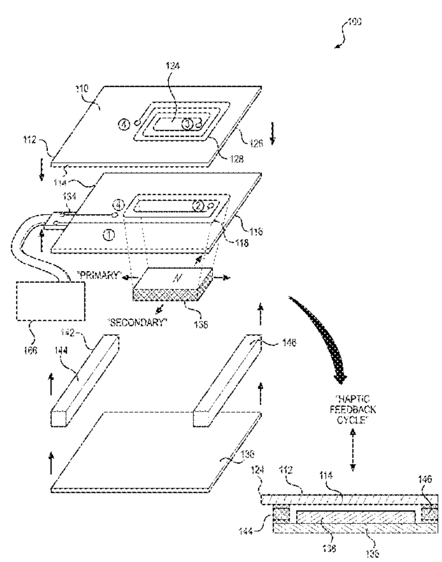
H01H 13/785	(2006.01)
H01H 13/85	(2006.01)

(52) **U.S. Cl.**

CPC ***G06F 3/0202*** (2013.01); ***G06F 3/016*** (2013.01); ***H01H 13/85*** (2013.01); *H01H 2003/008* (2013.01); *H01H 13/785* (2013.01); *H01H 2201/036* (2013.01); *H01H 2215/05* (2013.01)

(57) **ABSTRACT**

One variation of a system for a haptic actuator includes: a substrate; a baseplate; a magnetic element; and a set of spacer elements. The substrate includes: a first layer including a first spiral trace coiled in a first direction; and a second layer. The second layer is arranged below the first layer and includes a second spiral trace: coiled in a second direction opposite the first direction; and coupled to the first spiral trace to form an inductor. The substrate further includes terminals arranged about a periphery of the substrate and coupled to the inductor. The baseplate is arranged opposite the substrate. The magnetic element is: arranged on the baseplate; and defines a first polarity facing the inductor. The first set of spacer elements are: interposed between the baseplate and the substrate; arranged proximal edges of the baseplate; and defines a nominal gap between the magnetic element and the inductor.



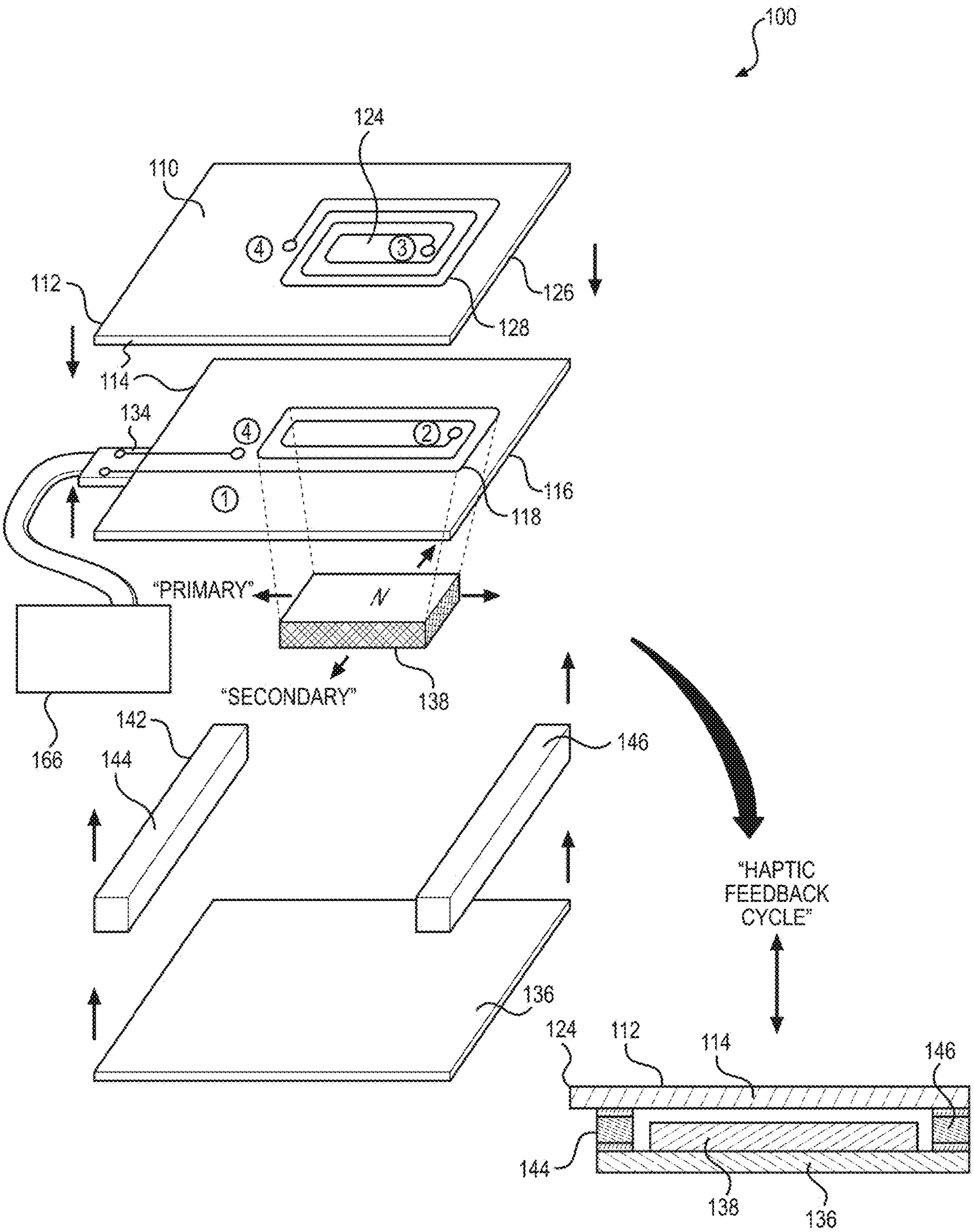
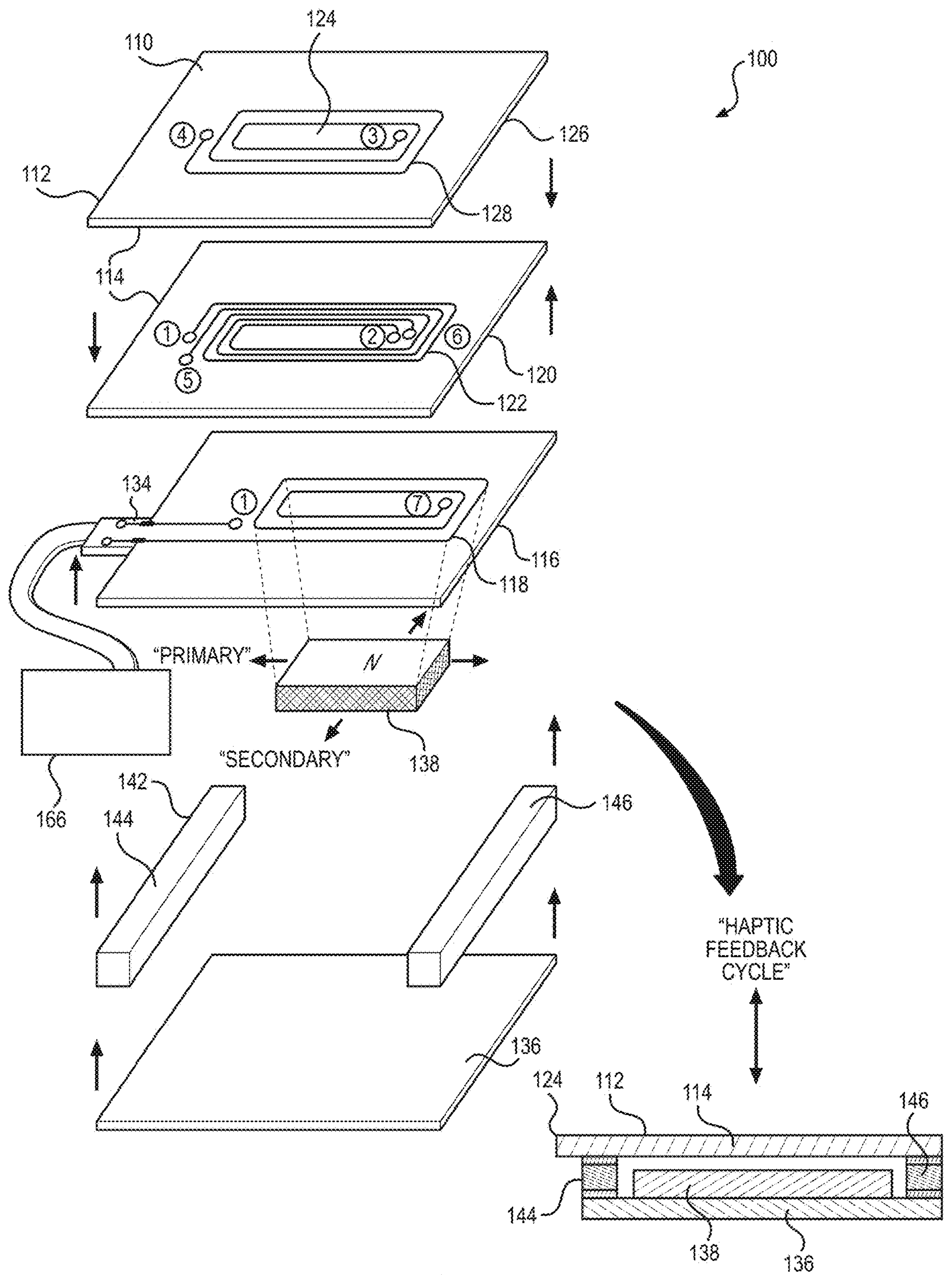

100
124
110
4
3
112
126
128
114
134
4
2
116
1
118
"PRIMARY"
N
"SECONDARY"
138
166
142
144
146
"HAPTIC FEEDBACK CYCLE"
136
124
112
114
146
144
138
136

FIGURE 1



100
110
124
126
112
128
114
120
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116
118
"PRIMARY"
N
"SECONDARY"
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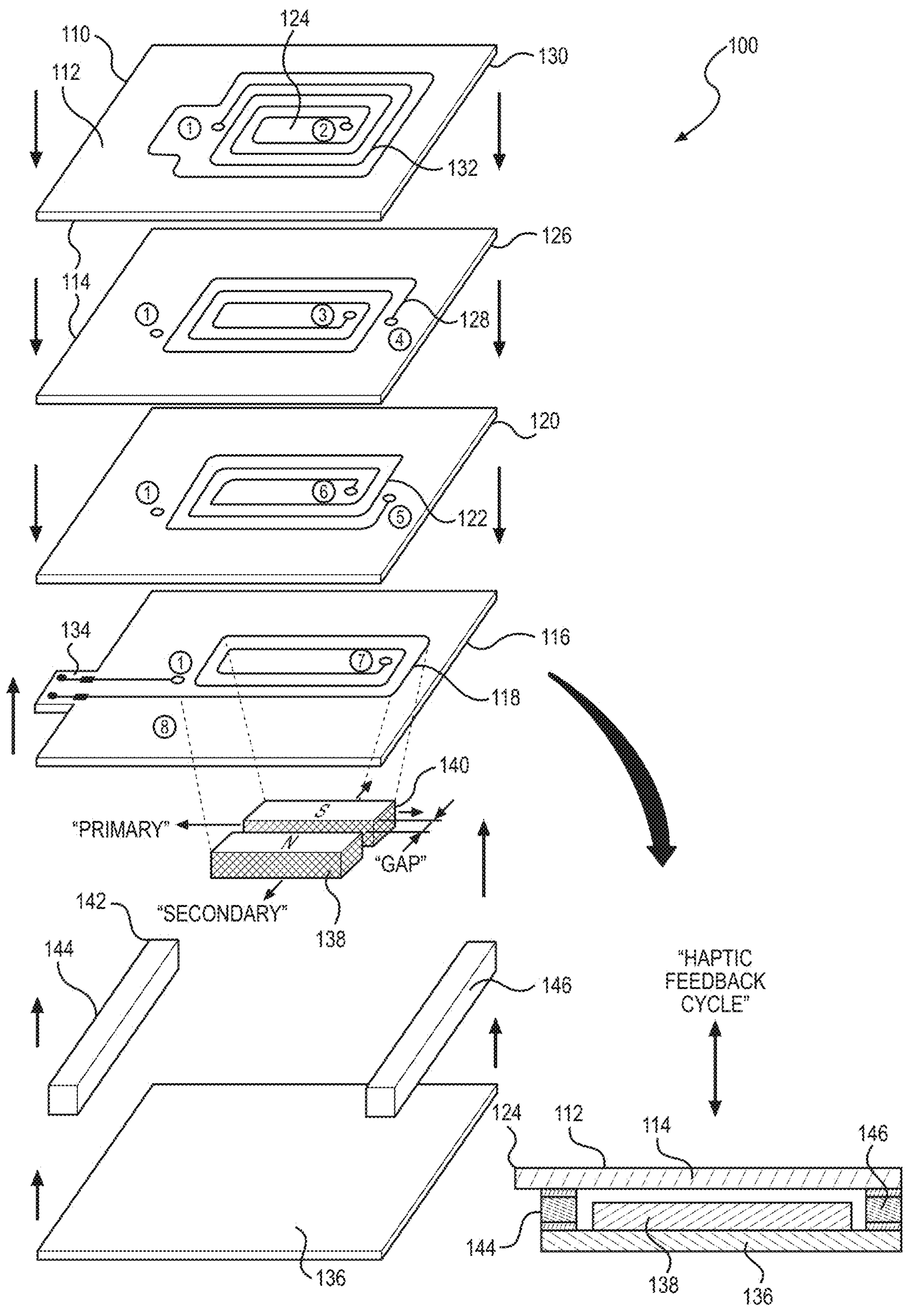
166
142
144
146
"HAPTIC FEEDBACK CYCLE"
136
124
112
114
146
144
138
136

FIGURE 2



110
112
124
130
100
1
2
132
114
126
1
3
128
4
120
1
6
122
5
134
116
1
7
118
8
140
S
"PRIMARY"
N
"GAP"
"SECONDARY"
142
138
144
146
"HAPTIC
FEEDBACK
CYCLE"
124
112
114
146
144
138
136
136

FIGURE 3

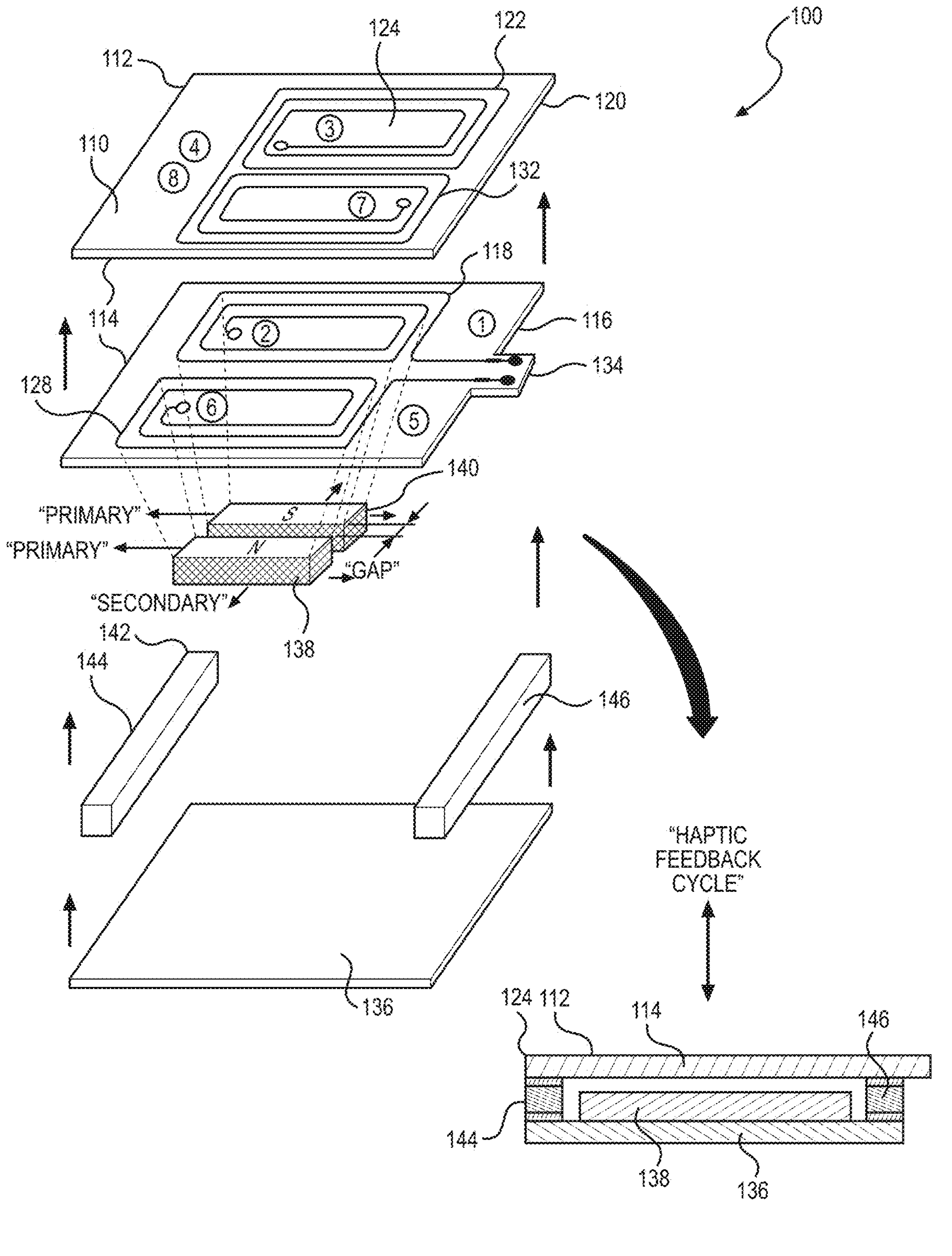

100
112
124
122
120
110
4
8
3
7
132
118
114
1
116
2
134
128
6
5
140
"PRIMARY"
S
"PRIMARY"
N
"GAP"
"SECONDARY"
138
142
144
146
"HAPTIC FEEDBACK CYCLE"
136
124 112
114
146
144
138
136

FIGURE 4

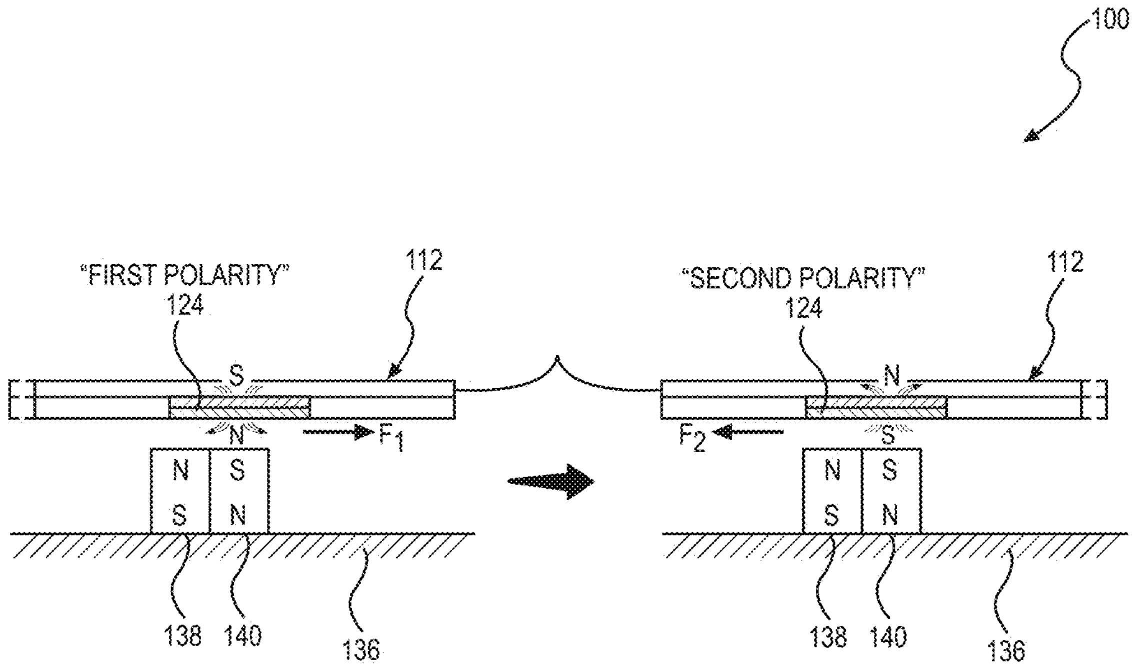


FIGURE 5A

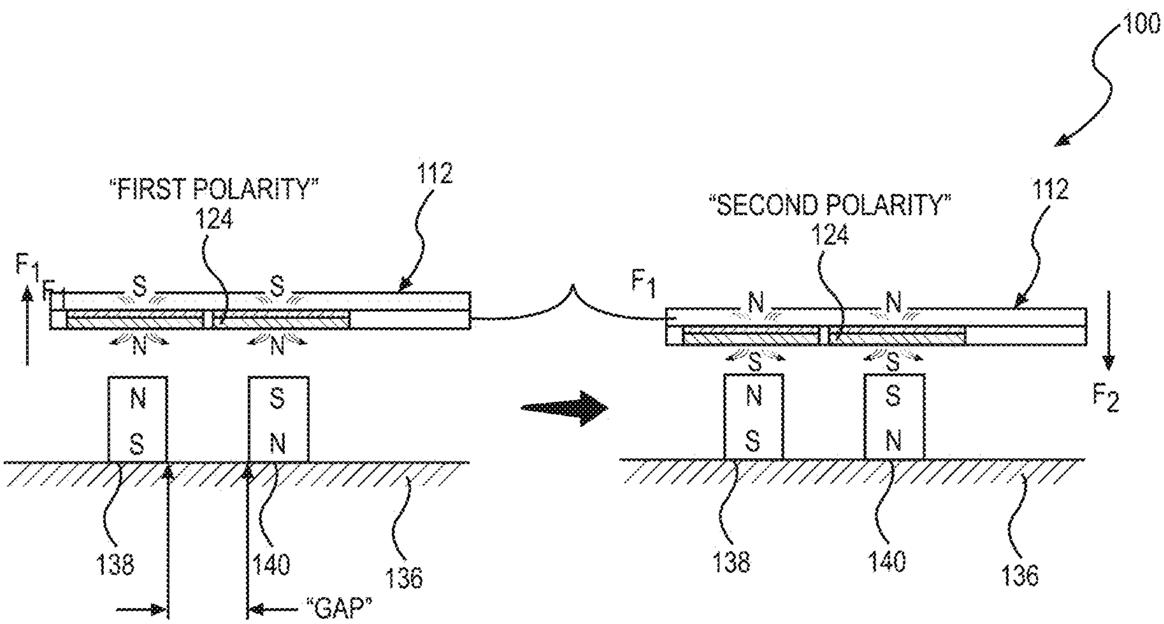


FIGURE 5B

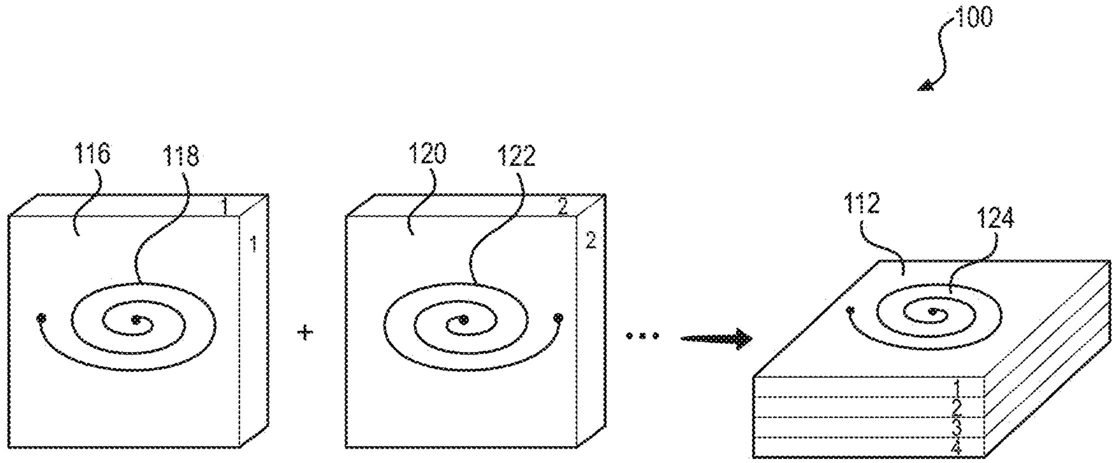


FIGURE 6A

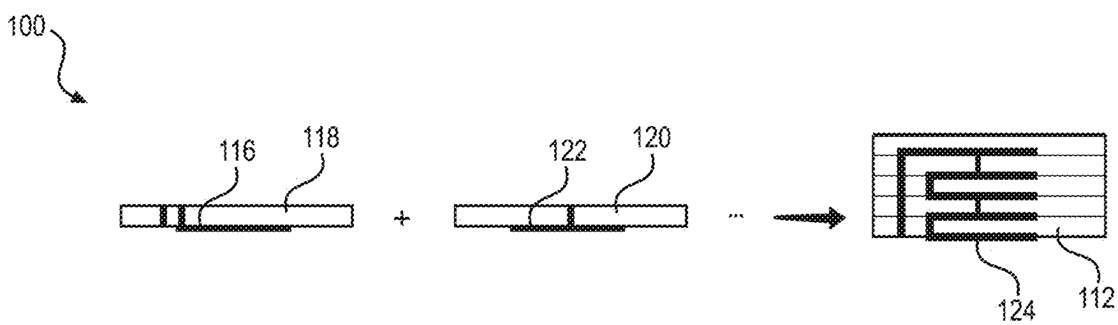


FIGURE 6B

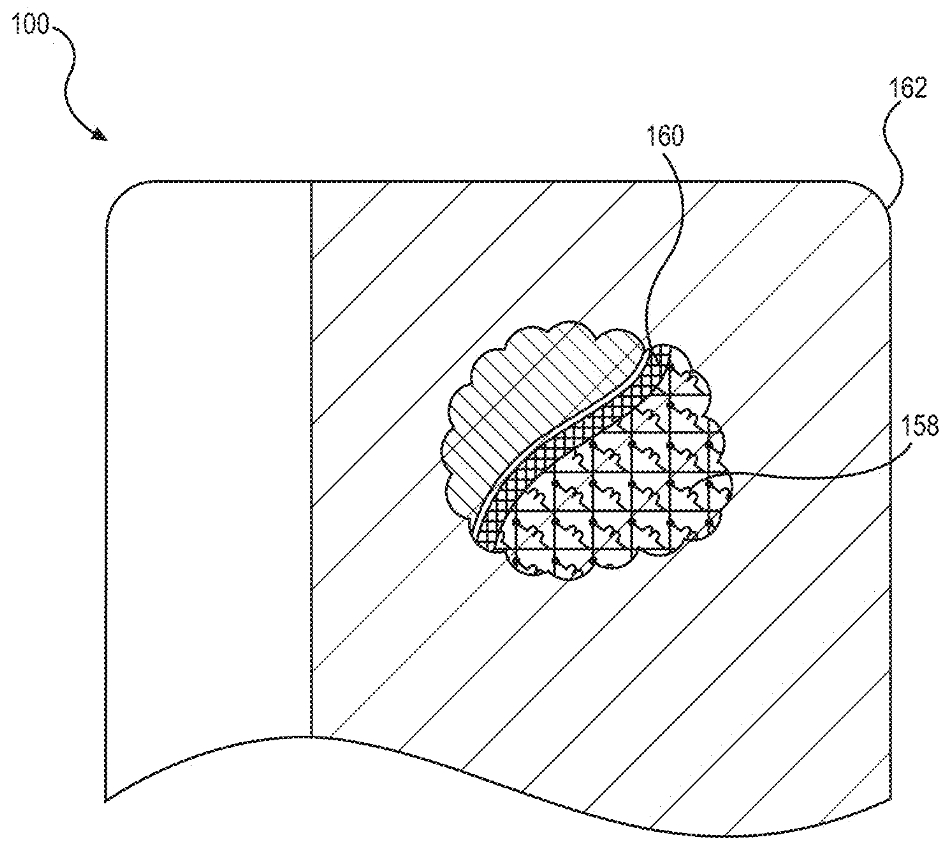


FIGURE 7

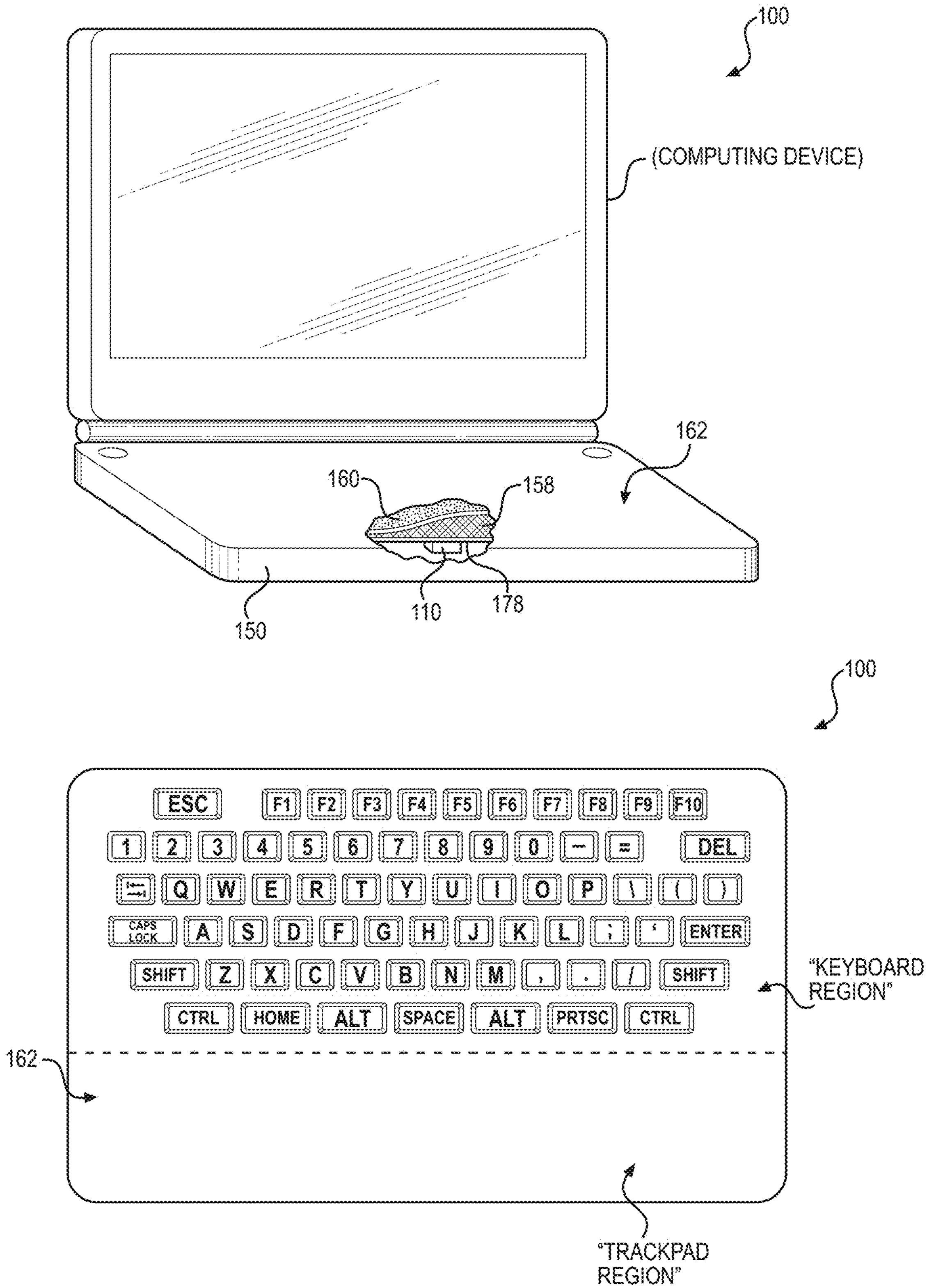

100
(COMPUTING DEVICE)
162
160
158
110
178
150
100
ESC
F1
F2
F3
F4
F5
F6
F7
F8
F9
F10
DEL
CAPS LOCK
ENTER
SHIFT
SHIFT
CTRL
HOME
ALT
SPACE
ALT
PRTSC
CTRL
"KEYBOARD REGION"
162
"TRACKPAD REGION"

FIGURE 8

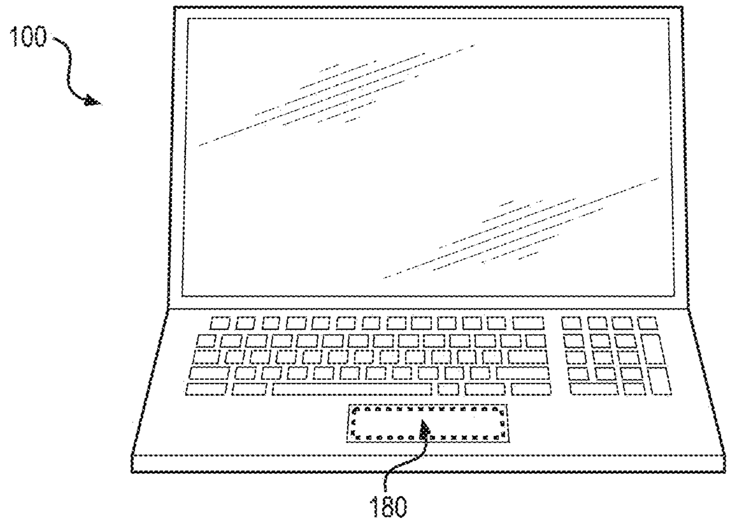


FIGURE 9A

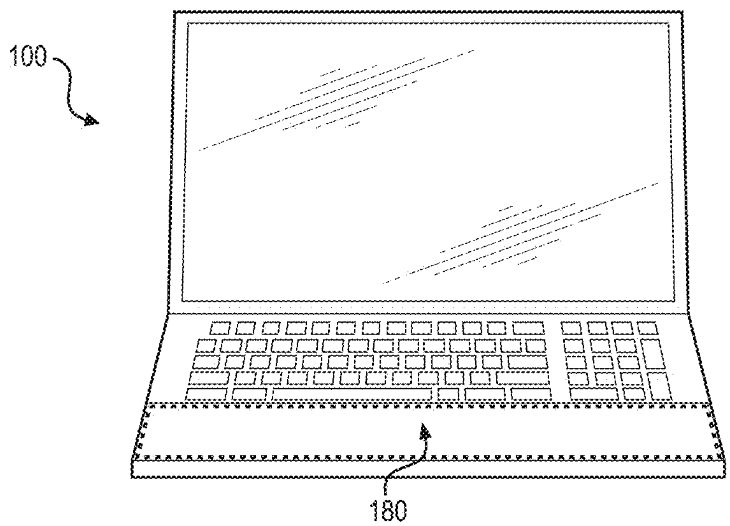


FIGURE 9B

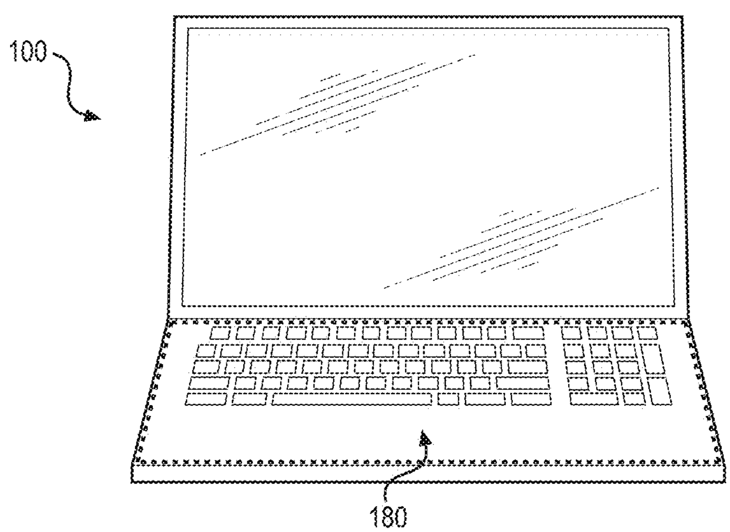


FIGURE 9C

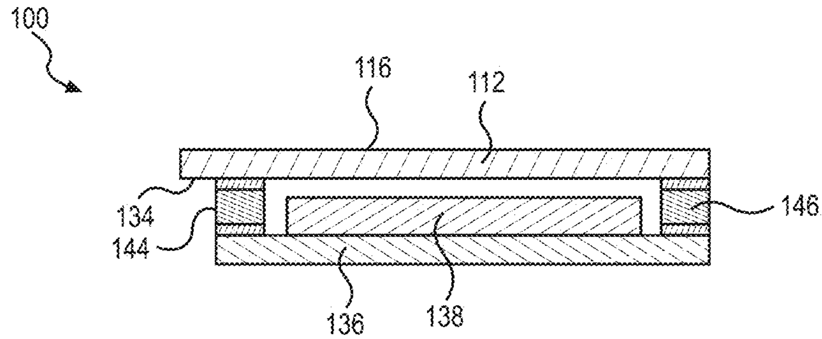


FIGURE 10A

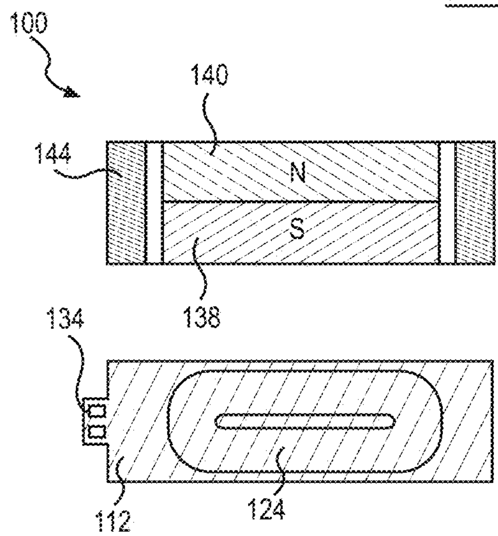


FIGURE 10B

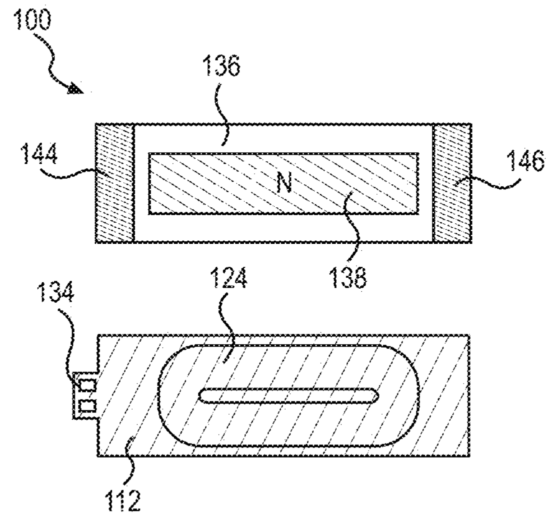


FIGURE 10C

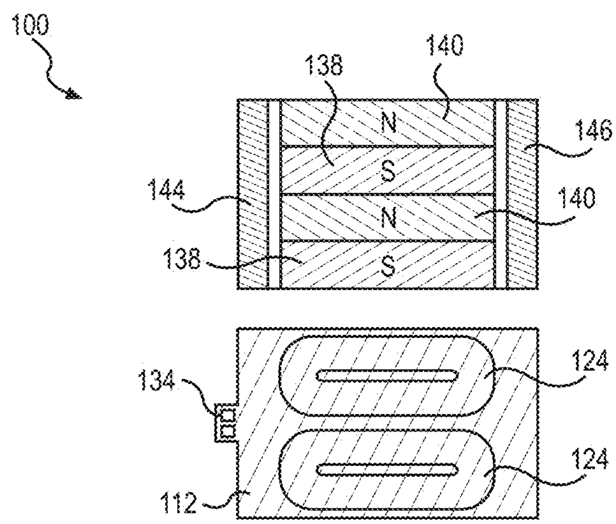


FIGURE 10D

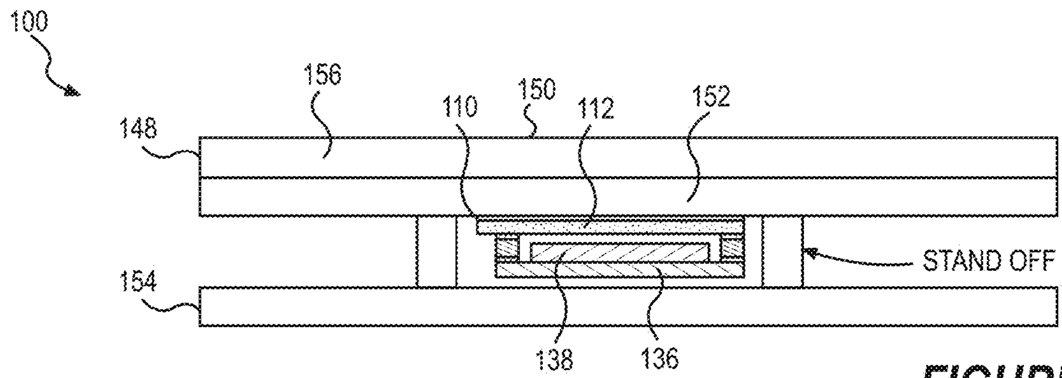


FIGURE 11A

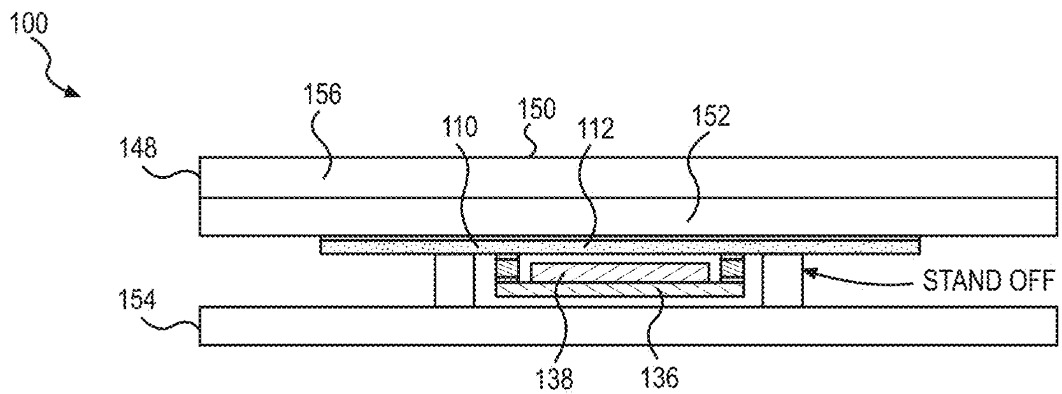


FIGURE 11B

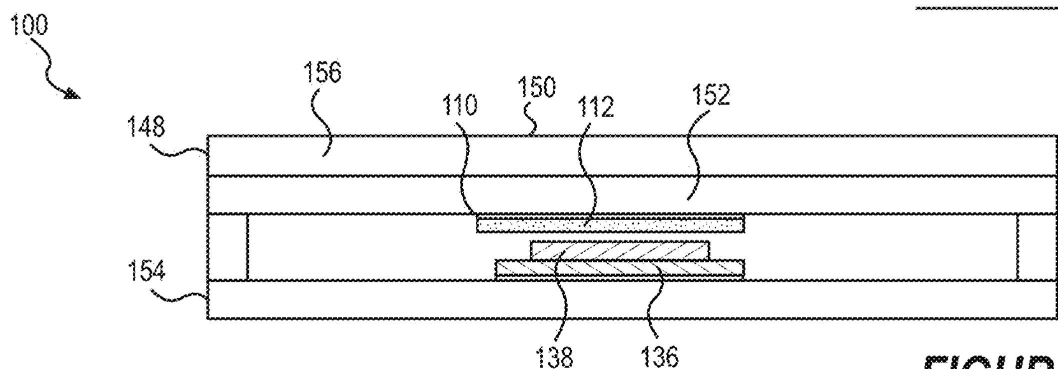


FIGURE 11C

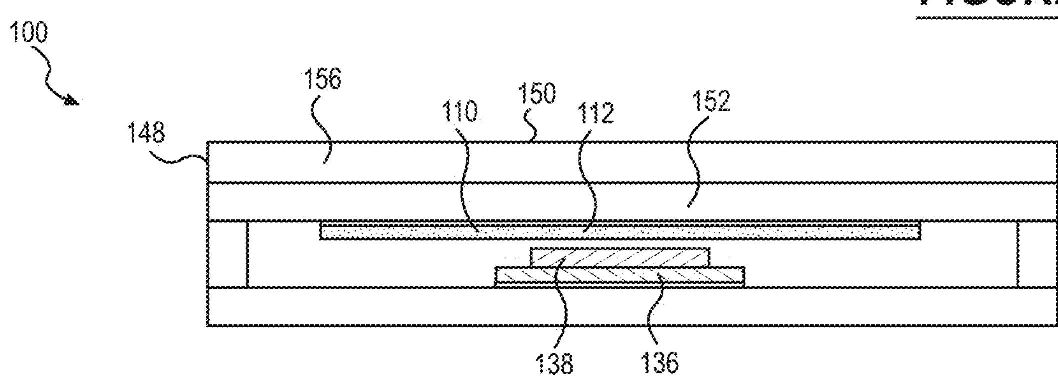


FIGURE 11D

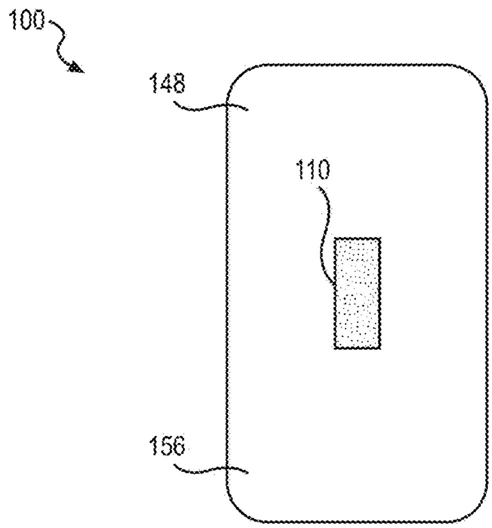


FIGURE 12A

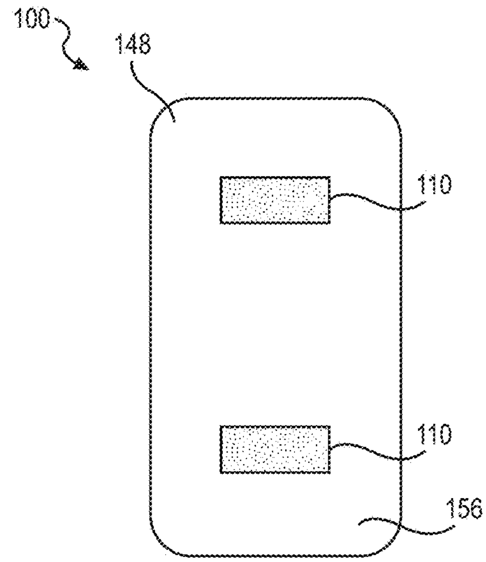


FIGURE 12B

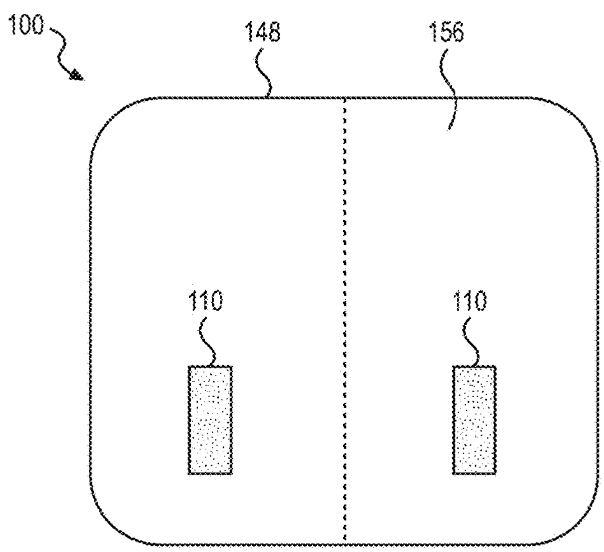


FIGURE 12C

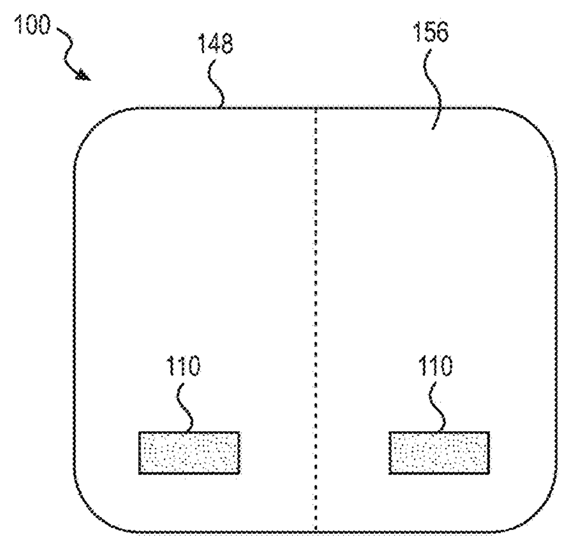


FIGURE 12D

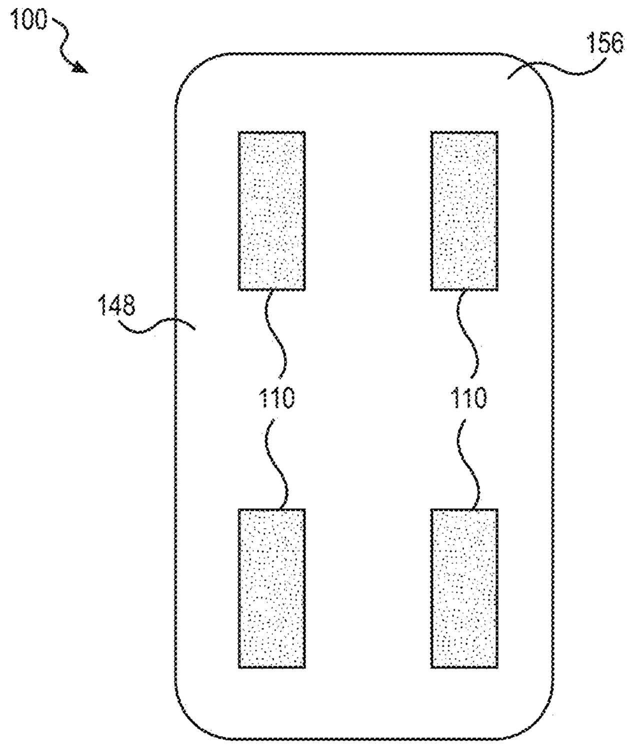


FIGURE 12E

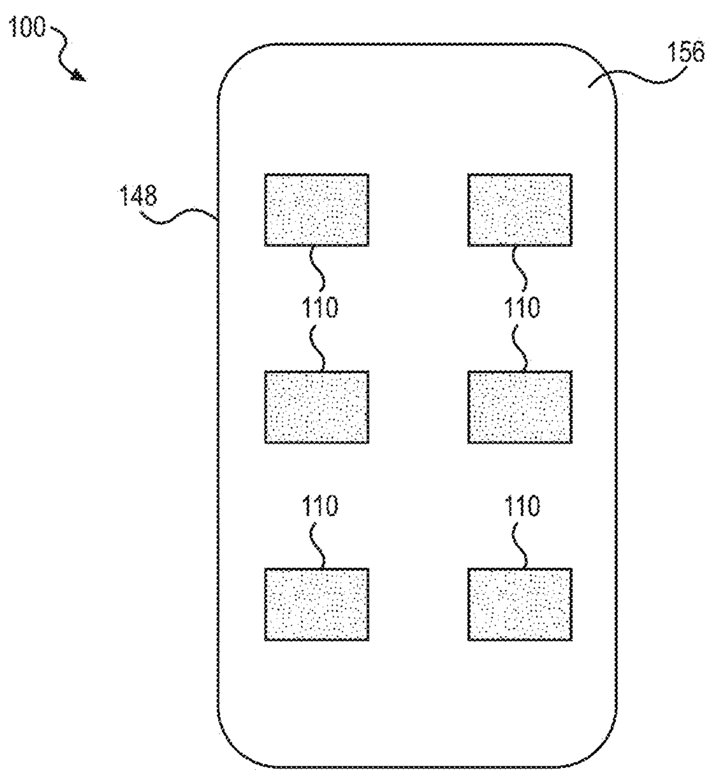


FIGURE 12F

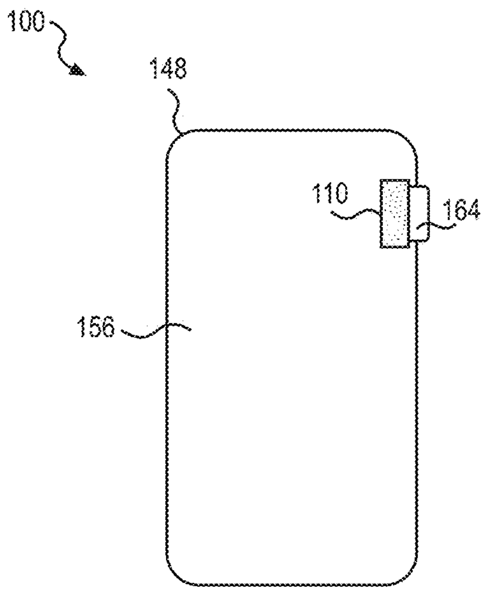


FIGURE 13A

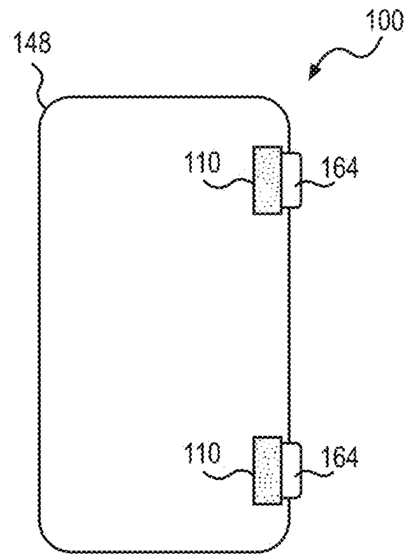


FIGURE 13B

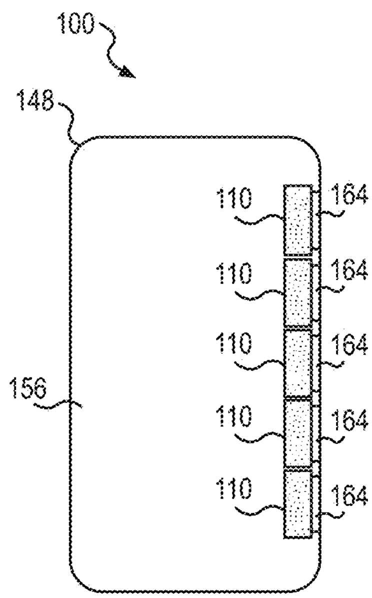


FIGURE 13C

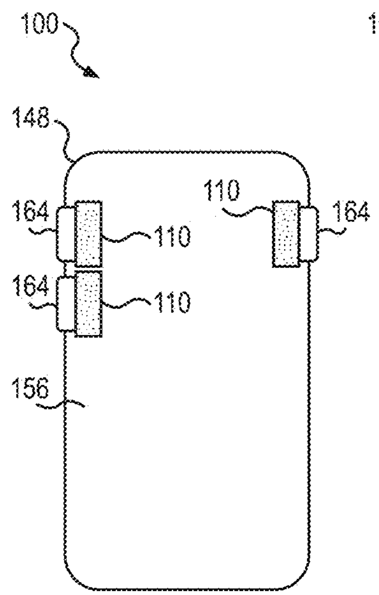


FIGURE 13D

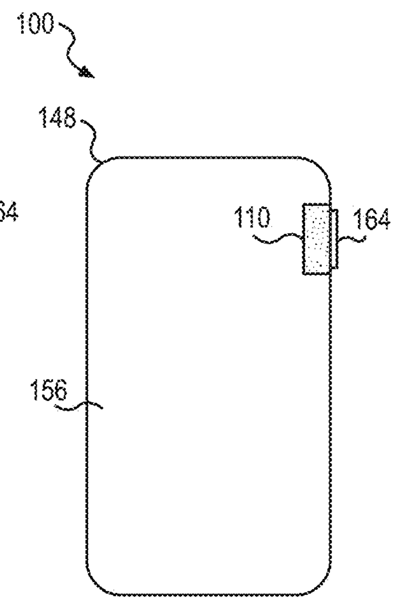
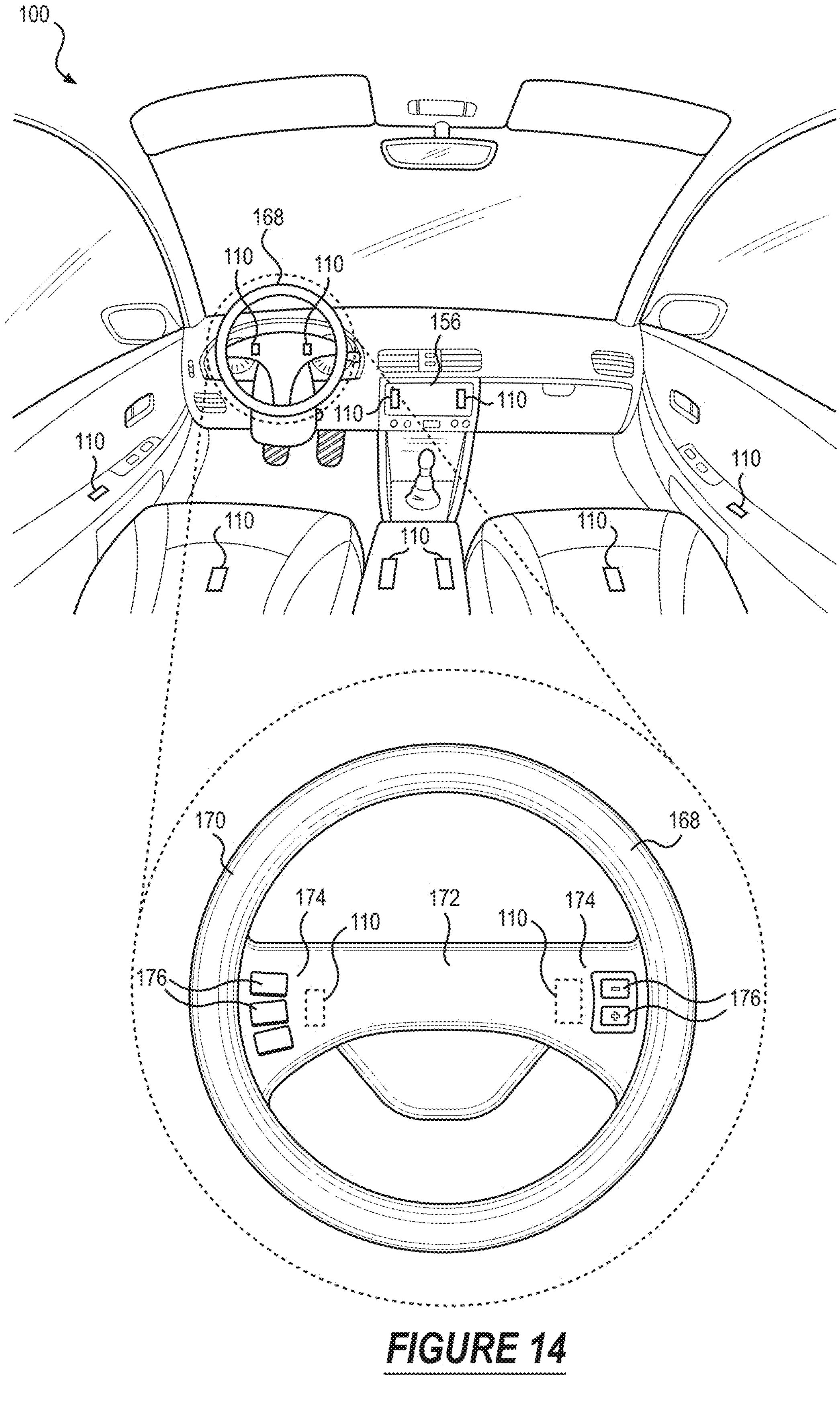


FIGURE 13E


100
168
110
110
156
110
110
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110
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170
168
174
172
174
110
110
176
176

FIGURE 14

HAPTIC ACTUATOR SYSTEM INCLUDING A MULTI-LAYER INDUCTOR AND A MAGNETIC ELEMENT

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application is a continuation of U.S. Non-Provisional application Ser. No. 18/128,923, filed on 30 Mar. 2023, which claims the benefit of U.S. Provisional Application No. 63/404,768, filed on 8 Sep. 2022, and 63/325,387, filed on 30 Mar. 2022, each of which is incorporated in its entirety by this reference.

[0002] U.S. Non-Provisional application Ser. No. 18/128,923 is also a continuation-in-part application of U.S. patent application Ser. No. 17/946,931, filed on 16 Sep. 2022, which is a continuation of U.S. patent application Ser. No. 17/626,669, filed on 12 Jan. 2022, which claims the benefit under 35 U.S.C. 371 to International Application No. PCT/US21/53660, filed on 5 Oct. 2021, which claims priority to U.S. Provisional Patent Application 63/088,359, filed on 6 Oct. 2020, each of which is incorporated in its entirety by this reference.

[0003] U.S. Non-Provisional application Ser. No. 18/128,923 is also a continuation-in-part application of U.S. patent application Ser. No. 17/855,747, filed on 30 Jun. 2022, which is a continuation of U.S. patent application Ser. No. 17/367,572, filed on 5 Jul. 2021, which claims priority to U.S. Provisional Application No. 63/048,071, filed on 3 Jul. 2020, which is incorporated in its entirety by this reference.

[0004] U.S. patent application Ser. No. 17/367,572 is also a continuation-in-part application of U.S. patent application Ser. No. 17/092,002, filed on 6 Nov. 2020, which is a continuation application of U.S. patent application Ser. No. 16/297,426, filed on 8 Mar. 2019, which claims the benefit of U.S. Provisional Application No. 62/640,138, filed on 8 Mar. 2018, each of which is incorporated in its entirety by this reference.

[0005] U.S. patent application Ser. No. 16/297,426 is also a continuation-in-part application of U.S. patent application Ser. No. 15/845,751, filed on 18 Dec. 2017, which is a continuation-in-part application of U.S. patent application Ser. No. 15/476,732, filed on 31 Mar. 2017, which claims the benefit of U.S. Provisional Application No. 62/316,417, filed on 31 Mar. 2016, and U.S. Provisional Application No. 62/343,453, filed on 31 May 2016, each of which is incorporated in its entirety by this reference.

[0006] This application is related to U.S. patent application Ser. No. 17/191,631, filed on 3 Mar. 2021, which is incorporated in its entirety by this reference.

TECHNICAL FIELD

[0007] This invention relates generally to the field of haptic actuators and more specifically to a new and useful slim haptic actuator system in the field of haptic actuators.

BRIEF DESCRIPTION OF THE FIGURES

[0008] FIG. **1** is a schematic representation of the system;

[0009] FIG. **2** is a schematic representation of a system;

[0010] FIG. **3** is a schematic representation of the system;

[0011] FIG. **4** is a schematic representation of the system;

[0012] FIGS. **5**A and **5**B are a schematic representation of the system;

[0013] FIGS. **6**A and **6**B are a schematic representation of the system;

[0014] FIG. **7** is a schematic representation of the system;

[0015] FIG. **8** is a schematic representation of the system;

[0016] FIGS. **9**A, **9**B, and **9**C are a schematic representation of the system;

[0017] FIGS. **10**A, **10**B, **10**C, and **10**D are a schematic representation of the system;

[0018] FIGS. **11**A, **11**B, **11**C, and **11**D are a schematic representation of the system;

[0019] FIGS. **12**A, **12**B, **12**C, **12**D, **12**E, and **12**F are a schematic representation of the system;

[0020] FIGS. **13**A, **13**B, **13**C, **13**D, and **13**E are a schematic representation of the system; and

[0021] FIG. **14** is a schematic representation of the system.

DESCRIPTION OF THE EMBODIMENTS

[0022] The following description of embodiments of the invention is not intended to limit the invention to these embodiments but rather to enable a person skilled in the art to make and use this invention. Variations, configurations, implementations, example implementations, and examples described herein are optional and are not exclusive to the variations, configurations, implementations, example implementations, and examples they describe. The invention described herein can include any and all permutations of these variations, configurations, implementations, example implementations, and examples.

1. System

[0023] As shown in FIG. **1**, a system **100** for delivering haptic feedback includes: a first haptic actuator **110**, a cover layer **162**, and a controller **166**.

[0024] The first haptic actuator **110** includes: a substrate **112**, a baseplate **136**, a first magnetic element **138**; and a first set of spacer elements **142**. The substrate **112** includes: a set of inductor layers **114** defining a first multi-layer inductor **124**; and a first set of terminals **134** arranged about a periphery of the substrate **112** and coupled to the first multi-layer inductor **124**. The baseplate **136** is arranged opposite the substrate **112**. The first magnetic element **138**: is arranged on the baseplate **136**; and defines a first polarity facing the first multi-layer inductor **124**. The first set of spacer elements **142**: are interposed between the baseplate **136** and the substrate **112**; are arranged proximal perimeter edges of the baseplate **136**; and defines a nominal gap between the first magnetic element **138** and the first multi-layer inductor **124**.

[0025] The cover layer **162** is arranged over the first haptic actuator **110** and defines a touch sensor surface.

[0026] The controller **166** is coupled to the first set of terminals **134** and is configured to, in response to detecting a first input on the touch sensor surface, drive an oscillating voltage across the first multi-layer inductor **124** to: induce alternating magnetic coupling between the first multi-layer inductor **124** and the first magnetic element **138**; and oscillate the substrate **112** and the cover layer **162** relative to the first magnetic element **138**.

[0027] As shown in FIGS. **1**, **2** and **4**, one variation of the system **100** for a haptic actuator **110** includes: a substrate **112**; a baseplate **136**; a first magnetic element **138**; and a first set of spacer elements **142**.

[0028] The substrate **112** includes: a first layer **116** including a first spiral trace **118** coiled in a first direction; and a second layer **120**. The second layer **120**: is arranged below the first layer **116**; and includes a second spiral trace **122**. The second spiral trace **122**: is coiled in a second direction opposite the first direction; is coupled to the first spiral trace **118**; and cooperates with the first spiral trace **118** to form a multi-layer inductor **124**. The substrate **112** further includes a first set of terminals **134** arranged about a periphery of the substrate **112** and coupled to the first multi-layer inductor **124**.

[0029] The baseplate **136** is arranged opposite the substrate **112**. The first magnetic element **138**: is arranged on the baseplate **136**; defines a first polarity facing the first multi-layer inductor **124**; and is configured to magnetically couple the multi-layer inductor **124** to oscillate the substrate **112** relative to the first magnetic element **138**. The set of spacer elements **142**: are interposed between the baseplate **136** and the substrate **112**; are arranged proximal perimeter edges of the baseplate **136**; and define a nominal gap between the first magnetic element **138** and the first multi-layer inductor **124**.

[0030] As shown in FIG. **3**, one variation of a system **100** for a haptic actuator **110** includes: a substrate **112**; a baseplate **136**; and a set of magnetic elements.

[0031] The substrate **112** includes: a first layer **116** including a first spiral trace **118** coiled in a first direction; and a second layer **120**. The second layer **120**: is arranged below the first layer **116**; and includes a second spiral trace **122**. The second spiral trace **122**: is coiled in a second direction opposite the first direction; is coupled to the first spiral trace **118**; and cooperates with the first spiral trace **118** to form a multi-layer inductor **124**. The substrate **112** further includes a first set of terminals **134** arranged about a periphery of the substrate **112** and coupled to the first multi-layer inductor **124**.

[0032] The baseplate **136** is arranged opposite the substrate **112**. The first set of magnetic elements: are arranged on the baseplate **136**; include a first magnetic element **138** and a second magnetic element **140**; and are configured to magnetically couple the first multi-layer inductor **124** to oscillate the substrate **112** parallel to the set of magnetic elements. The first magnetic element **138** defines a first polarity facing the multi-layer inductor **124**. The second magnetic element **140**: is arranged adjacent the first magnetic element **138**; and defines a second polarity, opposite the first polarity, facing the multi-layer inductor **124**.

2. Applications

[0033] Generally, in this variation, a system **100** for a human-computer interface (e.g., a mobile device **148**) includes: a touchscreen; a chassis **150**; a haptic actuator **110**; and a controller **166**. The chassis **150** includes: a middle frame **152**; and a rear frame **154** offset below the middle frame **152** and cooperating with the middle frame **152** to define a vertical gap within the chassis **150**. The haptic actuator **110** includes: a substrate **112** including a multi-layer inductor **124**; and a first magnetic element **138** arranged within the vertical gap within the chassis **150**.

[0034] In particular, the multi-layer inductor **124** and the first magnetic element **138** can cooperate to form a thin (e.g., 1.5 mm-thick) vibrator configured to oscillate the middle frame **152**—and thus the touchscreen supported on the middle frame **152**—and the rear frame **154** of the chassis **150**, such as when driven by the controller **166** responsive to application of an input on the touchscreen. For example, the multi-layer inductor **124** can be formed by a thin (e.g., 0.25 mm-thick) set of planar coil traces etched or fabricated on multiple layers within the substrate **112** and interconnected by vias extending through these layers. These interconnected planar coil traces can thus form one continuous inductor with multiple turns, one or more cores, and/or one or more windings facing (e.g., adjacent, arranged over) the first magnetic element **138**. The multi-layer inductor **124** can further include a set of terminals **134** connected to a set of planar coil traces and coupled to the controller **166**. Furthermore, the first magnetic element **138** is arranged below the multi-layer inductor **124** to form the unitary vibrator within the chassis **150** of the mobile device **148**.

[0035] In one example, the haptic actuator **110** includes a substrate **112** including: a first layer **116** including a first spiral trace **118** and bonded to a bottom side of the middle frame **152**; and a second layer **120** including a second spiral trace **122** and bonded to a bottom side of the first layer **116** of the substrate **112**. In this example, the first spiral trace **118** and the second spiral trace **122** of the substrate **112** cooperate to form the multi-layer inductor **124**.

[0036] In another example, the system **100** can include a set of spacer elements **142**: arranged proximal the multi-layer inductor **124** on the substrate **112**; and vertically supporting the first magnetic element **138** below the multi-layer inductor **124**. In particular, the set of spacer elements **142** can be bonded to a baseplate **136** (e.g., magnetic yoke) arranged over the multi-layer inductor **124**, and the first magnetic element **138** can be rigidly coupled to this baseplate **136** facing the multi-layer inductor **124** of the substrate **112**. In this example, the substrate **112**, the set of spacer elements **142**, the first magnetic element **138**, and the baseplate **136** form a unitary haptic actuator **110** of a particular height cooperating with the constrained vertical gap within the chassis **150**.

[0037] Therefore, the system **100** can include a haptic actuator **110** arranged within a height-constrained chassis **150** of a human-computer interface in order to deliver haptic feedback responses to a user interfacing with the human-computer interface, such as by delivering haptic feedback response to a palm of the user in contact with the rear frame **154** of the chassis **150**, and/or delivering haptic feedback response to a finger of the user in contact with the touchscreen and/or one or more buttons **164** (e.g., mechanical buttons, virtual buttons, soft buttons) on the human-computer interface.

3. Touch Sensor

[0038] The system **100** can include the haptic actuator **110** coupled to a touch sensor, such as integrated in a mobile device **148**, integrated in a trackpad module, and/or integrated at a steering wheel **168** for a vehicle, in order to deliver haptic feedback responsive to touch inputs detected at the touch sensor. In particular, the touch sensor: can be arranged below the cover layer **162** defining the touch sensor surface; and include a set of touch layers (e.g., rigid and/or flexible layers) that define the touch sensor. The set of touch layers can include: a top conductive layer and/or a second conductive layer, each including a set of traces that cooperate to form an array (e.g., grid array) of drive and sense electrode pairs **158** at the touch sensor. Thus, the system **100** can: read a set of electrical values from the touch sensor; and drive an oscillating voltage to the haptic actuator **110** in response to detecting a touch input on the touch sensor surface based on the set of electrical values.

3.1 Resistive Touch Sensor

[0039] In one implementation, the first and second conductive layers of the set of touch layers include columns of drive electrodes and rows of sense electrodes (or vice versa) that terminate in a grid array of drive and sense electrode pairs **158** on the top layer for the touch sensor. In this implementation, the system **100** further includes a force sensitive layer **160**: arranged over the top conductive layer of the set of touch layers (e.g., interposed between the top layer of the set of touch layers and the cover layer **162**); and exhibiting local changes in contact resistance across the set of drive and sense electrode pairs **158** responsive to location application of forces on the cover layer **162** (i.e., on the touch sensor surface). Furthermore, the first haptic actuator **110**: can be coupled (e.g., bonded) to a bottom surface of the second conductive layer in the set of touch layers; and is configured to oscillate the touch sensor surface responsive to touch inputs detected on the touch sensor surface.

[0040] Accordingly, during a scan cycle, the controller **166** can: serially drive the columns of drive electrodes; serially read electrical values—(e.g., voltages) representing electrical resistances across drive and sense electrode pairs **158**—form the rows of sense electrodes; detect a first touch input at a first location (e.g., an (x, y) location) on the touch sensor surface based on deviation of electrical values—read from a subset of drive and sense electrode pairs **158** adjacent the first location—from baseline resistance based electrical values stored for this subset of drive and sense electrode pairs **158**; and interpret a force magnitude of the first touch input based on a magnitude of this deviation. As described below, the controller **166** can then drive an oscillating voltage across the multi-layer inductor **124** in the substrate **112** during a haptic feedback cycle in response to the force magnitude of the first touch input exceeding a threshold input force.

[0041] The array of drive and sense electrode pairs **158** on the first and second conductive layers of the set of touch layers and the force sensitive layer **160** can thus cooperate to form a resistive touch sensor readable by the controller **166** to detect lateral positions, longitudinal positions, and force (or pressure) magnitudes of inputs (e.g., fingers, styluses, palms) on the touch sensor surface.

3.2 Capacitive Touch Sensor

[0042] In another implementation, the first and second conductive layers in the set of touch layers include columns of drive electrodes and rows of sense electrodes (or vice versa) that terminate in a grid array of drive and sense electrode pairs **158** on the top conductive layer in the set of touch layers.

[0043] During a scan cycle, the controller **166** can: serially drive the columns of drive electrodes; serially read electrical values (e.g., voltage, capacitance rise time, capacitance fall time, resonant frequency)—representing capacitive coupling between drive and sense electrode pairs **158**—from the rows of sense electrodes; and detect a first input at a first location (e.g., an (x, y) location) on the touch sensor surface based on deviation of electrical values—read from a subset of drive and sense electrode pairs **158** adjacent the first location—from baseline capacitance-based electrical values stored for this subset of drive and sense electrode pairs **158**. For example, the controller **166** can implement mutual capacitance or self-capacitance techniques to read capacitance values between these drive and sense electrode pairs **158** and to interpret inputs on the touch sensor surface based on these capacitance values.

[0044] The array of drive and sense electrode pairs **158** on the first and second conductive layers of the substrate **112** and the force-sensitive layer can thus cooperate to form a capacitive touch sensor readable by the controller **166** to detect lateral and longitudinal positions of inputs (e.g., fingers, styluses, palms) on the touch sensor surface.

3.3 Touchscreen

[0045] In one implementation, the system **100** includes a touchscreen, such as a touchscreen display **156** integrated into a chassis **150** of a mobile computing device, including: a display **156** element (e.g., rigid LED display **156**, flexible OLED display **156**); a set of drive and sense electrode pairs **158** arranged across the display **156**; and a cover layer **162** (e.g., glass layer) arranged over the touch sensor and defining a touch sensor surface. For example, the system **100** can include a double-sided PET layer defining a top side and a bottom side including (e.g., etched) a set of drive and sense electrode pairs **158**. In another example, the system **100** can include a printed layer defining a top side and a bottom side including the set of drive and sense electrode pairs **158**.

[0046] During a scan cycle, the controller **166** can: serially drive the columns of drive electrodes in the set of set of drive and sense electrode pairs **158**; serially read electrical values (e.g., voltage, capacitance rise time, capacitance fall time, resonant frequency)—representing capacitive coupling between drive and sense electrode pairs **158**—from the rows of sense electrodes in the set of set of drive and sense electrode pairs **158**; and detect a touch input at a first location (e.g., an (x, y) location) on the touch sensor surface based on deviation of electrical values—read from a subset of drive and sense electrode pairs **158** adjacent the first location—from baseline capacitance-based electrical values stored for this subset of drive and sense electrode pairs **158**. For example, the controller **166** can implement mutual capacitance techniques to read capacitance values between these drive and sense electrode pairs **158** and to interpret touch inputs on the touch sensor surface based on these capacitance values. The controller **166** can thus drive the oscillating voltage across the multi-layer inductor **124** to trigger a haptic feedback cycle in response to the touchscreen detecting the touch input on the touch sensor surface.

[0047] Therefore, the system **100** can: receive or integrate with the touchscreen (i.e., an integrated display **156** and touch sensor); and cooperate with the first magnetic element **138** and the controller **166** to vibrate the touch sensor surface over the touchscreen responsive to a touch input on the touch sensor surface, such as detected by a controller **166** coupled to the touchscreen.

[0048] In one implementation, the system **100** can include a touchscreen including a set of force sensor layers arranged below the display **156** element. The set of sensor layers includes: a first force layer (e.g., a second double sided print arranged on a second PET layer) including a first set of sensor traces (e.g., sense electrodes); and a second force layer arranged within the chassis **150** including a second set of sensor traces (e.g., drive electrodes) in alignment with the first set of sensor traces thereby forming the force sensor. In this implementation, the system **100** **100** can further include a set of deflection spacers: arranged below the set of force sensor layers; and coupled to a set of support locations defined along a bottom side of the touchscreen. The system **100** can thus: read a set of electrical values from the first set of sensor traces; and interpret a force magnitude of an input applied on the touch sensor surface based on deviations of the set of electrical values from baseline electrical values.

4. Haptic Actuator

[0049] Generally, the system **100** can include a haptic actuator **110** including: a substrate **112** defining a multi-layer inductor **124**; and a first magnetic element **138** cooperating with the multi-layer inductor **124** to form a thin (e.g., 1.3 mm to 1.6 mm-thick) unitary haptic actuator **110** arranged within a chassis **150** of a mobile device **148**. In particular, the haptic actuator **110** can be integrated into a computing device, such as a trackpad module, a smart watch, a laptop device, in order to deliver haptic feedback responsive to touch inputs received at the computing device. Additionally or alternatively, the haptic actuator **110** can also be integrated into non-computing devices, such as wristbands, steering wheels **168**, and/or arm rests, and coupled to an external controller **166** in order to deliver haptic feedback at the non-computing devices responsive to haptic feedback cycles executed by the external controller **166**.

4.1 Multi-Layer Inductor

[0050] The system **100** includes a multi-layer inductor **124** formed by a set of interconnected spiral traces fabricated within a set of conductive layers within the substrate **112** of the haptic actuator **110**. Generally, the total inductance of a single spiral trace may be limited by the thickness of the conductive layer. Therefore, the system **100** can include a stack of overlapping, interconnected spiral traces fabricated on a set of adjacent layers of the substrate **112** to form a multi-layer, multi-turn, and/or multi-core inductor that exhibits greater inductance—and therefore greater magnetic coupling to the set of magnetic elements—than a single spiral trace on a single conductive layer of the substrate **112**. These spiral traces can be coaxially aligned about a common vertical axis (e.g., centered over the set of magnetic elements) and electrically interconnected by a set of vias through the intervening conductive layers of the substrate **112**.

[0051] Furthermore, the substrate **112** can include conductive layers of different thicknesses. Accordingly, spiral traces within thicker conductive layers of the substrate **112** can be fabricated with narrower trace widths and more turns, and spiral traces within thinner conductive layers of the substrate **112** can be fabricated with wider trace widths and fewer turns in order to achieve similar electrical resistances within each spiral trace over the same coil footprint. For example, lower conductive layers within the substrate **112** can include heavier layers of conductive material (e.g., one-ounce copper approximately 35 microns in thickness) in order to accommodate narrower trace widths and more turns within the coil footprint in these conductive layers, thereby increasing inductance of each spiral trace and yielding greater magnetic coupling between the multi-layer inductor **124** and the set of magnetic elements during a haptic feedback cycle.

4.1.1 Single Core+Even Quantity of Coil Layers

[0052] In one implementation shown in FIG. **1**, the substrate **112** can include: a set of (e.g., two) conductive layers (e.g., flexible or rigid PCBA layers) etched to form a set of conductive traces; and a set of vias that connect the set of conductive traces across the set of conductive layers. In particular, the substrate **112** can include an even quantity of spiral traces fabricated within an even quantity of substrate layers within the substrate **112** to form a thin (e.g., 0.20 mm to 0.30 mm-thick) single-coil inductor.

[0053] For example, the substrate **112** can include a set of inductor layers **114** including a first layer **116** and a second layer **120**. In this example, the first layer **116** includes a first spiral trace **118** coiled in a first direction and defining a first end and a second end. In particular, the first spiral trace **118** can define a first planar coil spiraling inwardly in a clockwise direction from the first end at a periphery of the first planar coil to the second end proximal a center for the first planar coil. The second layer **120** includes a second spiral trace **122** coiled in a second direction opposite the first direction and defining a third end—electrically coupled to the second end of the first spiral trace **118**—and a fourth end. In particular, the second spiral trace **122** can define a second planar coil spiraling outwardly in the clockwise direction from the third end proximal the center of the second planar coil to the fourth end at a periphery of the second planar coil.

[0054] Accordingly: the second end of the first spiral trace **118** can be coupled to the third end of the second spiral trace **122** by a first via; and the first spiral trace **118** and the second spiral trace **122** can cooperate to form a single-core, two-layer inductor. The controller **166**: can be electrically connected (e.g., solder pads, ribbon cable, surface mounted) to the first end of the first spiral trace **118** and the fourth end of the second spiral trace **122**; and can drive these terminals of the multi-layer inductor **124** with an oscillating voltage during a haptic feedback cycle in order to induce an alternating magnetic field through the multi-layer inductor **124**, which couples the magnetic elements and oscillates the substrate **112** and therefore the cover layer **162** of the touchscreen arranged on the chassis **150**. In particular, when the controller **166** drives the multi-layer inductor **124** at a first polarity, current can flow in a continuous, clockwise direction through the first spiral trace **118** and the second spiral trace **122** to induce a magnetic field in a first direction around the multi-layer inductor **124**. When the controller **166** reverses the polarity across terminals of the multi-layer inductor **124**, current can reverse directions and flow in a continuous, counter-clockwise direction through the first spiral trace **118** and the second spiral trace **122** to induce a magnetic field in a second, opposite direction at the multi-layer inductor **124**.

[0055] Furthermore, in this implementation, the first end of the first spiral trace **118** can define a first terminal of the multi-layer inductor **124** and the second end of the second spiral trace **122** can define a second terminal of the multi-layer inductor **124**. The first terminal and the second terminal can be located on a periphery of the first layer **116** and the second layer **120** of the substrate **112** and thus enable direct connection to the controller **166** independent from the touch sensor.

[0056] In the aforementioned example, the substrate **112** can further include: a third layer **126** including a third spiral trace **128**; and a fourth layer **130** including a fourth spiral trace **132** in order to increase total inductance of the multi-layer inductor **124**. In this example, the third layer **126** includes a third spiral trace **128** coiled in the first direction and defining a fifth end—electrically coupled to the fourth end of the second spiral trace **122**—and a sixth end. In particular, the third spiral trace **128** can define a third planar coil spiraling inwardly in the clockwise direction from the fifth end at the periphery of the third planar coil to the sixth end proximal a center of the third planar coil. Furthermore, the fourth layer **130** includes a fourth spiral trace **132** coiled in the second direction and defining a seventh end—electrically coupled to the sixth end of the first spiral trace **118**—and an eighth end. In particular, the fourth spiral trace **132** can define a fourth planar coil spiraling outwardly in the clockwise direction from the seventh end proximal the center of the fourth planar coil to the eighth end at a periphery of the fourth planar coil.

[0057] Accordingly: the second end of the first spiral trace **118** can be coupled to the third end of the second spiral trace **122** by a first via; the fourth end of the second spiral trace **122** can be coupled to the fifth end of the third spiral trace **128** by a second via; the sixth end of the third spiral trace **128** can be coupled to the seventh end of the fourth spiral trace **132** by a third via; and the first, second, third, and fourth spiral traces, can cooperate to form a single-core, four-layer inductor. The controller **166** (or a driver): can be electrically connected to the first end of the first spiral trace **118** and the eighth end of the fourth spiral trace **132** (or "terminals" of the multi-layer inductor **124**); and can drive these terminals of the multi-layer inductor **124** with an oscillating voltage during a haptic feedback cycle in order to induce an alternating magnetic field through the multi-layer inductor **124**, which couples to the magnetic elements and oscillates the substrate **112**. In particular, when the controller **166** drives the multi-layer inductor **124** at a first polarity, current can flow in a continuous, clockwise direction through the first, second, third, and fourth spiral traces to induce a magnetic field in a first direction around the multi-layer inductor **124**. When the controller **166** reverses the polarity across terminals of the multi-layer inductor **124**, current can reverse directions and flow in a continuous, counter-clockwise direction through the first, second, third, and fourth spiral traces to induce a magnetic field in a second, opposite direction at the multi-layer inductor **124**.

[0058] Furthermore, in this implementation, because the multi-layer inductor **124** spans an even quantity (e.g., 2, 4) of conductive layers within the substrate **112**, the terminals of the multi-layer inductor **124** can be located on the peripheries of the first and last layers of the substrate **112** and thus enable direct connection to the controller **166** (or driver).

4.1.2 Single Core+Odd Quantity of Coil Layers

[0059] In another implementation shown in FIG. **2**, the multi-layer inductor **124** spans an odd number of (e.g., 3) conductive layers of the substrate **112**. In this implementation, a conductive layer of the substrate **112** can include two parallel and offset spiral traces that cooperate with other spiral traces in the multi-layer inductor **124** to locate the terminals of the multi-layer inductor **124** at the periphery of the multi-layer inductor **124** for direct connection to the controller **166** or driver.

[0060] In this example, the first inductive layer includes a first spiral trace **118** coiled in a first direction and defining a first end and a second end. In particular, the first spiral trace **118** can define a first planar coil spiraling inwardly in a clockwise direction from the first end at the periphery of the first planar coil to the second end proximal a center of the first planar coil. The second inductive layer includes a second spiral trace **122** coiled in a second direction opposite the first direction and defining a third end—electrically coupled to the second end of the first spiral trace **118** in the third layer **126**—and a fourth end. In particular, the second spiral trace **122** can define a second planar coil spiraling outwardly in the clockwise direction from the third end proximal the center of the second planar coil to the fourth end at a periphery of the second planar coil.

[0061] The first inductive layer further includes a third spiral trace **128** coiled in the first direction and defining a fifth end—electrically coupled to the fourth end of the second spiral trace **122** in the second layer **120**—and a sixth end. In particular, the third spiral trace **128** can define a third planar coil: spiraling inwardly in the clockwise direction from the fifth end at the periphery of the third planar coil to the sixth end proximal a center of the third planar coil; and nested within the first planar coil that also spirals inwardly in the clockwise direction within the first layer **116**.

[0062] Furthermore, a third layer **126** includes a fourth spiral trace **132** coiled in the second direction and defining a seventh end—electrically coupled to the sixth end of the first spiral trace **118**—and an eighth end. In particular, the fourth spiral trace **132** can define a fourth planar coil spiraling outwardly in the clockwise direction from the seventh end proximal the center of the fourth planar coil to the eighth end at a periphery of the fourth planar coil.

[0063] Accordingly: the second end of the first spiral trace **118** within the first layer **116** can be coupled to the third end of the second spiral trace **122** within the second layer **120** by a first via; the fourth end of the second spiral trace **122** within the second layer **120** can be coupled to the fifth end of the third spiral trace **128** within the first layer **116** by a second via; the sixth end of the third spiral trace **128** within the first layer **116** can be coupled to the seventh end of the fourth spiral trace **132** within the third layer **126** by a third via; and the first, second, third, and fourth spiral traces can cooperate to form a single-core, three-layer inductor. The controller **166**: can be electrically connected to the first end of the first spiral trace **118** within the first layer **116** and the eight end of the fourth spiral trace **132** within the third layer **126** (or "terminals" of the multi-layer inductor **124**); and can drive these terminals of the multi-layer inductor **124** with an oscillating voltage during a haptic feedback cycle in order to induce an alternating magnetic field through the multi-layer inductor **124**, which couples to the magnetic elements and oscillates the substrate **112**. In particular, when the controller **166** drives the multi-layer inductor **124** at a first polarity, current can flow in a continuous, clockwise direction through the first, second, third, and fourth spiral traces within the second, third, and fourth layers **130** of the substrate **112** to induce a magnetic field in a first direction around the multi-layer inductor **124**. When the controller **166** reverses the polarity across terminals of the multi-layer inductor **124**, current can reverse directions and flow in a continuous, counter-clockwise direction through the first, second, third, and fourth spiral traces to induce a magnetic field in a second, opposite direction at the multi-layer inductor **124**.

[0064] Therefore, in this implementation, the substrate **112** can include an even number of single-coil layers and an odd number of two-coil layers selectively connected to form a multi-layer inductor **124** that includes two terminals located on the periphery of the multi-layer inductor **124**.

4.1.3 Double Core+Even Quantity of Coil Layers

[0065] In another implementation shown in FIG. **4**, the substrate **112** includes an even quantity of spiral traces fabricated within an even quantity of substrate layers within the substrate **112** to form a dual-core inductor (i.e., two separate single-core inductors connected in series).

[0066] In this example, the first layer **116** includes a first spiral trace **118** coiled in a first direction and defining a first end and a second end. In particular, the first spiral trace **118** can define a first planar coil spiraling inwardly in a clockwise direction from the first end at the periphery of the first planar coil to the second end proximal a center of the first planar coil. The second layer **120** includes a second spiral trace **122** coiled in a second direction opposite the first direction and defining a third end—electrically coupled to the second end of the first spiral trace **118**—and a fourth end. In particular, the second spiral trace **122** can define a second planar coil spiraling outwardly in the clockwise direction from the third end proximal the center of the second planar coil to the fourth end at a periphery of the second planar coil. Accordingly: the second end of the first spiral trace **118** can be coupled to the third end of the second spiral trace **122** by a first via; and the first and second spiral traces **122** can cooperate to form a first single-core, four-layer inductor.

[0067] Additionally, in this example, the first layer **116** also includes a third spiral trace **128**: arranged adjacent the first spiral trace **118**; coiled in the second direction; and defining a fifth end and a sixth end, the fifth end electrically coupled to the first end of the first spiral trace **118**. Furthermore, the second layer **120** also includes a fourth spiral trace **132**: arranged adjacent the second spiral trace **122**; coiled in the first direction; defining a seventh end and an eighth end; and cooperating with the third spiral trace **128** to form a second multi-layer inductor. The seventh end is electrically coupled to the sixth end of the third spiral trace **128** and the eighth end defines a third terminal in the first set of terminals **134**.

[0068] The controller **166**: can be electrically connected to the set of terminals **134** and can drive these terminals with an oscillating voltage during a haptic feedback cycle in order to induce: a first alternating magnetic field through the first single-core, two-layer inductor (formed by the first and second spiral trace **122***s*); and a second alternating magnetic field—in phase with the first alternating magnetic field—through the second single-core, two-layer inductor (formed by the third and fourth spiral traces). In particular, when the controller **166** drives the two-layer, dual-core inductor at a first polarity, current can flow: in a continuous, clockwise direction through the first and second spiral traces **122** to induce a magnetic field in a first direction around the first single-core, two-layer inductor; and in a continuous, clockwise direction through the fourth and fifth spiral traces to induce a magnetic field in the first direction around the second single-core, two-layer inductor.

4.1.4 Double Core+Odd Quantity of Coil Layers

[0069] In a similar implementation, the substrate **112** includes an odd quantity of spiral traces fabricated within an odd quantity of substrate layers within the substrate **112** to form a dual-core inductor. For example, the dual-core inductor can include two single-coil, three-layer inductors connected in series. In this example, each single-coil, three-layer inductor includes: an even number of single-coil layers; and an odd number of two-coil layers selectively connected to form a single-coil, three-layer inductor that includes two terminals located on the periphery of the single-coil, three-layer inductor, as described above.

4.2 Magnetic Element

[0070] In one implementation, the system **100** includes: a baseplate **136** (e.g., a magnetic ferrous yoke) arranged below the substrate **112**; the first magnetic element **138** rigidly coupled to the baseplate **136** and facing the multi-layer inductor **124**; and a set of spacer elements **142** vertically supporting the baseplate **136**—and therefore the magnetic element-below the substrate **112** to form a unitary haptic actuator **110** configured to transfer lateral and/or vertical oscillating forces to the chassis **150** and the touchscreen. In particular, the spiral traces within the multi-layer inductor **124** can span a coil footprint, such as a rectangular or ellipsoidal footprint including: long sides parallel to a primary axis of the multi-layer inductor **124**; and short sides parallel to a secondary axis of the multi-layer inductor **124**.

[0071] In one example, the system **100** includes a set of spacer elements **142** including: a first spacer bonded to a bottom side of the substrate **112**; arranged about a first short side of the substrate **112**; extending a particular height (e.g., 0.90 mm to 1.10 mm) below the substrate **112**; and bonded to an upper side of the baseplate **136**. Additionally, in this example, the system **100** includes: a second spacer bonded to the bottom side of the substrate **112**; arranged about a second short side, opposite the first short side, of the substrate **112**; extending the particular height below the substrate **112**; and bonded to the upper side of the baseplate **136** to form a nominal gap (e.g., 0.20 mm to 0.30 mm-gap) between the multi-layer inductor **124** and the first magnetic element **138**. The first spacer and the second spacer cooperate with baseplate **136** to locate the first magnetic element **138** facing the multi-layer inductor **124** and thus forming a unitary haptic actuator **110** of a thin (e.g., 1.3 mm to 1.6 mm-thick) profile located within the chassis **150** of the mobile device **148**. Furthermore, the set of spacer elements **142** are formed of a low-durometer or elastic material that deflects laterally (or "shears") to enable the substrate **112** to translate laterally within the chassis **150** responsive to alternating magnetic coupling between the multi-layer inductor **124** and the first magnetic element **138***s* during a haptic feedback cycle.

4.2.1 Vertical Oscillation

[0072] In one implementation, the first magnetic element **138** is arranged relative to the multi-layer inductor **124** in order to induce an oscillating force—between the multi-layer inductor **124** and the first magnetic element **138**—normal to the touch sensor surface such that the substate oscillates vertically within the chassis **150** during a haptic feedback cycle.

[0073] In this implementation, the system **100** can include: the first magnetic element **138**: arranged within the chassis **150** of a mobile device **148**; defining a first magnetic polarity facing the multi-layer inductor **124**; approximately centered under the multi-layer inductor **124**; and extending laterally across the primary axis of the multi-layer inductor **124**. The first magnetic element **138** can thus generate a magnetic field that extends predominantly vertically toward the multi-layer inductor **124** and that is approximately centered under the multi-layer inductor **124**. More specifically, the first magnetic element **138** can generate a magnetic field that extends predominantly normal to the touchscreen proximal the center of the multi-layer inductor **124**. The controller **166** can then drive the multi-layer inductor **124** to a positive voltage during a haptic feedback cycle, and the multi-layer inductor **124** can generate a magnetic field that extends vertically through the substrate **112** in a first vertical direction, which: repels the first magnetic element **138** (arranged with the first polarity facing the multi-layer inductor **124**); and yields a first vertical force in a first vertical direction. When the controller **166** then reverses the voltage across the multi-layer inductor **124** during this haptic feedback cycle, the multi-layer inductor **124** can generate a magnetic field that extends vertically through the substrate **112** in a second, opposite vertical direction, which: attracts the first magnetic element **138**; yields a second vertical force in a second, opposite vertical direction; and draws the substrate **112** downward and back toward the first magnetic element **138**.

[0074] Therefore, by oscillating the polarity of the multi-layer inductor **124**, the controller **166** can: induce oscillating interactions (i.e., alternating attractive and repelling forces) normal to the touchscreen between the multi-layer inductor **124** and the first magnetic element **138**; and thus oscillate the substrate **112**—and thus the touchscreen-vertically (e.g., normal to the middle frame **152** and the rear frame **154** of the chassis **150**).

4.2.2 Vertical Oscillation: Dual-Core Multi-Layer Inductor

[0075] In this implementation the system **100** includes the substrate **112** including two adjacent single-core, multi-layer inductors connected in series and in phase (i.e., phased by 0°), and a first magnetic element **138**: defining a first magnetic polarity facing the first single-core multi-layer inductor **124**; approximately centered under the first single-core multi-layer inductor **124**; and extending laterally across the primary axis of the first single-core multi-layer inductor **124**. The system **100** can similarly include a second magnetic element **140**: arranged adjacent the first magnetic element **138**; defining the first magnetic polarity facing the second single-core multi-layer inductor **124**; approximately centered under the second single-core multi-layer inductor **124**; and extending laterally across the primary axis of the second single-core multi-layer inductor **124**.

4.2.3 Horizontal Oscillation

[0076] In another implementation, as described above, the system **100** can be configured for horizontal oscillations of the touchscreen by exchanging the first magnetic element **138** that spans the width of and is centered under the multi-layer inductor **124** for a pair of opposing magnetic elements arranged under the multi-layer inductor **124**, and on each of the primary axis of the multi-layer inductor **124**.

[0077] In this implementation, the system **100** can include a first magnetic element **138**: arranged within the chassis **150** of the mobile device **148**; defining a first magnetic polarity facing the multi-layer inductor **124**; and extending along a first side of the primary axis. In this implementation, the system **100** can similarly include a second magnetic element **140**: arranged within the chassis **150** of the mobile device **148**; defining a second magnetic polarity facing the multi-layer inductor **124**; and extending along a second side of the primary axis adjacent the first magnetic element **138**. In particular, the first magnetic element **138** can be arranged immediately adjacent and the second magnetic element **140**. The first and second magnetic element **140**_s_ can be arranged directly under the multi-layer inductor **124** and can face the multi-layer inductor **124** with opposing polarities. When the controller **166** drives the multi-layer inductor **124** with an alternating voltage (or current), the multi-layer inductor **124** can generate a magnetic field that extends vertically through the substrate **112** (e.g., normal to the substrate **112**) and interacts with the opposing magnetic fields of the first and second magnetic element **140**_s_. More specifically, when the controller **166** drives the multi-layer inductor **124** to a positive voltage during a haptic feedback cycle, the multi-layer inductor **124** can generate a magnetic field that extends vertically through the substrate **112** in a first vertical direction, which: attracts the first magnetic element **138** (arranged with the first polarity facing the multi-layer inductor **124**); repels the second magnetic element **140** (arranged with the second polarity facing the multi-layer inductor **124**); yields a first lateral force in a first lateral direction; and shifts the substrate **112** laterally in the first lateral direction. When the controller **166** then reverses the voltage across the multi-layer inductor **124** during this haptic feedback cycle, the multi-layer inductor **124** can generate a magnetic field that extends vertically through the substrate **112** in the opposing vertical direction, which: repels the first magnetic element **138**; attracts the second magnetic element **140**; yields a second lateral force in a second, opposite lateral direction; and shifts the substrate **112** laterally in the second lateral direction.

[0078] Therefore, by oscillating the polarity of the multi-layer inductor **124**, the controller **166** can: induce oscillating interactions (i.e., alternating attractive and repelling forces)—parallel to the touchscreen—between the multi-layer inductor **124** and the magnetic elements; and thus oscillate the substrate **112** and the touchscreen horizontally.

4.2.4 Horizontal Oscillation: Dual-Core Multi-Layer Inductor

[0079] In one implementation, the system **100** includes: the substrate **112** including two adjacent single-core, multi-layer inductors connected in series; and a first magnetic element **138** defining a first magnetic polarity facing the first single-core multi-layer inductor **124**, and extending along a first side of a first primary axis of the first single-core multi-layer inductor **124**; a second magnetic element **140** defining a second magnetic polarity facing the first single-core multi-layer inductor **124**, and extending along a second side of the first primary axis adjacent the first magnetic element **138**; a third magnetic element defining the second magnetic polarity facing the second single-core multi-layer inductor **124**, and extending along a first side of a second primary axis of the second single-core multi-layer inductor **124**; and a fourth magnetic element defining the first magnetic polarity facing the second single-core multi-layer inductor **124**, and extending along a second side of the second primary axis adjacent the third magnetic element.

[0080] Accordingly, by oscillating the polarity of the first and second single-core multi-layer inductors **124**—which include traces that spiral in the same direction and are therefore in phase—the controller **166** can: induce oscillating interactions parallel to the substrate **112** between the first single-core multi-layer inductor **124**, the first magnetic element **138**, and the second magnetic element **140** and between the second single-core multi-layer inductor **124**, the third magnetic element, and the fourth magnetic element; and thus oscillate the substrate **112** horizontally.

4.3 Waterproofing

[0081] In one implementation, the system **100** includes a set of spacer elements **142** including: a first spacer element **144** arranged proximal a first lateral edge of the baseplate **136**; and interposed between the baseplate **136** and a bottom layer of the substrate **112**; and a second spacer element **146** arranged proximal a second lateral edge, opposite the first lateral edge, of the baseplate **136** and interposed between the baseplate **136** and the bottom layer of the substrate **112**. Thus, in this implementation, the haptic actuator **110** includes: a third lateral edge, normal to the first lateral edge and the second lateral edge; and a fourth lateral edge, opposite the third lateral edge, each exposed and susceptible to environmental damage (e.g., dust damage, water damage). Accordingly, the system **100** can include a waterproofing membrane: extending across the third lateral edge and the fourth lateral edge of the haptic actuator **110**; retained about a perimeter of the substrate **112**; and cooperating with the baseplate **136** to seal the haptic actuator **110**. For example, the waterproofing membrane can include a silicone or PTFE (e.g., expanded PTFE) film bonded over the substrate **112** and the baseplate **136**. The system **100** can also include a glass or other cover layer **162** bonded over the waterproofing membrane and extending up to a perimeter of the substrate **112**. Therefore, the system **100** can prevent moisture and particulate ingress into the haptic actuator **110** and onto the substrate **112** and the first magnetic element **138**.

5. Mobile Device Chassis Integration

[0082] Generally, the system **100** includes a chassis **150** including: a middle frame **152** supporting the touchscreen; and a rear frame **154** arranged below the middle frame **152** and defining a vertical gap between the middle frame **152** and the rear frame **154**. The system **100** further includes the haptic actuator **110**: arranged intermediate the middle frame **152** and the rear frame **154**; and bonded to the middle frame **152** and/or the rear frame **154** in order to transfer oscillating forces generated by the haptic actuator **110** to the middle frame **152**—and therefore the touchscreen—and the rear frame **154** of the chassis **150**.

5.1 Middle Frame Integration

[0083] In one implementation, the system **100** includes: the haptic actuator **110** including the substrate **112** coupled (e.g., adhesively bonded) to the middle frame **152** of the chassis **150**; and a set of standoffs arranged proximal the haptic actuator **110** within the chassis **150**. In this implementation, the set of standoffs: is coupled (e.g., adhesively bonded, rigidly mounted) to the middle frame **152** and the rear frame **154** of the chassis **150**; vertically supports the rear frame **154** below the middle frame **152**; and is configured to transfer oscillating forces generated by the haptic actuator **110**—including the substrate **112** bonded to the middle frame **152**—to the rear frame **154** of the chassis **150**, thereby delivering these oscillating forces, such as to the user's palm operating a mobile device **148**.

[0084] In one example, the system **100** includes a substrate **112** including a first layer **116**: arranged (e.g., adhesively bonded to) the middle frame **152** of the chassis **150**; and a second layer **120** arranged below the first layer **116**. In particular the first layer **116** defines: a top side adhesively bonded to a bottom side of the middle frame **152** of the chassis **150**; and a bottom side adhesively bonded to a top side of the second layer **120**. In this example, the system **100** further includes: the set of spacer elements **142** vertically supporting a baseplate **136** below the substrate **112**; and the first magnetic element **138** rigidly coupled to the baseplate **136** and facing the multi-layer inductor **124**. In particular, the substrate **112**, set of spacer elements **142**, first magnetic element **138**, and the baseplate **136** cooperate to define a particular height (e.g., 1.4 mm to 1.7 mm-thickness) extending within the vertical gap between the middle frame **152** and the rear frame **154**. Additionally, the system **100** can include a set of standoffs: arranged proximal the haptic actuator **110** within the chassis **150**; vertically supporting the rear frame **154** below the middle frame **152**; and defining the vertical gap between the middle frame **152** and the rear frame **154**. In this example, the set of standoffs can include a first standoff: arranged proximal a first side of the haptic actuator **110**; and arranged intermediate the middle frame **152** and the rear frame **154**. Additionally, the set of standoffs can include a second standoff: arranged proximal a second side, opposite the first side, of the haptic actuator **110**; arranged intermediate the middle frame **152** and the rear frame **154**; and cooperating with the first standoff to define the vertical gap within the chassis **150**. Furthermore, the set of standoffs can be formed of a low-durometer or elastic material that deflects laterally within the chassis **150** responsive to alternating magnetic coupling between the multi-layer inductor **124** and the first magnetic element **138** during the haptic feedback cycle.

[0085] Therefore, the system **100** can, during a haptic feedback cycle, drive an oscillating voltage through the multi-layer inductor **124** in order to induce magnetic coupling between the multi-layer inductor **124** and the first magnetic element **138**, thereby oscillating the substrate **112** bonded to the middle frame **152** of the chassis **150**. As a result, the oscillating forces generated by the haptic actuator **110** are transferred: to the touchscreen supported on the middle frame **152** via the substrate **112** bonded to the middle frame **152** of the chassis **150**; and to the rear frame **154** of the chassis **150** via the set of standoffs arranged proximal the haptic actuator **110** within the chassis **150**.

[0086] In another implementation, the system **100** includes a haptic actuator **110** including a multi-layer inductor **124** integrated into an existing printed circuit board assembly (PCBA) arranged within the chassis **150** of a mobile device **148**. In this implementation, the system **100** includes a PCBA: arranged (e.g., adhesively bonded to) a bottom side of the middle frame **152** of the chassis **150**; and including substrate layers defining the multi-layer inductor **124** facing the first magnetic element **138** to form the haptic actuator **110** within the chassis **150**. Additionally, the set of standoffs can be arranged: intermediate the PCBA and the rear frame **154** within the chassis **150**; and proximal the multi-layer inductor **124** in the PCBA in order to define the vertical gap within the chassis **150**. The system **100** can then drive an oscillating voltage through the multi-layer inductor **124** integrated in the PCBA in order to induce magnetic coupling between the PCBA and the first magnetic element

138, thereby oscillating the PCBA and therefore the touchscreen arranged over the middle frame **152** of the chassis **150**.

[0087] In one example, the system **100** includes a PCBA including: a top layer arranged (e.g., adhesively bonded to) a bottom side of the middle frame **152** of the chassis **150**; an intermediate layer arranged below the top layer and including a first spiral trace **118**; and a bottom layer arranged below the intermediate layer and including a second spiral trace **122** cooperating with the first spiral trace **118** to form the multi-layer inductor **124** facing the first magnetic element **138**. In this example, the system **100** includes a set of spacer elements **142**: arranged below the bottom layer of the PCBA, proximal the multi-layer inductor **124** on the PCBA; and vertically supporting the first magnetic element **138** below the multi-layer inductor **124** within the chassis **150**. Additionally, the system **100** includes a set of standoffs including a first standoff: arranged proximal a first side of the multi-layer inductor **124** on the PCBA; and arranged intermediate the PCBA and the rear frame **154** of the chassis **150**. Furthermore, the set of standoffs includes a second standoff: arranged proximal a second side, opposite the first side, of the multi-layer inductor **124** on the PCBA; and arranged intermediate the PCBA and the rear frame **154** of the chassis **150** to define the vertical gap within the chassis **150**.

[0088] Therefore, the system **100** can drive an oscillating voltage through the multi-layer inductor **124** integrated within the PCBA in order to induce magnetic coupling between the multi-layer inductor **124** and the first magnetic element **138** and oscillate the PCBA, thereby eliminating external electrical connections from the controller **166** directly to the haptic actuator **110** within the chassis **150** of the mobile device **148**.

5.2 Rear Frame Integration

[0089] In one implementation, the system **100** includes the haptic actuator **110** including: the substrate **112** arranged (e.g., adhesively bonded to) a bottom side of the middle frame **152** of the chassis **150**; a baseplate **136** (e.g., magnetic yoke) arranged (e.g., adhesively bonded to) a top side of the rear frame **154** of the chassis **150** below the multi-layer inductor **124**; and the first magnetic element **138** rigidly coupled to the baseplate **136** and facing the multi-layer inductor **124** to form the haptic actuator **110** within the chassis **150**. In this implementation, the first magnetic element **138**: is located approximately centered to the multi-layer inductor **124** of the substrate **112**; extends laterally across a primary axis of the multi-layer inductor **124**; and is coupled to the baseplate **136** to define a nominal gap between the substrate **112** and the first magnetic element **138**. In particular, in this implementation, the system **100** can eliminate flexible coupling between the substrate **112** and the first magnetic element **138** of the haptic actuator **110** and transfer oscillating forces—generated from the haptic actuator **110**—directly to the middle frame **152** and the rear frame **154** of the chassis **150**.

[0090] In one example, the system **100** can drive an oscillating voltage across the multi-layer inductor **124** in the substrate **112** in order to induce magnetic coupling between the multi-layer inductor **124** and the first magnetic element **138**, which in turn: oscillates the substrate **112**—bonded to the middle frame **152** of the chassis **150**—and thus the touchscreen; and oscillates the baseplate **136** bonded to the rear frame **154** of the chassis **150**. Therefore, the system **100** can deliver haptic feedback (e.g., oscillating forces) directly to the middle frame **152** and the rear frame **154** of the chassis **150** via the haptic actuator **110**, thereby reducing or eliminating dampening of this haptic feedback resulting from rigid coupling of: the first magnetic element **138** to the substrate **112** via the set of spacer elements **142**; and the rear frame **154** to the middle frame **152** of the chassis **150** via the set of standoffs.

[0091] In another implementation, the system **100** includes a haptic actuator **110** including: a multi-layer inductor **124** integrated into an existing printed circuit board assembly (PCBA) arranged within the chassis **150** of a mobile device **148**; a baseplate **136** (e.g., magnetic yoke) arranged (e.g., adhesively bonded) to a top side of the rear frame **154** of the chassis **150** below the multi-layer inductor **124**; and the first magnetic element **138** rigidly coupled to the baseplate **136** and facing the multi-layer inductor **124** to form the haptic actuator **110** within the chassis **150**. In this implementation, the system **100** includes the PCBA: arranged (e.g., adhesively bonded) to a bottom side of the middle frame **152** of the chassis **150**; and including substrate layers defining the multi-layer inductor **124** facing the first magnetic element **138** to form the haptic actuator **110** within the chassis **150**. Additionally, the first magnetic element **138**: is located approximately centered to the multi-layer inductor **124** of the PCBA; extends across a primary axis of the multi-layer inductor **124**; and coupled to the baseplate **136** to define a nominal gap between the substrate **112** and the first magnetic element **138**. Therefore, the system **100** can include a haptic actuator **110** including: a multi-layer inductor **124** integrated into an existing PCBA within the chassis **150** of a mobile device **148**; and a first magnetic element **138** directly bonded to a rear frame **154** of the chassis **150** and facing the multi-layer inductor **124** of the PCBA. As a result, the system **100** can eliminate external electrical connections from the controller **166** to the haptic actuator **110** within the chassis **150** and eliminate dampening of oscillating forces—generated by the haptic actuator **110**—resulting from rigid coupling of the substrate **112** to the first magnetic element **138**.

5.3 Haptic Actuator Localization

[0092] Generally, the system **100** can include a set of haptic actuators arranged within the chassis **150** of a mobile device **148** in order to deliver localized haptic feedback response to regions of the touchscreen coupled to the chassis **150**.

5.3.1 Touchscreen Haptic Feedback Localization

[0093] In one implementation, the system **100** can include: a first haptic actuator **110** arranged within the chassis **150** and below a first region of the touchscreen; and a second haptic actuator arranged within the chassis **150** and below a second region of the touchscreen. The system **100** can thus: detect a touch input on the touchscreen; interpret a particular region of the touch input on the touchscreen; and drive an oscillating voltage to a particular haptic actuator **110** arranged below the particular region of the touchscreen in order to deliver a localized haptic feedback response to this first region of the touchscreen during a haptic feedback cycle.

[0094] In another implementation, the system **100** can include: a first touchscreen arranged on the chassis **150**; and a second touchscreen arranged adjacent to the first touchscreen on the chassis **150**. Additionally, the system **100** can include: a first haptic actuator **110** arranged within the chassis **150** below the first touchscreen; and a second haptic actuator arranged within the chassis **150** below the second touchscreen. The system **100** can then selectively drive an oscillating voltage to these haptic actuators responsive to detecting inputs on the first touchscreen and/or the second touchscreen on the chassis **150**, thereby delivering haptic feedback response to the first touchscreen and the second touchscreen during a haptic feedback cycle.

5.3.2 Button Haptic Feedback Localization

[0095] Generally, a "button" as referred to herein is an element of a user interface (e.g., virtual, mechanical) which a user can select to perform a particular action. In one implementation, the system **100** can include: a haptic actuator **110** arranged proximal a lateral edge within the chassis **150**; and a button **164** coupled (e.g., mechanically coupled) to the haptic actuator **110** at the lateral edge of the chassis **150** (e.g., embedded within the lateral edge of the chassis **150**, protruding from the chassis **150**). The system **100** can thus, detect a touch input at the button **164** arranged at the lateral edge of the chassis **150**; and drive an oscillating voltage to the haptic actuator **110**—coupled to the button **164** at the lateral edge of the chassis **150**—in order to transfer oscillating forces from the haptic actuator **110** to the button **164** and thus deliver a localized haptic feedback response to a user interfacing with the button **164** of the mobile device **148**.

[0096] In one example, the button **164** includes a mechanical switch: arranged about a lateral edge of the mobile device **148** (e.g., flush with the lateral edge, proud from the lateral edge); and coupled to the haptic actuator **110**. In another example, the button **164** defines a virtual button: arranged at the lateral edge of the mobile device **148**; and defining a touch sensor (e.g., resistive touch, capacitive touch) configured to detect lateral touch inputs applied by a user. Thus, the system **100** can: detect a touch input at a particular location about the lateral edge of the mobile device **148**; and trigger a haptic feedback cycle at the haptic actuator **110** in order to deliver haptic feedback in response to detecting the touch input. In another example, the button **164** defines a touch region about the lateral edge of the mobile device **148** arranged adjacent the haptic actuator **110**. In this example and as described below, the system **100** can: read a set of electrical values from the multi-layer inductor **124** at the haptic actuator **110**; detect a touch input at the touch region based on deviations of the set of electrical values from baseline electrical values; and trigger a haptic feedback cycle at the haptic actuator **110** in response to detecting the touch input.

[0097] In another implementation, the system **100** can include: a first set of haptic actuators arranged proximal a first lateral edge within the chassis **150**; and a second set of haptic actuators arranged proximal a second lateral edge, opposite the first lateral edge, within the chassis **150**. In this implementation, each haptic actuator **110**, in the first set of haptic actuators can include a button **164** coupled (e.g., mechanically) coupled to the haptic actuator **110** at the first lateral edge of the chassis **150**. Similarly, each haptic actuator **110**, in the second set of haptic actuators include a button **164** coupled (e.g., mechanically) coupled to the haptic actuator **110** at the first lateral edge of the chassis **150**. The system **100** can thus, detect a first touch input at a first button **164** arranged on the first lateral edge of the chassis **150**; detect a second touch input at a second button **164** arranged on the second lateral edge of the chassis **150**; and drive a first oscillating voltage to a first haptic actuator **110** coupled to the first button **164** at the first lateral edge of the chassis **150**; and drive a second oscillating voltage to a second haptic actuator coupled to the second button **164** at the second lateral edge of the chassis **150**.

[0098] In one example, the system **100** can include a haptic actuator **110**: arranged within the vertical gap of the chassis **150**; and arranged proximal a first lateral edge of the chassis **150**. In this example, the haptic actuator **110** includes: a substrate **112** including a set of inductor layers **114** forming a multi-layer inductor **124**; and a magnetic element defining the first polarity and facing the multi-layer inductor **124**. Furthermore, the system **100** includes a button **164**: arranged flush with the first lateral edge of the chassis **150**; coupled to the haptic actuator **110**; and defining a touch sensor surface at the mobile device **148**. The controller **166** is configured to, in response to detecting a touch input at the touch sensor surface, drive an oscillating voltage across the multi-layer inductor **124** to: induce alternating magnetic coupling between the multi-layer inductor **124** and the magnetic element; and oscillate the touch sensor surface relative the magnetic element.

[0099] In yet another implementation as described in U.S. Non-Provisional application Ser. No. 17/722,994, filed on 18 Apr. 2022, which is hereby incorporated in its entirety by this reference, the system **100** can be integrated into a mobile device **148** (e.g., a smartphone, a tablet, a laptop computer) defining a continuous pressure sensor along one or more sides of the mobile device and thus enable the mobile device to detect both force magnitudes and locations of inputs along the side of the mobile device over a range of force magnitudes and over a (nearly-) continuous range of location. In particular, the system **100** can include: a sensor module arranged behind side of a mobile device; and a controller that detects locations and force magnitudes of inputs on the side of the mobile device based on sense signals output by the sensor module, dynamically links these side inputs to particular input types based on these input characteristics and/or virtual buttons rendered on a display of the mobile device adjacent the locations of these side inputs, and then triggers context-dependent (e.g., application-specific) command functions at the mobile device and execute haptic feedback cycles at the haptic actuators in the mobile device based on these input types. For example, the sensor module can be integrated into a side of a mobile device (e.g., in place of mechanical buttons) in order to transform the perimeter of the mobile device into a force-sensitive input surface. The controller (or other processor in the mobile device) can then dynamically reassign regions or segments of the side of the mobile device to different input types (e.g., volume control, camera shutter control) based on: a lock screen, home screen, or application open on the mobile device; an orientation of the mobile device; a last touch location on the side of the mobile device; and/or custom settings entered by the user.

6. Modifying Haptic Feedback Output

[0100] In one implementation, the system **100** can be modified to increase haptic feedback response from the haptic actuator **110** within the chassis **150** while maintaining a target height within the vertical gap within the chassis **150**. In one example, a width and length of the substrate **112** and the first magnetic element **138** can be concurrently increased while maintaining the target height within the chassis **150**, which in turn increases haptic feedback response from the haptic actuator **110**. In another example, the system **100** can include a haptic actuator **110** including: a substrate **112** including a dual-core multi-layer inductor **124**; and a set of magnetic elements arranged over the dual-core multi-layer inductor **124** to increase haptic feedback response from the haptic actuator **110**.

[0101] In another implementation, the system **100** can increase haptic feedback response from the haptic actuator **110** within the chassis **150** by increasing a vertical height of the haptic actuator **110** within the vertical gap within the chassis **150**. For example, the system **100** can be modified, such as by increasing thickness of the first magnetic element **138**, and/or increasing copper thickness for the spiral traces of the multi-layer inductor **124**, thereby increasing haptic feedback output by the haptic actuator **110**.

7. Variation: Inductive Force Sensing

[0102] In one variation, the system **100** includes: a touchscreen; a chassis **150**; a haptic actuator **110**; and a controller **166**. The touchscreen includes a set of drive and sense electrode pairs **158**. The chassis **150** includes: a middle frame **152** arranged below the touchscreen; and a rear frame **154** arranged below the middle frame **152** and defining a vertical gap between the middle frame **152** and the rear frame **154**. The haptic actuator **110** is arranged within the vertical gap and includes: a substrate **112**; and a first magnetic element **138**. The substrate **112** includes a first layer **116** and a second layer **120**. The first layer **116**: is arranged below the middle frame **152** of the chassis **150**; and includes a first spiral trace **118** coiled in a first direction and defining a first terminal at a periphery of the substrate **112**. The second layer **120**: is arranged below the first layer **116**; includes a second spiral trace **122** coiled in a second direction, opposite the first direction, coupled to the first spiral trace **118** and defining a second terminal at the periphery of the substrate **112**; and cooperates with the first spiral trace **118** to form a multi-layer inductor **124**. The first magnetic element **138**: is arranged below the substrate **112**; and defines a first polarity facing the multi-layer inductor **124**.

[0103] In this variation, the controller **166** is configured to: read a first set of electrical values from the multi-layer inductor **124** during a first time period; interpret a touch input at the touchscreen based on a first change in electrical values in the first set of electrical values; and, in response to interpreting the touch input, drive an oscillating voltage across the multi-layer inductor **124** during a first haptic feedback cycle to induce alternating magnetic coupling between the multi-layer inductor **124** and the first magnetic element **138** in order to oscillate the touchscreen.

8. Example: Seamless Mobile Device

[0104] In one implementation, the system **100** includes: a haptic actuator **110** integrated into a human-computer interface system **100** (e.g., a laptop device); a cover layer **162** defining a seamless trackpad surface and/or a seamless keyboard surface across the chassis **150**; and a controller **166** configured to trigger the haptic actuator **110** to oscillate the seamless trackpad surface and/or seamless keyboard surface responsive to touch inputs applied to the touch sensor surface.

[0105] In one example, the system **100** can include: a substrate **112**; a rigid (e.g., aluminosilicate glass) layer; an array of spring elements; a coupling plate; a haptic feedback actuator; and a controller **166**. The substrate **112** includes: a top layer; a bottom layer; an array of force sensors arranged on the bottom layer; and an array of support locations arranged on the bottom layer adjacent the array of force sensors. The rigid layer (hereinafter the "glass layer"): includes a top layer defining a touch sensor surface and a bottom layer extending across the top layer of the substrate **112**; and is bonded (e.g., with a pressure sensitive adhesive) to the top layer of the substrate **112**.

[0106] The array of spring elements is configured to couple the substrate **112** to the chassis **150** and to yield to displacement of the substrate **112** downward toward the chassis **150** responsive to forces applied to the touch sensor surface, each spring element in the array of spring elements coupled to the substrate **112** at a support location in the array of support locations. The coupling plate is configured to couple to the chassis **150** adjacent the array of spring elements and effect capacitance values of the array of force sensors responsive to displacement of the substrate **112** toward the coupling plate.

[0107] The haptic actuator **110**: is arranged below the substrate **112**; and is configured to oscillate the touch sensor surface in a vertical direction (i.e., the z-direction) in response to interpreting a force magnitude exceeding a target force magnitude for an input applied to the touch sensor surface. The controller **166** is configured to read capacitance values from the array of force sensors and interpret force magnitudes of inputs applied to the touch sensor surface based on capacitance values read from the array of force sensors.

[0108] In another example, the chassis **150** defines a cavity **178** proximal a trackpad region of the chassis **150**. In this example, the cover layer **162**: defines a continuous surface across the trackpad region of the chassis **150**; and defines a first touch region **180** within the trackpad region of the cover layer **162**. Additionally, the system **100** includes a touch sensor layer: arranged below the first touch region **180** of the cover layer **162**; and comprising a first set of drive and sense electrode pairs **158** patterned across the touch sensor layer and defining a touch sensor. The haptic actuator **110**: is arranged within the cavity **178** of the chassis **150**; and includes the substrate **112** including a top layer bonded to the touch sensor layer. Thus, the controller **166** is configured to: read a first set of electrical values from the first set of drive and sense electrode pairs **158**; and detect the first touch input on the touch sensor surface based on the first set of electrical values.

[0109] In yet another example, the system **100** can include a mobile device **148** including: a touch display encompassing a front face and lateral sides of the device; and a set of haptic actuators **110** arranged within a chassis supporting the touch display. Thus, the mobile device **148** can define a seamless touch sensor surface encompassing the front face and the lateral sides of the mobile device **148**. Additionally, or alternatively, the touch display can also encompass the rear face of the mobile device **148**. Therefore, the system **100** can: detect touch inputs applied at locations on the seamless touch sensor surface; and execute haptic feedback cycles at a haptic actuator **110** (or set of haptic actuators) arranged within the mobile device **148** in response to detecting inputs on the seamless touch sensor surface.

9. Example: Vehicle Integration

[0110] In one implementation, the system **100** includes a haptic actuator **110**: arranged within a vehicle, such as at a display screen in the vehicle, at the steering wheel **168**, and/or at the arm rest of the vehicle; and configured to—responsive to control inputs received by an operator within the vehicle—deliver haptic feedback to the operator and/or passenger within the vehicle.

[0111] In one example, the system **100** includes a steering wheel **168** including: a rim **170** rotatable about a first axis to steer a vehicle; and a hub **172** coupled to the rim **170** and defining a first input region **174** and a cavity **178** proximal the first input region **174**. In this example, the haptic actuator **110** is arranged within the cavity **178** of the hub **172**. Furthermore, the cover layer **162**: extends across the first input region **174** of the hub **172**; and defines a first key location **176** over the first haptic actuator **110**. Thus, the controller **166** is configured to, in response to detecting the first touch input at the touch sensor surface, register a first keystroke of a first key type associated with the first key location **176** defined over the first haptic actuator **110**. In one variation of this example, the first key location **176** can correspond to a volume control (e.g., volume up, volume down) for an infotainment system **100** of the vehicle. Therefore, in response to detecting a first touch input at the first key location **176**, the controller **166** can: modify volume of media broadcast within the vehicle; and trigger a haptic feedback cycle at the haptic actuator **110** to deliver haptic feedback at the first key location **176** on the hub **172** of the steering wheel **168**.

[0112] Therefore, the system **100** can include the haptic actuator **110** arranged within the vehicle (e.g., steering wheel **168**, vehicle seat, display screen, arm rest) in order to deliver haptic feedback responsive to user inputs detected by the controller **166** within the vehicle.

[0113] The systems and methods described herein can be embodied and/or implemented at least in part as a machine configured to receive a computer-readable medium storing computer-readable instructions. The instructions can be executed by computer-executable components integrated with the application, applet, host, server, network, website, communication service, communication interface, hardware/firmware/software elements of a user computer or mobile device **148**, wristband, smartphone, or any suitable combination thereof. Other systems and methods of the embodiment can be embodied and/or implemented at least in part as a machine configured to receive a computer-readable medium storing computer-readable instructions. The instructions can be executed by computer-executable components integrated by computer-executable components integrated with apparatuses and networks of the type described above. The computer-readable medium can be stored on any suitable computer readable media such as RAMs, ROMs, flash memory, EEPROMs, optical devices (CD or DVD), hard drives, floppy drives, or any suitable device. The computer-executable component can be a processor but any suitable dedicated hardware device can (alternatively or additionally) execute the instructions.

[0114] As a person skilled in the art will recognize from the previous detailed description and from the figures and claims, modifications and changes can be made to the embodiments of the invention without departing from the scope of this invention as defined in the following claims.

I claim:

1. A system comprising:
- a first haptic actuator comprising:
  - a substrate comprising a first inductor; and
  - a baseplate arranged opposite the substrate;
  - a first magnetic element:
    - arranged on the baseplate; and
    - defining a first polarity facing the first inductor; and
  - a first set of spacer elements:
    - interposed between the baseplate and the substrate;
    - arranged proximal perimeter edges of the baseplate; and
    - defining a nominal gap between the first magnetic element and the first inductor;
- a controller configured to drive an oscillating voltage across the first inductor to induce alternating magnetic coupling between the first multi-layer inductor and the first magnetic element.

2. The inventions as shown and/or described herein.

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